B. Anjan Kumar Prusty
Rachna Chandra
P.A. Azeez *Editors*

Wetland Science

Perspectives From South Asia

Springer

Wetland Science

B. Anjan Kumar Prusty • Rachna Chandra
P.A. Azeez
Editors

Wetland Science

Perspectives From South Asia

Springer

Editors
B. Anjan Kumar Prusty
Environmental Impact Assessment Division
Gujarat Institute of Desert Ecology
Bhuj, Gujarat, India

Rachna Chandra
Terrestrial Ecology Division
Gujarat Institute of Desert Ecology
Bhuj, Gujarat, India

P.A. Azeez
Sálim Ali Center for Ornithology and Natural History
Coimbatore, Tamil Nadu, India

ISBN 978-81-322-3713-6 ISBN 978-81-322-3715-0 (eBook)
DOI 10.1007/978-81-322-3715-0

Library of Congress Control Number: 2017933841

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer (India) Pvt. Ltd.
The registered company address is: 7th Floor, Vijaya Building, 17 Barakhamba Road, New Delhi 110 001, India

We owe this book to our teachers and mentors who introduced us to the mystifying wetland habitats. Further, we dedicate this compilation to researchers and field staff who have spent years looking at wetlands and their linkages with human society.

Foreword

It gives me great pleasure to introduce the book *Wetland Science: Perspectives From South Asia* edited by Dr. B. Anjan Kumar Prusty, Dr. Rachna Chandra and Dr. P.A. Azeez. The contents of this carefully edited work will be of great interest to many people working on the conservation and management of wetlands in South Asia.

Wetlands are always fascinating because of their diverse types, the range of critical ecosystem services that they provide which support millions of people, and their rich biodiversity, including a large variety of plant and animal species adapted to specific water regimes.

Wetlands although unique ecosystems on their own are considered as 'ecotones', wherein their distinctiveness is not adequately recognized. Hence, there is a case to be made for wetland science as a distinct discipline, taking input from associated fields including terrestrial and aquatic ecology, environmental chemistry, hydrology and engineering in a typically multidisciplinary perspective. Wetland management, as the applied side of wetland science, requires systematic understanding of the intricate structural and functional aspects of the system, with inputs from sociological, legal, institutional and economic aspects in addition to disciplines such as biology, ecology and hydrology.

Six of the countries of South Asia (Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka) are contracting parties to the Convention on Wetlands (Ramsar 1971). As a result, they have shown their international commitments to the wise use of wetlands throughout their territory, together with the long-term conservation of their priority wetlands by designating those sites as Wetlands of International Importance ('Ramsar Sites'), and they have agreed to cooperate nationally and internationally to conserve transboundary wetlands and their resources. By 2016, a total of 66 Ramsar Sites showing a wonderful diversity of wetland types have been designated in these six South Asian countries. These range from the lake Mai Pokhari at 2,122 m in Nepal to the mangrove and tidal flats of the Indus Delta in

Pakistan. For sustainability, it is to be hoped that many more wetland areas in the region will be conserved and wisely used, including in the countries of Afghanistan and the Maldives which have not so far acceded to the Convention.

This book is in line with the efforts and initiatives in conserving the wetlands in South Asia by describing the issues facing them and substantiating it with case studies, on Ramsar Sites and other important wetlands. The facts and case studies presented in this book will not only be helpful for students, researchers and site managers but also for the highest levels of policy and decision making of executive authorities in wetland conservation, including the Ramsar Secretariat. Planning this book in the form of a consolidation of information and case studies on wetlands, for large habitat contiguity and diversity in the South Asian region, will benefit researchers in the field as well as the wetland site managers.

I commend the editors for their exemplary efforts in bringing out this volume with 30 technical chapters under eight different themes. The opening chapter provides an introduction to the outline of the book. Similarly, the final set of chapters conclude the compilation in a logical manner with case studies on legal and institutional frameworks and participatory wetland management, which are currently essential in conserving and managing these unique habitats. I therefore congratulate the editors and the publisher for bringing out this book of topical significance, and I am sure that it will serve as a vital reference, since there are few comparable accounts available.

Ramsar Convention on Wetlands
Gland, Switzerland

Ania Grobicki

Preface

Wetlands, a major feature of landscape in almost all parts of the world, are among the important ecosystems on Earth. From time immemorial, wetlands and river valleys have played a decisive role in nurturing many cultures and civilizations. However, the history of dealing with wetlands by humankind is fraught with misunderstanding and fear. Wetlands are disappearing at alarming rates across the globe, apparently since they were largely considered synonymous with wastelands to be filled up, drained, occupied and diverted for other human needs, disregarding the vital ecological services these ecosystems offer and the ecological goods we derive from them. A more recent and global issue that concerns both coastal and inland wetlands is the climate change. Limited investigations and experiments, especially in paddy fields, and lack of scientifically robust data have put the wetlands responsible for high methane emissions and ensuing changes in climate. It appears that international pressures from various interest groups have also added to this postulation. Nevertheless, it appears that we are yet to estimate with certainty the role of wetlands as net carbon sources or sinks. In fact, these enigmatic ecosystems need further scientific investigations regarding their role in the Earth system, especially with respect to their structural and functional roles and the ecological services they offer.

Wetlands, as a unique ecosystem, have properties that are not adequately covered by terrestrial and aquatic ecology, suggesting that there is a case to be made for wetland science as a distinct discipline, taking input from many fields, including terrestrial and aquatic ecology, environmental chemistry, hydrology and engineering in a typically multidisciplinary perspective. Wetlands are unique in many ways, of which their hydrologic characteristics and roles as ecotones between terrestrial and aquatic systems are notable. Wetland management, as the applied side of wetland science, requires systematic understanding of the various aspects of the system, balanced with legal, institutional and economic realities and expertise from disciplines of biology, ecology and hydrology. The wetland science is not an issue concerning hydrology and water management or confined to be a domain of biologists or ecologists. Wetland science essentially needs to draw upon knowledge base from other disciplines such as sociology, economics, hydrology and engineering as well. Wetlands are closely connected with humankind than any other ecosystems, for their intimate role in human sociocultural development, migration, spread and settlement across the globe. In recent years, wetland science is picking up as interest in wetlands grows; so do professional societies, as well as a number of journals and literature concerned with wetlands.

In the past couple of decades, advances in environmental and ecological studies have shed light on the intricacies of wetlands: their values are being recognized, and wetland protection is considered imperative in many parts of the world. The academia and the managers have well acknowledged that the wetlands perform several invaluable functions and offer several tangible and intangible services and commodities to humanity. To a lesser extent, but progressively more, the policy makers are also getting conscious of the importance of the wetlands for sustainable development of the humankind. Overt and covert release of chemical-laden wastes by industries, explicit and surreptitious dumping of solid wastes and unscientific and wanton application of agrochemicals that ultimately reach the wetlands have drawn the attention of researchers to chalk out strategies for the conservation, sustainable utilization and management of wetlands. This book is an attempt to acknowledge the discipline 'wetland science' and to bring together research findings, reviews and synthesis on different aspects of the wetlands of South Asia. To date, 'wetland science', a thorough interdisciplinary field, is not much known and treated as a compact and distinct discipline. A course in 'wetland science' is also not known to be taught in any well-known universities around the globe, though the topics falling under this discipline are generally handled more or less in a disjunct style under the discipline 'ecology' or under the exceptionally broad 'environmental studies' or such fields. It is high time that 'wetland science' needs to be acknowledged as an interdisciplinary subdiscipline and requires an attempt to consolidate various topics under it and to present them comprehensively.

The idea of this book was conceived by the editors during their research on wetlands and a greater realization that for the large habitat contiguity and diversity in the South Asian region, a consolidation of information and case studies on wetlands would be a worthwhile attempt for the benefit of the research in the field. This book is an outcome of intense efforts by the editors for the last (almost) 2 years, which involved exploring and identifying research groups working on wetlands in the South Asian region, obtaining their contributions pertinent to the identified themes of the book, screening the contributions, reviewing, several rounds of revision of the selected manuscripts, editing and refining. In total, we received around 60 contributions from experts from various countries. Of these, for various reasons, we could accommodate but only 30 chapters. The chapters present and discuss diverse issues on wetlands in the region, as case studies. The chapters are segregated under different themes that represent broad issues of concern in a systematic manner keeping in mind students, researchers and general readers at large. The readers of the book will be exposed to basics, theory with case studies and examples from the region. It would be also useful for students of graduate and higher levels and researchers in allied fields such as environmental studies, limnology, wildlife biology, aquatic biology, marine biology and landscape ecology. We hope that this book would also serve as a reference base on wetlands and facilitate further deliberations on specific issues to bring in a sustainable future for the wetland habitats of this region.

Bhuj, Gujarat, India — B. Anjan Kumar Prusty
Bhuj, Gujarat, India — Rachna Chandra
Coimbatore, Tamil Nadu, India — P.A. Azeez
October 30, 2016

Acknowledgements

At the outset, we would like to thank our teachers and mentors for introducing us to wetland habitats as experimental sites during our early research career. It gives us great pleasure in expressing our deep sense of gratitude and indebtedness to our teachers and mentors **Prof. P. C. Mishra** [expert member, National Green Tribunal (NGT), Government of India]; **Prof. D. K. Banerjee**, **Prof. C. K. Varshney**, **Prof. Brij Gopal** and **Prof. V. Subramanian** (formerly with the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India); **Dr. V. S. Vijayan** and **Dr. Lalitha Vijayan** (formerly of Bombay Natural History Society and Sálim Ali Centre for Ornithology and Natural History); and **Prof. S. K. Sahu** (Department of Environmental Sciences, Sambalpur University, India). Further, **Prof. B. C. Choudhury** (formerly with the Wildlife Institute of India, Dehradun) and **Dr. A. R. Rahmani** (Bombay Natural History Society, Mumbai) have been always a source of encouragement for us providing vital inputs in experimenting and researching in different wetland habitats. This section will not be complete without acknowledging **Mr. K. Arup Kumar Patro (late)**, then senior programme coordinator at MS Swaminathan Research Foundation (MSSRF), Chennai, India, who introduced the chief editor to wetlands (during his post-graduation and predoctoral research years) and impressed him about the need for wetland research in India.

The idea of this book came up in our mind during our earlier days of research in Keoladeo National Park (KNP), India. The multiphase research project in KNP provided us enough impetus to explore various ecological issues in the KNP wetland ecosystem, an inland wetland system. Our work at KNP provided us confidence to expand our interest to other wetland habitats such as coastal wetland and mangroves. Thus, in the last couple of years, much of our (BAKP and RC) attention was devoted to coastal wetland ecosystems and mangrove habitats through various research projects executed by **Gujarat Institute of Desert Ecology (GUIDE)**, Bhuj, India. While researching on wetlands, we always felt the need for a compilation that consolidates different environmental issues on various wetland habitats in India, which has large habitat contiguity with many other South Asian nations.

We express our sincere gratitude to the funding agencies which supported us in researching on wetlands, *viz.* the **Ministry of Environment, Forests and Climate Change (MoEF & CC)**, Government of India, New Delhi; **Department of Science**

and Technology (DST), New Delhi; **Council of Scientific and Industrial Research (CSIR)**, New Delhi; **Planning Commission of India**, New Delhi; **Science and Engineering Research Board (SERB)**, New Delhi; **Department of Science, Technology and Environment (DSTE)**, Puducherry, India; and **UNESCO International Hydrological Programme (IHP)**.

At Gujarat Institute of Desert Ecology (GUIDE), we are grateful to **Dr. V. Vijay Kumar** (Director, GUIDE) for his constant support and encouragement during this intensive exercise that resulted in this book.

We are grateful to the forest officers whose support and assistance made us to continue research on wetland habitats. **Dr. G. V. Reddy** IFS, Chief Wildlife Warden, Rajasthan, India) and **Mr. K. C. A. Arun Prasad** [IFS, Member Secretary, Rajasthan State Pollution Control Board (RSPCB)] are greatly acknowledged. **Mr. Rajpal Singh** [Member, State Board for Wildlife, Rajasthan (India)] has always been supportive and open to discussions on ecological issues of wetlands. This book has its origin from some of the discussions we had with him before. Further, various senior officers who have served in the capacity of Director of Keoladeo National Park owe special mention, *viz*. **Mr. K. R. Anoop**, IFS; **Dr. Khyati Mathur**, IFS; and **Mr. Bijo Joy**, IFS. Other forest officers at KNP, **Mr. Rajendra Gupta** and **Mr. Bholu Abrar Khan**, were always a source of encouragement during our research works in KNP wetland ecosystem.

While writing this acknowledgement, our heart goes to the researchers who had expressed interest in this compilation. In total, we had received 60 contributions at various levels for this book; however, for various reasons, we could accommodate only half of that in the final version. Several experts extended their comments during different stages of this book compilation. **Dr. Babar Khan**, **Dr. Beth Middleton**, **Dr. Bibhu Prasad Nayak**, **Dr. Chandra Sekhar Bahinipati**, **Dr. G. Thirumaran**, **Prof. Moniruzzaman Khondker**, **Ms. Nidhi Jamwal**, **Mr. Nitin Tiwari**, **Dr. Ritu Singh**, **Dr. S. Manasi**, **Dr. Shalini Dhyani**, **Dr. Sudheera M. W. Ranwala**, **Mr. Shawahiq Siddiqui** and **Dr. Quazi Zahangir Hossain** are specially acknowledged for their inputs.

We immensely thank our publisher **Springer Nature** for entrusting us and making the delivery of the book on time. We are grateful for their timely response during various stages of this book project and patience with our delays and repeated doubts and clarifications.

We also owe a debt of gratitude to many teachers, friends, colleagues and students and to all those who have contributed variously in bringing out this volume in its present shape whom we might have missed mentioning here. We would be grateful to the esteemed reader for their comments and suggestions on this newborn, so that our plans of compiling a second volume on more specific themes of wetland science would be fruitful. We hope the editors justify their aspirations.

October 30, 2016

Dr. B. Anjan Kumar Prusty
Dr. Rachna Chandra
Dr. P.A. Azeez
(Editors)

Contents

About the Editors

Dr. B. Anjan Kumar Prusty (Chief Editor) is Senior Scientist, Division of Environmental Impact Assessment, Gujarat Institute of Desert Ecology, India. He holds a Ph.D. in Environmental Sciences for his works on environmental biogeochemistry with emphasis on heavy metal speciation in wetlands. His areas of research interests include river basins (environmental flow and contaminant budgeting, interbasin water transfer, aquatic ecosystem health), wetlands, contaminant transfer models, environmental impact assessment (monitoring and planning and eco-sensitive areas), trace metal speciation in matrices such as water and soil and environmental health implications. He is involved in designing and teaching modules in Environmental Sciences and Sustainability Studies in various universities including Indira Gandhi National Open University (IGNOU), India. He is a member of academic, scientific and professional bodies such as UNESCO International Hydrological Programme (IHP), IUCN Species Survival Commission, IUCN Wildlife Health Specialist Group (WHSP) and IUCN Goose Specialist Group (GSP).

Dr. Rachna Chandra (Co-Editor) holds a Ph.D. in Environmental Sciences. She specializes in heavy metal contamination, heavy metal dynamics and mobility through various trophic levels and phyto-extraction and remediation techniques in different ecosystems and has been in the field for more than a decade. She has been also working on nutrient dynamics, metal speciation/fractionation, sources and sinks of heavy metals, factors governing metal pollution and developing management strategies to arrest contamination. Currently, she studies coastal areas and mangrove habitats in the west coast of India. She is a recipient of various academic awards including the DST-INSPIRE Faculty Award by the Government of India. She also teaches Environmental Sciences in KSKV Kachchh University, India, and has been involved in developing teaching modules for universities such as Indira Gandhi National Open University (IGNOU). She has several research articles in peer-reviewed scientific journals, in addition to several book chapters, and papers in conference proceedings to her credit.

Dr. P.A. Azeez (Co-Editor) holds a Ph.D. in Environmental Sciences and has more than 35 years of research and teaching experience in Ecology and Environmental Sciences. He is currently attached with Salim Ali Centre for Ornithology and Natural History (SACON), where he was the director until early 2016. His areas of interest include environmental assessment, environmental chemistry, environmental management, ecological systems mainly with respect to ecosystem goods and services, wetland ecology, animal ecology focusing on species interactions, urbanization and sustainable development. He serves in various capacities in research and academics, and has been a member/chair of several committees constituted by the Government of India, universities and also the judicature. He has several publications to his credit, and several students have completed their doctoral studies under his guidance.

Abbreviations

ACU	Adult Cattle Unit
ACVS	*Ashirawandh Cheriya Vikas Samithi*
ADFOs	Assistant Deputy Forest Officers
AGDS	Acoustic Ground Discrimination Systems
AMSL	Above Mean Sea Level
ANI	Andaman and Nicobar Islands
APHB	Andhra Pradesh Housing Board
APOWA	Action for Protection of Wild Animals
AWB	Asian Wetland Bureau
AWiFS	Advance Wide-Field Sensors
AWS	Ashtamudi Wetland System
BCCSAP	Bangladesh Climate Change Strategy and Action Plan
BECA	Bangladesh Environment Conservation Act
BIS	Bureau of Indian Standards
BoBSSS	Bon-o-Bhumi Sanskar Sthayee Samiti
BOD	Biochemical Oxygen Demand
BPL	Below Poverty Line
BPM	Bivariate Probit Model
BPR	Bivariate Probit Regression
BPSG	Biological and Planetary Sciences and Applications Group
BTEX	Benzene, Toluene, Ethylbenzene and Xylene
BWDB	Bangladesh Water Development Board
CAF	Central Asian Flyway
CBA	Cost-Benefit Analysis
CBD	Convention on Biological Diversity
CBOs	Community-Based Organizations
CCA	Coast Conservation Act
CCAC	Coast Conservation Advisory Council
CE	Choice Experiments
CEA	Central Environmental Authority
CESS	Centre for Earth Science Studies
CF	Contamination Factor
CFP	Ciguatera Fish Poisoning

CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CLRP	Constrained Long-Range Transportation Plan
CMS	Convention on the Conservation of Migratory Species of Wild Animals
CO_2-e	Carbon Dioxide equivalent
COD	Chemical Oxygen Demand
CoMBINe	Coastal and Marine Biodiversity Integration Network
COP	Conference of the Contracting Parties
CPR	Common Property Resource
CR	Critically endangered
CREE	Centre for Rural Empowerment and Environment
CRZ	Coastal Regulation Zone
CSTR	Combined Stirred Tank Reactor
CV	Contingent Valuation
CVM	Contingent Valuation Method
CWs	Constructed Wetlands
CZMA	Coastal Zone Management Authority
CZMP	Coastal Zone Management Plan
CZP	Coastal Zone Policy
DD	Data Deficient
DEM	Digital Elevation Model
DFO	Divisional Forest Officer
DNAPL	Dense Nonaqueous Phase Liquids
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DPSIR	Driver-Pressure-State-Impact-Response
DWF	Dry Weather Flow
DWLC	Department of Wildlife Conservation
EBA	Endemic Bird Area
EC	Electrical Conductivity
ECA	Ecologically Critical Area
EDCs	Eco-development Committees
EEZ	Exclusive Economic Zone
EF	Enrichment Factor
EIA	Environmental Impact Assessment
Eif	Potential Ecological Risk Index
EKMA	East Kolkata Management Authority
EKW	East Kolkata Wetlands
EKWRG	East Kolkata Wetland Recycling Region
EMR	Electromagnetic Radiation
EN	Endangered
ENSO	El Niño-Southern Oscillation
EoL	Encyclopedia of Life
EPA	Environmental Protection Agency

ERMS	European Register of Marine Species
ESbA	Ecosystem Services-Based Adaptation
ETM+	Enhanced Thematic Mapper
EVRI	Environmental Valuation Reference Inventory
FAO	Food and Agriculture Organization
FCC	False-Colour Composite
FCDI	Flood Control, Drainage and Irrigation
FD	Forest Department
FDST	Forest Dwelling Scheduled Tribe
FGD	Focus Group Discussion
FID	Flame Ionization Detector
FPCs	Forest Protection Committees
FSI	Forest Survey of India
FWS	Free Water Surface
GBIF	Global Biodiversity Information Facility
GCRMN	Global Coral Reef Monitoring Network
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographical Information System
GLOMIS	Global Mangrove Database and Information System
GMB	Ganges-Meghna-Brahmaputra
GoK	Gulf of Kachchh
GPS	Global Positioning System
GROMS	Global Registry of Migratory Species
GRoWI	Global Review of Wetland Resources and Priorities for Wetland Inventory
GWP	Global Warming Potential
HAL	High-Altitude Lakes
HAW	High-Altitude Wetlands
HF	Horizontal Flow
HPM	Hedonic Price Method
HPNP	Horton Plains National Park
HRVS	High-Resolution Visible Sensor
HSSF	Horizontal Subsurface Flow
HTL	High Tide Line
HYV	High-Yielding Varieties
IBAs	Important Bird and Biodiversity Areas
ICEF	India-Canada Environment Facility
ICHIM	International Conferences on Hypermedia and Interactivity in Museums
ICIO	International Conference on Indian Ornithology
ICRAN	International Coral Reef Action Network
ICRZ	Island Coastal Regulation Zone
ICZM	Integrated Coastal Zone Management
I-geo	Geo-Accumulation Index

IGNP	Indira Gandhi Nahar Pariyojna
IHP	International Hydrological Programme
IIMP	Integrated Island Management Plan
IIT	Indian Institute of Technology
IPCC	Intergovernmental Panel on Climate Change
IPZ	Island Protection Zone
IRS	Indian Remote Sensing
ISB	Indian Sundarban
ISIS	International Species Information System
ISRO	Indian Space Research Organisation
IUCN	International Union for Conservation of Nature
IWMI	International Water Management Institute
IWRM	Integrated Water Resource Management
JFM	Joint Forest Management
JFMCs	Joint Forest Management Committees
JMM	Joint Mangrove Management
KCF	Knuckles Conservation Forest
KMC	Kolkata Municipal Corporation
KNP	Keoladeo National Park
LADS	Laser Airborne Depth Sounder
LC	Least Concern
LiDAR	Light Detection and Ranging
LISS	Linear Imaging Self-Scanning
LNAPL	Light Nonaqueous Phase Liquids
LWs	Lowland Wetlands
MBC	Microbial Biomass Carbon
MBP	Man and the Biosphere Programme
MBRC	Madaripur Beel Route Canal
MCB	Mass Coral Bleaching
MCPAs	Marine and Coastal Protected Areas
MCRCF	Marine and Coastal Resources Conservation Foundation
MCRMP	Millennium Coral Reef Mapping Project
ME	Ministry of Environment, Sri Lanka
MEA	Millennium Ecosystems Assessment
MESP	Marine Ecosystem Services Partnership
MFF	Mangroves for the Future
MFPs	Minor Forest Products
MGNREGS	Mahatma Gandhi National Rural Employment Guarantee Scheme
MHW	Mid-Hill Wetlands
MIR	Middle Infrared
MLD	Million Litre Per Day
MNDWI	Modified Normalized Difference Water Index
MoEF & CC	Ministry of Environment, Forest and Climate Change
MoEF	Ministry of Environment and Forests
MP	Market Price

MSSRF	MS Swaminathan Research Foundation
MTT	Mahigeer Tarquati Tanzeem
NAPA	National Adaptation Programme of Action
NAPL	Nonaqueous Phase Liquids
NARA	National Aquatic Resources Research and Development Agency
NARIS	Korean Natural History Research Information System
NASA	National Aeronautics and Space Administration
NBA	National Biodiversity Authority
NBSAP	National Biodiversity Strategies and Action Plan
NCCP	National Climate Change Policy
NCESS	National Centre for Earth Science Studies
NCS	National Conservation Strategy
NDPI	Normalized Difference Pond Index
NDTI	Normalized Difference Turbidity Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NE	Not Evaluated
NEA	National Environment Act
NEAP	National Environmental Action Plan
NEE	Net Ecosystem Exchange
NEH	National Engineering Handbook
NEMAP	National Environmental Management Action Plan
NEP	National Environmental Policy
NFP	National Forest Policy
NGOs	Non-Governmental Organizations
NHWAA	National Heritage Wilderness Areas Act
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
NOEP	National Ocean Economics Program
NPP	Net Primary Production
NPW	National Policy on Wetlands
NSF	National Spatial Framework
NT	Near Threatened
NTFP	Non-Timber Forest Produce
NWFPs	Non-Wood Forest Products
NWIA	National Wetland Inventory and Assessment
NWM	Nationwide Wetland Mapping
NWMP	National Water Management Plan
NWP	National Wetland Policy
NWSC	National Wetland Steering Committee
OBIA	Object-Based Image Analysis
OBIS	Ocean Biogeographic Information System
OC	Organic Carbon
OFT	Optimal Foraging Theory
PAHs	Polycyclic Aromatic Hydrocarbons

PAs	Protected Areas
PBC	Plant Biomass Carbon
PCBs	Polychlorinated Biphenyls
PCE	Perchloroethylene
PCS	Point Calimere Sanctuary
PEPA	Pakistan Environmental Protection Act
PES	Payment for Ecosystem Services
PF	Plug Flow
PFA	Production Function Approach
PIL	Public Interest Litigation
PLI	Pollution Load Index
PMNH	Pakistan Museum of Natural History
POC	Particulate Organic Carbon
PSP	Paralytic Shellfish Poisoning
PWPA	Peak Wilderness Protected Area
RCF	Root Concentration Factor
RDA	Redundancy Analysis
RE	Reference Element
REDD	Reducing Emissions from Deforestation and Forest Degradation
RF	Radiative Forcing
RI	Potential Toxicity Response Index
RPC	Replacement Cost
RUM	Random Utility Method
SA	South Asia
SAC	Space Applications Centre
SACEP	South Asia Co-operative Environment Programme
SAP	Strategic Action Plan
SASAP	South Asian Seas Action Plan
SASP	South Asian Seas Programme
SBR	Sundarbans Biosphere Reserve
SCS	Soil Conservation Service
SDGs	Sustainable Development Goals
SDO	Sonmiani Development Organization
SES	Socio-ecological system
SF	Surface Flow
SHGs	Self-Help Groups
SIDS	Small Island Developing States
SLED	Sustainable Livelihood Enhancement and Diversification
SLR	Sea-Level Rise
SMF	Sundarbans Mangrove Forest
SNP	Sundarbans National Park
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SONARS	Sound Navigation and Ranging
SPOT	Systeme Probatoire d' Observation de la Terra

SRES	Special Report on Emissions Scenarios
SRI	Systematic Rice Intensification
SSDCN	Society for Social Development and Conservation of Nature
SSF	Subsurface Flow
STR	Sundarbans Tiger Reserve
SWF	Storm Weather Flow
SWIR	Shortwave Infrared
TA	Total Alkalinity
TC	Travel Cost
TCSF	Transpiration Concentration Stream Factor
TDS	Total Dissolved Solids
TEEB	The Economics of Ecosystems and Biodiversity
TEV	Total Economic Value
TH	Total Hardness
THM	Trihalomethane
TISM	Tank in Series Model
TM	Thematic Mapper
TPH	Total Petroleum Hydrocarbons
TTD	Tirumala Tirupati Devasthanams, India
TUDA	Tirupati Urban Development Authority, India
TWs	Treatment Wetlands
UNCCD	United Nations Convention to Combat Desertification
UNCED	United Nations Conference on Environment and Development
UNCLOS	United Nations Convention on the Law of the Sea
UNCSD	United Nations Conference on Sustainable Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
USGS	United States Geological Services
VF	Vertical Flow
VIMS	Virginia Institute of Marine Science
VMC	Village Mangrove Council
VU	Vulnerable
WCED	World Commission on Environment and Development
WFCs	Wetland Facilitating Committees
WFD	Water Framework Directive
WHC	World Heritage Convention
WHO	World Health Organization
WMC	Wetland Management Committees
WoRMS	World Register of Marine Species
WQI	Water Quality Index
WRR	Waste Recycling Region
WSSD	World Summit on Sustainable Development

WTP	Willingness to Pay
WWF	World Wide Fund for Nature
ZOBODAT	Zoological Botanical Database

Part I

Wetlands Introductory

An Introduction to Wetland Science and South Asian Wetlands

1

Ketan S. Tatu and James T. Anderson

Abstract

A novice student in wetland science may initially find oneself in a state of dilemma about how do wetlands differ from waterbodies. Further, the student might get baffled on coming across multiple definitions of the term "wetland". The present chapter attempts to elucidate confusion over this fundamental issue at the outset and then leads the student to gain multi-faceted knowledge about wetlands including extent, distribution and types of wetlands in the world and in South Asia (especially, in India). We also discuss meaning and significance of hydric soil, hydrology and hydrophytes, issues of threats impacting wetlands, wetland conservation and conservation policies (especially, Ramsar Convention). The chapter is specifically written for the students of South Asian countries where the subject of wetland science or wetland ecology is not as widely found in formal university curriculum as in the developed countries of Europe and North America.

Keywords

Ramsar convention • South Asia • Water • Wetlands • Wetland definition

K.S. Tatu (✉)
Gujarat Ecological Education and Research (GEER) Foundation, Indroda Nature Park, PO Sector 7, Gandhinagar 382007, India
e-mail: ketantatu@gmail.com

J.T. Anderson
Division of Forestry and Natural Resources, West Virginia University, PO Box 6125, Morgantown, WV 26506-6125, USA
e-mail: jim.anderson@mail.wvu.edu

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_1

1.1 Waterbody and Wetland

Many scientists in India and elsewhere in South Asia are conversant with the word "waterbody". Various dictionaries (e.g. New Oxford Dictionary of English) define waterbody with minor variations as (i) any significant accumulation of water, generally on a planet's surface, (ii) a body of water forming a physiographical feature or (iii) a part of Earth's surface covered with water (e.g. seas, lakes, reservoirs, rivers). In fact, for ages, waterbody has been an umbrella word widely used in this region to refer to all the water-related land-use or land cover features, including lakes, ponds, reservoirs, estuaries, canals and rivers. Waterbody is a broad term that encompasses all types of aquatic and wetland systems (Anderson 2012a). However, since the early 1980s, another word related to aquatic areas gained popularity in the region, i.e. "wetland".

Since the 1970s, the international treaty called the "Convention on Wetlands of International Importance", popularly known as the "Ramsar Convention of 1971", has globally come into force for conservation and wise use of wet or watery lands. This intergovernmental treaty defines the term wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial; standing or flowing; fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six meters" (Navid 1989). Thus, the definition of the term wetland as per the Ramsar Convention of 1971 is almost all encompassing, especially due to the use of the word "water" in the definition. It includes all lakes and rivers, underground aquifers, swamps and marshes, wet grasslands, peatlands, oases, estuaries, deltas and tidal flats, mangroves and other coastal areas, coral reefs and various man-made wetlands. Therefore, one may say that in India and other countries of South Asia, wherein the definition of wetlands adopted by the Ramsar Convention of 1971 is widely recognized, the terms "wetlands" and "waterbodies" can be considered synonymous, with the exception that as far as marine/coastal areas are concerned, the term "wetland" is applicable to only those areas where depth of water does not exceed 6 m at low tide. The 6 m depth limit was likely contrived as the approximate maximum depth at which sea ducks dive to feed (Anderson 2012b).

In its initial years, the "Convention on the Wetlands of International Importance" was known as the "Convention on Wetlands of International Importance especially as Waterfowl Habitat", and hence as per prediction of Navid (1989), this definition of wetlands might have originated from an effort to embrace all the wetland habitats of migratory waterbirds (Scott and Jones 1995; Mitsch and Gosselink 2000).

Certainly, the Ramsar Convention's definition is more relevant from the viewpoint of conservation and management of wetlands. In addition, there are several definitions of wetlands in North America that are adopted and used by jurisdictional and managerial agencies. One primary definition has been adopted by the US Army Corps of Engineers and the US Environmental Protection Agency (EPA). The EPA has defined the term wetlands as those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions (Environmental Laboratory 1987).

However, a student or a researcher of ecological sciences who has professional interest in science of the wetlands may have to look for some other definitions that take into account hydrological and ecological characteristics of wetlands. Moreover, a serious student of ecology should also be conversant with select definitions of the term wetland that are in use worldwide.

1.2 Scientific Definitions of Wetlands Focusing on Its Transitional Character

Wetlands are a conundrum to scientists trying to fit all wetlands into a single universal definition. This is because apart from having great geographical extent, wetlands have varied hydrological conditions in which they are found (Mitsch and Gosselink 2000). The hydrology of wetlands may be governed by saturation or shallow inundation of soil with natural or man induced, long standing to temporary surface waters or due to the water table at, near or above the land surface. Tarnocai et al. (1988) defined wetlands as lands that are saturated with water long enough to promote wetland or aquatic processes. A step forward from mere common sense to some scientific (ecological) understanding would lead one to the fact that "wetlands are the ecosystems whose formation has been dominated by water and whose processes and characteristics are largely governed by water" (Maltby 1986).

Search for a more scientific definition would reveal that there is a group of definitions, all originating in North America (particularly the USA), that emphasize the transitional characteristics of wetlands. Smith (1980) described wetlands as a halfway world between terrestrial and aquatic ecosystems, exhibiting some of the characteristics of both. Baldassarre and Bolen (1994) stated that wetlands represent transitional zones between upland and aquatic ecosystems, and therefore they exhibit some characteristics of each. Among the definitions that emphasize the transitional characteristics of wetlands, one adopted by the US Fish and Wildlife Service (Cowardin et al. 1979) is among the most quoted. It defines wetlands as "wetlands are the lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water". Wetlands must have one or more of the following three attributes: (i) at least periodically, the land supports predominantly hydrophytes; (ii) the substrate is predominantly undrained hydric soil; and (iii) the substrate is saturated with water or covered by shallow water at some time during the growing season of each year (Cowardin et al. 1979).

1.2.1 Wetland Attributes in US Fish and Wildlife Service Definitions

The 1979 US Fish and Wildlife Service definition (Cowardin et al. 1979) emphasized three attributes, and if at least one of them is met at a site, that site can be considered a wetland. Though there are a variety of wetlands, all wetlands share three common characteristics in terms of hydrology, soil and hydrophytes (USGS National Wetlands Research Center 2014).

1.2.1.1 Wetland Hydrology

Wetland hydrology refers to the particular hydrologic conditions that are necessary for formation and maintenance of wetlands. Wetland hydrology encompasses the distribution and flow of all water that is added to, lost from, or stored in a wetland (Rosenberry and Hayashi 2013). It is the sum total of water level variations, water flow and frequency of water influx over time. It reflects the pathways by which water arrives and departs (e.g. precipitation, runoff, evapotranspiration, tides), which affect nutrient and energy fluxes resulting from such movement (Baldassarre and Bolen 1994).

Hydrology is the *key* factor in a wetland ecosystem. It is probably the single-most important determinant for the establishment and maintenance of definite types of wetlands and the processes therein (Mitsch and Gosselink 1986; Baldassarre and Bolen 1994). Hydrology plays a role in transportation of sediments, nutrients and toxic materials into and out of wetlands. It directly modifies and changes wetlands' physicochemical environments, particularly oxygen availability and related chemistry such as nutrient availability, pH and toxicity (Mitsch and Gosselink 2000). Some of the major concepts associated with wetland hydrology are wetland hydroperiod (i.e. the seasonal pattern of the water level in a wetland) and wetland water budget (i.e. the balance between the inflows and outflows of water, Rosenberry and Hayashi 2013). Important components of water budget are precipitation, evapotranspiration, surface flows, groundwater fluxes and tides in riparian and coastal wetlands (Mitsch and Gosselink 2000).

1.2.1.2 Soil

Wetlands are the areas where *hydric soils* predominate. Hydric soils refer to those soils frequently flooded, ponded or saturated long enough (i.e. minimum about 7–10 days covering ecologically critical periods of wetland plant and animal growth) to create anaerobic conditions in the upper layer (Baldassarre and Bolen 1994; Mitsch and Gosselink 2000). Such soils typically have anaerobic conditions in the upper layer due to consistent wetness. Typically, the presence of such soils can be inferred in the field if macrophytes exist in the soil as only such plants are adapted to grow in anaerobic wet soils.

1.2.1.3 Hydrophytes

Hydrophytes are plants that grow and reproduce in waters or wet soils due to their morphological, physiological and reproductive adaptations to tolerate excessive wetness and resulting anaerobic condition in the wetland soils. Weaver and Clements (1929) considered hydrophytes to be plants that grow in water, in soil covered by water or in soil that is usually saturated. Daubenmire (1968) defined hydrophytes as any plant growing in a soil that is at least periodically deficient in oxygen due to excessive water content. Conventionally, only herbaceous plants were considered to be hydrophytes, but in modern times, hydrophytes can either be herbaceous or woody (Tiner 1991).

1.2.2 Other Scientific Definitions

A wetland enthusiast in India may often come across man-made waterbodies like irrigation reservoirs, village ponds or suburban reservoirs full of hydrophytes and waterbirds, which in no way appear to be transitional or halfway between terrestrial and aquatic systems. Rather, they appear as stand-alone aquatic ecosystems within an agrarian or rural terrestrial landscape. In such situations, one may become confused. If there is no transition between terrestrial and aquatic systems, is the waterbody in front of them a wetland? According to the definition adopted for the Ramsar Convention of 1971 (see Sect. 1.1), it is certainly a wetland. Moreover, there is a type or a category of wetlands (usually inland wetlands) that are considered *isolated wetlands* or *geographically isolated wetlands*. Tiner (2003) defined isolated wetlands as "wetlands which are wholly surrounded by uplands". The National Research Council (USA) defines an isolated wetland as "a wetland not adjacent to another waterbody" (NRC 1995; Leibowitz 2003). There are several other jurisdictional and scientific definitions of the term wetlands. An example of the definitions adopted by governments of some countries or regions is given below:

- **Canadian definition:** Land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and different types of biological activities which are adapted to a wet environment (National Wetlands Working Group 1988).
- **Australian definition:** Areas of permanent or periodic/intermittent inundation, whether natural or artificial, with water that is static, flowing, fresh, brackish or salty, including areas of marine water, the depth of which at low tide does not exceed 6 m (DERM 2010).
- **Water Framework Directive (WFD) of European Commission:** Wetlands are diverse and hydrologically intricate ecosystems and are likely to develop within a hydrological gradient while transitioning between terrestrial to mainly aquatic habitats (European Commission 2003). They are characterized by standing or slowly moving waters (European Commission 2003). Common features include hydric soils, microorganisms, hygrophilous vegetation and fauna, which have adapted to chemical and biological processes reflective of periodic or permanent flooding and/or water logging (European Commission 2003).
- **Indian definition [under Wetland (Conservation and Management) Rules of 2010, the Ministry of Environment, Forests and Climate Change, Government of India]:** Area of marsh, fen, peatland or water, natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salty, including areas of marine water, the depth of which at low tide does not exceed 6 m. The definition includes all inland waters such as lakes, reservoirs, tanks, backwaters, lagoons, creeks, estuaries and man-made wetlands, as well as

the zone of direct influence on wetlands (i.e. the drainage area or catchment region of wetlands) as determined by the authority, but it does not include main river channels, paddy fields and the coastal wetland covered under the notification of the Ministry of Environment and Forests (Government of India) (S.O. number 114(E) dated the 19 February, 1991, published in *The Gazette of India*, Extraordinary, Part II, Section 3, Subsection (ii) of dated the 20 February 1991).

An amalgamation of the two definitions, namely, the definition by the Ramsar Convention and the definition widespread in North America (i.e. US Fish and Wildlife Service's definition) with some modifications, may help in better describing wetland ecosystem. It may be as follows: "Wetlands are natural, seminatural, man-made, or man-induced water-saturated, or inundated areas (with their waters at, near, or above the land surface) either located at the transition between terrestrial and aquatic habitats or existing in the form of geographically isolated entities, with slowly moving or standing fresh, brackish, or salty waters, including areas of marine waters in which the depth does not exceed two meters at low tide. To be qualified as a wetland, the area should satisfy at least one of the following conditions: (1) at least periodically, the land supports predominantly hydrophytes, (2) the substrate is predominantly undrained hydric soil, and (3) the substrate is saturated with water or covered by shallow water at some time during the growing season of each year".

1.3 Wetlands in the World: Area, Distribution and Types

In the modern world, the number of wetlands is declining, wetland area is shrinking and wetland diversity is decreasing, mainly due to human's unsustainable developmental activities. Therefore, it is important to understand the historic and current abundance, distribution and diversity of wetlands existing on our planet.

Wetlands exist in all the continents of the world except in Antarctica. In the early 1980s, Maltby and Turner (1983) estimated that 8.6 million km^2 (more than 6.4% of the land surface of the world) was wetland. Later, Finlayson and Davidson (1999) included nearshore marine areas as one of the categories of wetlands as per the Ramsar Convention definition and estimated that the worldwide extent of wetlands is 12.8 million km^2 (8.6% of land surface area and 2.51% of total surface area of the Earth). However, based on several other previous studies, Mitsch and Gosselink (2007) estimated the extent of the world's wetlands as 7–10 million km^2 (about 5–8% of land surface area and 1.37–1.96% of the total surface area of Earth). Global distributions of major wetland areas and areas with major wetlands are pictorially depicted in "wetlands" (Mitsch and Gosselink 2007), and based on it, the same is shown in Fig. 1.1.

Finlayson and Davidson (1999) have given regional minimum estimates for wetland area, and they are as follows:

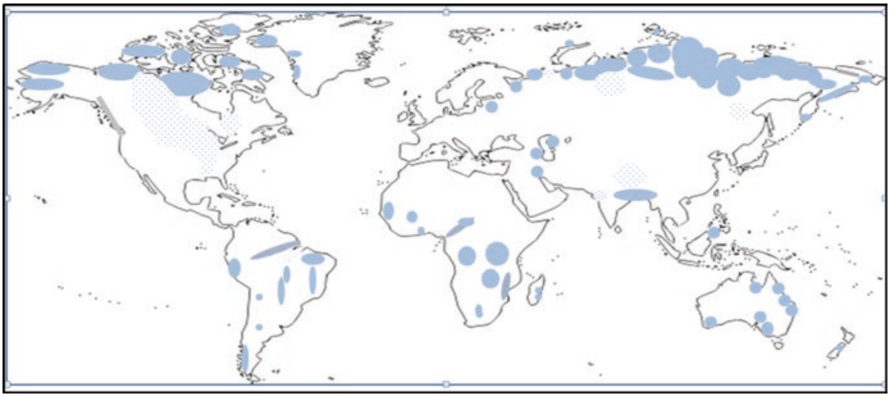


Fig. 1.1 Major wetland areas (shown by *blue smudges*) and areas with abundant wetlands (shown by *spotted pattern*) in the world (Adopted from Mitsch and Gosselink 2007)

Africa: 1,213,220–1,246,860 km^2
Asia: 2,042,450 km^2
Eastern Europe: 2,292,170 km^2
Neotropics: 4,149,170 km^2
North America: 2,415,740 km^2
Oceania: 357,500 km^2
Western Europe: 288,220 km^2

Matthews and Fung (1987) gave distribution of wetlands in world by climatic zones. They estimated 2.7 million km^2 wetland area in polar/boreal zone, 0.7 million km^2 in temperate zone and 1.9 million km^2 wetland area in the tropical/subtropical zone. In addition, they estimated 1.5 million km^2 of rice paddies.

Under broad considerations, there are two types of wetlands based on spatial location: coastal and inland. Wetlands can further be divided based on their origin or formation as natural or man-made (artificial). Wetlands are also categorized as saline (>45,000 μMhos/cm^3), brackish (500–45,000 μMhos/cm^3) or fresh (<500 μMhos/cm^3) based on salinity levels (Stewart and Kantrud 1971). In addition, there are some basic wetland types based on ecological viewpoints, including:

- Marshes – seasonally or permanently inundated wetlands dominated by emergent herbaceous vegetation adapted to saturated soil conditions
- Salt marshes – halophyte-dominated marshes bordering salt water waterbodies characterized by tidal or nontidal water level fluctuations
- Swamps – wetlands dominated by trees or shrubs (e.g. mangrove swamp)
- Peatlands – a general term for wetlands having the tendency of accumulating partially decayed vegetation
- Bogs – a type of peatland having no noticeable incoming or outgoing flow of water and supporting acidophilic mosses
- Fens – a type of peatland that receive some drainage from the mineral soils in environs and usually has marshlike vegetation

The above-mentioned types of wetlands are well-known ones. However, there are numerous other types of wetlands across the globe due to variation in physico-chemical and biological characteristics. It is difficult to describe and document all of them. Therefore, the types of wetlands all over the world are documented here through two widely used classification systems; the first is "Wetlands and Deep Water Habitats of United States" by Cowardin et al. (1979) published by US Fish and Wildlife Service and the second is the Ramsar Classification of Wetland Types published by the Ramsar Secretariat.

As per the classification system suggested by Cowardin et al. (1979), wetlands and deep water habitats are defined separately because traditionally the term wetland has not included deep permanent water in the USA. Deep water habitats, unlike wetlands, are permanently flooded lands wherein surface waters are stable or everlasting and too deep to support emergent hydrophytes. Though both wetlands and deep water habitats are considered separate ecological entities, both of them are included in the classification system by Cowardin et al. (1979) as wetlands are found continuous with deep water habitats in the USA. This system has a hierarchical approach analogous to taxonomic classification used to identify species of plants and animals (Mitsch and Gosselink 2000). The broadest level in the classification is "system" that narrows down further to "subsystem" and "class" (which can further be subcategorized as subclasses, dominant types and modifiers) (Mitsch and Gosselink 2000). The classification system is given in Table 1.1.

Table 1.1 Classification of wetlands and deep water habitats

Systems	Subsystems	Class
Marine	Subtidal	Rock bottom
		Unconsolidated bottom
		Aquatic bed
		Reef
	Intertidal	Aquatic bed
		Reef
		Rocky shore
		Unconsolidated shore
Estuarine	Subtidal	Rock bottom
		Unconsolidated bottom
		Aquatic bed
		Reef
	Intertidal	Aquatic bed
		Reef
		Streambed
		Rocky shore
		Unconsolidated shore
		Emergent wetland
		Scrub-shrub wetland
		Forested wetland

(continued)

Table 1.1 (continued)

Systems	Subsystems	Class
Riverine	Tidal	Rock bottom
		Unconsolidated bottom
		Aquatic bed
		Streambed
		Rocky shore
		Unconsolidated shore
		Emergent wetland
	Lower perennial	Rock bottom
		Unconsolidated bottom
		Aquatic bed
		Rocky shore
		Unconsolidated shore
		Emergent wetland
	Upper perennial	Rock bottom
		Unconsolidated bottom
		Aquatic bed
		Rocky shore
		Unconsolidated shore
	Intermittent	Streambed
Lacustrine	Limnetic	Rock bottom
		Unconsolidated bottom
		Aquatic bed
	Littoral	Rock bottom
		Unconsolidated bottom
		Aquatic bed
		Rocky shore
		Unconsolidated shore
		Emergent wetland
Palustrine		Rock bottom
		Unconsolidated bottom
		Aquatic bed
		Streambed
		Unconsolidated shore
		Moss-Lichen wetland
		Emergent wetland
		Scrub-shrub wetland
		Forested wetland

Adapted from: Classification of Wetlands and Deep Water Habitats of the United States (Cowardin et al. 1979)

While Cowardin et al. (1979)'s classification system has five main categories (as "Systems"), Ramsar Convention's "Classification System for Wetland Types" has three main categories of wetlands, *viz.* "marine/coastal wetlands", "inland wetlands" and "human-made wetlands". Under these categories, a total of 42 wetland types are identified (Table 1.2).

Table 1.2 Wetland classification system as per Ramsar Convention

Marine/coastal wetlands	
A. Permanent shallow marine waters (in most cases <6 m at low tide)	Sea bays and straights
B. Marine subtidal aquatic beds	Kelp bed
	Seagrass bed
	Tropical marine meadows
C. Coral reefs	
D. Rocky marine shore	Rocky offshore islands
	Sea cliffs
E. Sand, shingle or pebble shore	Sandy bars and spits
	Sandy islets
	Dune systems
	Humid dune slacks
F. Estuarine waters	Permanent water of estuaries
	Estuarine systems of deltas
G. Intertidal mud, sand or salt flats	
H. Intertidal marshes	Salt marshes
	Salt meadows
	Saltings
	Raised salt marshes
	Tidal brackish marshes
	Tidal freshwater marshes
I. Intertidal forested wetlands	Mangrove swamps
	Nipah swamps
	Tidal freshwater swamp forests
J. Costal brackish/saline lagoons (brackish to saline lagoons ≥1 relatively narrow connection with sea	
K. Coastal freshwater lagoons	
Zk(a). Karst and subterranean hydrological systems (marine/coastal)	
Inland wetlands	
L. Permanent inland deltas	
M. Permanent rivers/streams/creeks	Waterfalls
N. Seasonal/intermittent/irregular rivers/streams/creeks	
O. Permanent freshwater lakes (>8 ha)	Large oxbow lakes
P. Seasonal/intermittent freshwater lakes (>8 ha)	Floodplain lakes
Q. Permanent saline/brackish/freshwater/alkaline lakes	
R. Seasonal/intermittent saline/brackish/alkaline lakes and flats	
Sp. Permanent saline/brackish/alkaline/marshes /pools	
Ss. Seasonal/intermittent saline/brackish/alkaline/ marshes/pools	
Tp. Permanent freshwater marshes/pools	Ponds (<8 ha)
	Marshes and ponds on inorganic soils

(continued)

Table 1.2 (continued)

Ts. Seasonal/intermittent freshwater marshes/pools on inorganic soils	Sloughs
	Potholes
	Seasonally flooded meadows
	Sedge marshes
U. Non-forested peatlands	Shrub or open bogs
	Swamps
	Fens
Va. Alpine wetlands	Alpine meadows
	Temporary waters from snowmelt
Vt. Tundra wetlands	Tundra pools
	Temporary waters from snowmelt
W. Shrub-dominated wetlands	Shrub swamps
	Shrub-dominated freshwater marshes
	Shrub carr
Xf. Freshwater, tree-dominated wetlands	Alder thicket on inorganic soil
	Freshwater swamp forests
	Seasonally flooded forests
	Wooded swamps on inorganic soil
Xp. Forest peatland	Peatswamp forests
Y. Freshwater springs	Oases
Zg. Geothermal springs	
Zk(b). Karst and subterranean hydrological systems (inland)	
Human-made wetlands	
1. Aquaculture(fish/shrimps) ponds	
2. Ponds (generally <8 ha)	Farm ponds
	Stock ponds
	Small tanks
3. Irrigated land	Irrigation channels
	Ricefields
4. Seasonally flooded agricultural land	Intensively managed or grazed wet meadow or pasture
5. Salt exploitation site	Saltpans
	Salines
6. Water storage areas	Reservoirs/barrages/dams/ impoundments (>8 ha)
7. Excavations	Gravel/brick/clay pits
	Burrow pits
8. Waste water treatment area	Sewage farms
	Settling ponds
	Oxidation basins
9. Canals and drainage channels and ditches	
Zk(c). Karst and other subterranean hydrological systems (human made)	

Adapted from: Ramsar Convention Secretariat 2013

1.4 Wetlands in South Asia (Excluding India): Area, Distribution and Types

It is complex to determine the precise status of the extent of wetlands in South Asia in totality. However, the extent of wetlands in some South Asian countries as per various sources is given in Table 1.3. Further, country-specific major area of wetlands, areas with abundant wetlands and protected wetlands are presented in Table 1.4.

To understand the typology of South Asian wetlands, a wetland classification scheme (given below as Table 1.5) developed by Gopal and Krishnamurthy (1992) can be taken into account.

Table 1.3 Extent of wetlands in some countries of South Asia (except India)

Country	Area under wetlands	Source of information
Nepal	At least 5% of the land area	Nepal Biodiversity Strategy (HMGN/MFSC 2002)
Pakistan	About 10% of the land area of the country	Pakistan National Wetland Policy In: Rec. Zool. Surv. Pakistan 21:96–98 (2012) http://pakistanwetlands.org/record/18_19.pdf
Bangladesh	70,000–80,000 km^2 or about 50% of land area	State and management of wetlands in Bangladesh by Byomkesh et al. (2009)
Sri Lanka	9600 km^2 (considering reservoirs, lakes, ponds and marshes and paddy)	Gopal and Krishnamurthy (1992)

Table 1.4 Distribution of wetlands in South Asian countries

Country	Major area of wetlands or area with abundant wetlands	Protected wetlands
Afghanistan (Scott 1995)	Afghanistan possesses few wetlands other than its major river systems rising in the high mountain ranges in the centre and northeast of the country	Band-e Amir Lake was declared a national park (410.00 km^2) in September 1973. The two main areas, Imam Sahib and Darqad, of the Amu Darya Marshes are declared as Important Bird Areas (IBA) by BirdLife International. The Kole Hashmat Khan Lake was declared a Waterfowl Sanctuary by the Directorate of Wildlife and National Parks in 1973, but this has never been legally gazetted. It has been identified as an IBA site. Dasht-e-Nawar Lake was declared a National Flamingo and Waterfowl Sanctuary by the Directorate of Wildlife and National Parks in 1974
	Hamun-e Puzak is the largest lake system and it is one of a group of three large freshwater lakes in the Sistan Basin (an inland drainage basin surrounded by desert on the border with Iran)	
	These wetlands receive most of their water from the Helmand River and Khash River, which rise in the Hindu Kush	
	The only other large natural lakes are two brackish to saline lakes in the central highlands, Dasht-e-Nawar and Ab-e Istada, both of which are renowned as breeding areas for the greater flamingo *Phoenicopterus ruber*, and two high-altitude freshwater lakes, ZorKol and Chaqmaqtin, in the Pamir ranges in the Wakhan Corridor. Kole Hashmat Khan, a small eutrophic lake in the foothills of the Hindu Kush near Kabul, is the only remaining waterbody of the formerly extensive wetlands on the plain of Kabul. Other notable wetlands include a chain of six lapis lazuli lakes separated by travertine terraces in the Band-e Amir valley and several small freshwater lakes along the Kabul River, notably Lake Sarobi and Lake Duronta. In the north, there were formerly extensive floodplain wetlands along the Amu Darya River on the border with Tadzhikistan, but much of this habitat has probably now been lost to agriculture	
Bhutan (Anonymous 1989a)	Bhutan mainly has river systems and scattered small, high-altitude glacial lakes in the Himalayan range. There are three main groups of glacial lakes: (i) a group of several lakes, the largest about 3 km^2 in extent in the northwestern part of the Jigme Dorji Wildlife Sanctuary; (ii) a group of 11 small lakes (all less than 1 km^2 in extent) at 4000–4500 m elevation in western Bhutan (27°30′N, 89°08′E); and (iii) a group of 6 small lakes at similar altitudes a little further to the east (27°34′N, 89°30′E)	Jigme Dorji Wildlife Sanctuary was established in 1974
	The river systems flow southwards in steep-sided valleys and gorges through all the main vegetation zones from alpine snow and ice down to the subtropical forests of the foothills. The major river systems are the Torsa, Raidak (Wong Chu), Sankosh (Mo Chu) and Manas	
	In some of the more remote valleys, such as the Popshika and Khalong Chu, significant natural marshes remain	

(continued)

Table 1.4 (continued)

Country	Major area of wetlands or area with abundant wetlands	Protected wetlands
Bangladesh (Akonda 1989)	Bangladesh possesses enormous wetland areas, and during the rainy season, about half of the country could be classified as wetland	Wetlands such as Hakaluki Haor, Sundarbans, Tanguar Haor, Kawadighi Haor, etc. are protected areas
	The principal wetlands are rivers and streams, shallow freshwater lakes and marshes (*haor*s, *baor*s and *beel*s), water storage reservoirs, fishponds, seasonally flooded cultivated plains and estuarine systems with extensive mangrove swamps	
	There are about 700 rivers in Bangladesh, including small mountain streams, meandering seasonal creeks, muddy channels (*khal*s) and major rivers with their numerous tributaries and distributaries. The total length of the rivers has been estimated at 24,140 km. In some regions, such as Patuakhali and Barisal, they form an intricate network across the land. All of the rivers, with the exception of those in the Chittagong region, belong to one of the three major river systems, the Ganges-Padma, the Brahmaputra-Jamuna and the Surma-Meghna. The largest river in Bangladesh, the Lower Meghna, is the joint stream of the Padma, the Meghna and the Dhaleswari	
	Most *haor*s are found in eastern Mymensingh and Sylhet, in a region known as the haor basin. All *baor*s are situated in the moribund delta of the Ganges in Kushtia, Jessore and Faridpur. Over a thousand *beel*s in the country, the greatest concentrations being in the main delta region (Rajshahi, Pabna, Kushtia, Jessore, Faridpur, Comilla and Noakhali), in the haor basin (eastern Mymensingh and Sylhet). There are very few *beel*s in the Chittagong region, and most of these contain water only in the rainy season	
	There are extensive grass and reed marshes along many of the rivers in the Chittagong Hill Tracts, particularly the lower course of the Sajjak River. There are only three true lakes in the country: Rainkhyongkine and Bogakine in the Chittagong Hill Tracts and Ashuhila beel at the northern end of the Barind Tract. The only large artificial lake is Kaptai reservoir in the Chittagong Hill Tracts	
	Other artificial waterbodies include many thousands of small tanks and fishponds scattered throughout the country and large areas of shrimp ponds, particularly in the Chittagong and Khulna regions. The government is actively encouraging shrimp culture, and major aquaculture schemes have been developed in recent years in the Chokoria Sundarbans and Moheshkhali area in Cox's Bazar	

(continued)

Table 1.4 (continued)

Country	Major area of wetlands or area with abundant wetlands	Protected wetlands
	Vast areas of the low-lying alluvial plains between the rivers are flooded during the rainy season	
	The coastal zone extends for some 480 km from the Indian border in the west to the Burmese border in the southeast. It includes the numerous low-lying islands and vast mangrove swamps (Sundarbans) in the eastern part of the Ganges-Brahmaputra delta, the similar but much smaller estuarine systems along the Chittagong coast (Chokoria Sundarbans and Naaf estuary) and a single coral island off the extreme southern tip of the country (St. Martin's Island)	
India (Wolstencroft et al. 1989)	The tanks and reservoirs of the Deccan plateau together with the lagoons and other remaining wetlands of the west coast of the peninsula The vast saline expanses of Rajasthan, Gujarat and the Gulf of Kutch The freshwater lakes and reservoirs from Gujarat eastwards through Rajasthan and Madhya Pradesh The deltaic wetlands and lagoons of India's east coast The marshes, jheels, terai swamps and chaur lands of the Gangetic Plain The floodplain of the Brahmaputra and the marshes and swamps in the hills of Northeast India and the Himalayan foothills The lakes and rivers of the montane (primarily Palaearctic) region of Kashmir and Ladakh The wetlands (primarily mangrove associations) of India's island arcs	Several wetlands such as Keoladeo National Park, Chilika Lake (Nalabana), Kolleru Lake, Nalsarovar Lake, Pulicat Lake, Bhitarkanika, Gulf of Kachchh (Marine National Park), Gulf of Mannar, Point Calimere, Wild Ass Sanctuary (Little Rann of Kachchh), Kachchh Desert Sanctuary (Great Rann of Kachchh)
Maldives (Faria 2015)	In the Maldives, there are natural depressions or wetlands (locally known as *Kulhi)* situated within or partly along the coast. These wetlands are either brackish or freshwater, may be linked to lagoons and almost always support mangroves. Of the 1190 Maldivian islands, only 41 islands have wetlands, making conservation of these ecosystems a priority. The Maldives has the seventh largest coral reef system in the world	-
Nepal (Anonymous 1989b)	Due to lack of a coastline, and predominance of mountainous terrain, Nepal does not have many wetlands	Many of Nepal's most important wetlands are included within protected areas (reserves). Most of the important highland lakes are situated in the three large Himalayan

(continued)

Table 1.4 (continued)

Country	Major area of wetlands or area with abundant wetlands	Protected wetlands
	There are three major river systems fed by the snows and glaciers of the Himalayas: the Kosi in the east, the Gandak in the centre and the Karnali in the west. There are numerous smaller rivers rising in the Mahabharat and Siwalik ranges	national parks (Sagarmatha, Langtang and SheyPhoksumdo
	Other wetlands include about 50 km^2 of small lakes scattered throughout the country, 12 km^2 of man-made reservoirs, 50 km^2 of village tanks and ponds and some 1850 $km^2$of rice paddies. Large reservoirs under construction in the Gandak River system (450 km^2), Bagmati River basin (90 km^2) and Karnali River basin (240 km^2) will add a further 800 km^2 of surface water area when completed	
Pakistan (Rao 1989)	Water storage reservoirs on large rivers in the northern Punjab, Azad Kashmir and North-West Frontier province (NWFP; Khyber Pakhtunkhwa province) were constructed mainly for irrigation purposes and the generation of electricity and now supports large numbers of wintering waterfowl. Examples include Chashma Barrage, Taunsa Barrage and the Marala, Rasool and Qadirabad Headworks in Punjab province, Mangla Dam in Azad Kashmir and Tarbela reservoir in NWFP	Lal Suhanra National Park, Margalla Hills National Park, Chashma Lake Wildlife Sanctuary, Drigh Lake Wildlife Sanctuary, Hub Dam Wildlife Sanctuary, Hadero Lake Wildlife Sanctuary, Haleji Lake Wildlife Sanctuary, Hawkes Bay/Sandspit Wildlife Sanctuary, Keti Bundar North Wildlife Sanctuary, Keti Bunder South Wildlife Sanctuary, Khabbaki Lake Wildlife Sanctuary, Kharrar Lake Wildlife Sanctuary, Kinjhar (Kairi) Lake Wildlife Sanctuary, Langh Lake Wildlife Sanctuary, Nammal Lake Wildlife Sanctuary, Rasool Barrage Wildlife Sanctuary, Taunsa Barrage Wildlife Sanctuary, Bund Khushdil Khan Game Reserve, Head Islam Game Reserve, 3132 ha, established 1978, Qadirabad Game Reserve, Indus Dolphin Sanctuary, Nara Game Reserve, Rawal Lake Game Reserve, Zangi Nawar Game Reserve, Thanedar Wala Game Reserve and Bajwat Game Reserve
	Brackish lakes with small water catchment areas in semiarid hill ranges in the north-central part of the country, e.g. Nammal, Khabbaki, Ucchali, Jahiar and Kalar Kahar lakes in Punjab province	
	Small water storage dams in the submontane tracts, e.g. Kandar, Tanda, Baran, Warsak and Darwazai Dams in NWFP, Nammal Lake in Punjab province and Akara Dam and Band Khushdil Khan in Balochistan province	
	Brackish lakes fed by seepage, e.g. Malugul Dhand and Thanedar Wala in NWFP, Kharrar Lake in Punjab province and Phoosna and a number of other lakes in Sindh province	
	Fresh to slightly brackish lakes, dhands and ponds obtaining their water supply from canals, springs and streams and managed for specific purposes. Examples include Patisar Lake in Lal Suhanra National Park, Punjab province, which was originally maintained as a stopgap source of water for irrigation; Kinjhar Lake, Sindh province, and Hub Dam, Sindh/Balochistan, which are maintained as a supply of drinking water for Karachi and irrigation water to agricultural lands in Sindh and Balochistan; and Haleji Lake, Sindh province, which is maintained as a stopgap supply of water for Karachi in the event of closure of the Kinjhar pipeline for cleaning	

(continued)

Table 1.4 (continued)

Country	Major area of wetlands or area with abundant wetlands	Protected wetlands
	Saline marshes which receive their water supply from irrigation canals and have become saline because of the presence of salts in the soil and high rates of evaporation, e.g. Pugri, Kur and Kharki wetlands in Sindh province	
	Freshwater marshes maintained by seepage from irrigation canals, e.g. Beroon Kirthar Canal and Kund Lake in Balochistan province	
	Deltas and estuaries with extensive intertidal mudflats along the coast of Sindh and Balochistan	
	Estuarine mangrove forest and mangrove swamps, particularly in the Indus Delta and in creeks near Karachi	
	Small offshore islands with nesting seabirds and marine turtles, e.g. Astola Island in Balochistan	
	Areas of rice paddies, flooded agricultural land and seasonally flooded grassland scattered throughout the Indus floodplains	
Sri Lanka (Kotagama et al. 1989)	The wetlands of Sri Lanka can be very broadly considered under three groups: (a) offshore and marine systems, (b) coastal systems and (c) inland systems	Several of the well-established national parks such as Wilpattu and Yala include significant wetlands, while other important sites, such as Chundikkulam, Kokkilai, Kalametiya, Bundala and Wirawila Tissa, have been designated as sanctuaries. A large part of the very important villus system of Mahaweli River has received protected status in the Flood Plains National Park and Somawathiya National Park
	(a) Offshore and marine systems: These include shallow sea bays and straits, offshore islands and islets. (b) coastal systems: These include estuaries, brackish to saline lagoons and mangrove swamps, along with rocky seacoasts, sandy beaches, salterns, saltpans and aquaculture ponds. Estuaries: There are some 45 estuaries around the coast of Sri Lanka, belonging to two types: basin estuaries (e.g. Puttalam Lagoon, Negombo Lagoon and Jaffna Lagoon) and riverine estuaries (e.g. Kaluganga estuary and Kelani Ganga estuary). Sand barrier formation in recent years has transformed some basin estuaries into lagoons (e.g. Koggala Lagoon). In other cases, e.g. Batticaloa Lagoon and Kokkilai Lagoon, sand barriers erase the connection with the sea during a part of the year. Lagoons: There are some 40 true lagoons around the coast of Sri Lanka. They are most common along the southern, southeastern and eastern coasts. The total area of the lagoons is estimated at about 20.0 km^2. Mangroves: Mangroves are discretely distributed along the coastline and are absent along exposed shorelines, particularly in the southwest, south and northeast. The main mangrove areas are situated in Mullaitivu, Trincomalee, Kathiraveli, Vakarai, Panichankerni, Valaichenai, Batticaloa, Karaitivu, Komari, Pottuvil, Hambantota, Pilinawa, Matara, Galle, Gintota, Muthurajawela, Negombo, Chilaw, Mundel, Puttalam, Kalpitiya and Mannar and on the Jaffna Peninsula. The area of mangroves is 63 km^2 in the districts of Colombo, Ampara, Gampaha, Trincomalee, Batticaloa and Puttalam alone, and the total area of mangroves is likely to be close to 100 km^2	

(continued)

Table 1.4 (continued)

Country	Major area of wetlands or area with abundant wetlands	Protected wetlands
	Inland systems: The natural freshwater habitats consist of about 9 large rivers and 94 small rivers (4563 km in length), numerous streams (particularly in the wetzone), extensive marshes and many small permanent and seasonal ponds. Although there are no large natural lakes in Sri Lanka, there are many floodplain lakes of the varzea type, known as villus. They cover a total area of about 125 km^2. Many of the large villus are situated in the Mahaweli River system in the east. Wilpattu National Park, in the west, also possesses a number of very small freshwater villus along with a unique group of salt villus inland. Man-made freshwater wetlands: These wetlands or "wewa", vary in size from a few hectares to 6500 ha at full spill level. The 9 major rivers, about 25 smaller rivers and their numerous tributary rivers and streams drain a total of 103 basins. Man-made lakes (tanks and reservoirs): The most common freshwater habitats are the irrigation tanks, of which there are over 10,000 in Sri Lanka. The total area of these man-made lakes exceeds 170,000 ha	

Table 1.5 A wetland classification scheme for South Asian countries

I. **Saline wetlands**
A. *Wetlands associated with permanent flooding*
(i) Herbaceous vegetation (coastal beds of kelp and angiosperms)
(ii) Woody vegetation (mangroves)
B. *Wetlands associated with temporary flooding*
(Inland saline habitats with 1–3 months of flooding)
(i) Herbaceous vegetation – halophytes
(ii) Woody vegetation – saline scrubs
II. **Freshwater wetlands**
A. *Wetlands associated with permanent waterbodies*
(a) Lotic habitats (rivers and streams)
(i) Herbaceous vegetation – reeds (*Phragmites, Arundo*), bamboos (*Bambusa*), canes (*Calamus*) and other grasses
(ii) Woody vegetation – riparian fringing forests
(b) Lentic habitats (lakes/reservoirs)
(i) Herbaceous vegetations
Submerged, floating, floating leaved macrophytes only
Short emergent vegetation (sedges family)
Tall emergent vegetation – reeds (*Phragmites*) and cattails (*Typha*)
(ii) Woody vegetation

(continued)

Table 1.5 (continued)

B. *Wetlands associated with temporary waterbodies*
(3–9 months of flooding)
(a) Lotic habitats (floodplains of streams and rivers)
(i) Herbaceous vegetation – reeds (*Phragmites*), cattails (*Typha*), grasses (*Saccharum*, *Erianthus*, *Paspalum*), sedges (*Cyperus*, *Scirpus*) and herbs
(ii) Woody vegetation – floodplains forests
(b) Lentic habitats (*ponds*, *tanks*, *reservoirs*)
Submerged, floating, floating leaved macrophytes only
Short emergent vegetation (sedges family)
Tall emergent vegetation – reeds (*Phragmites*) and cattails (*Typha*)

Source: Gopal and Krishnamurthy (1992)

1.5 Wetlands in India

The wetlands of India are categorized into eight basic types (Wolstencroft et al. 1989), which are as follows:

1. Tanks and reservoirs of the Deccan plateau together with the lagoons and other remaining wetlands of the west coast of the peninsula
2. Vast saline expanses of Rajasthan, Gujarat and the Gulf of Kutch
3. Freshwater lakes and reservoirs from Gujarat eastwards through Rajasthan and Madhya Pradesh
4. Deltaic wetlands and lagoons of India's east coast
5. Marshes, jheels, terai swamps and chaur lands of the Gangetic Plain
6. Floodplain of the Brahmaputra and the marshes and swamps in the hills of Northeast India and the Himalayan foothills
7. Lakes and rivers of the montane (primarily Palaearctic) region of Kashmir and Ladakh
8. Wetlands (primarily mangrove associations) of India's island arcs

Space Applications Centre (2011) has estimated total wetland area of India as 152,606 km^2, which accounts for 4.64% of the country's geographical area, and the detailed break-up is given in Table 1.6.

Statewise distribution of wetlands in terms of percentage share reveals that Gujarat, with 34,700 km^2 wetland area, ranks first with respect to the total wetland area in the country (constituting 22.77% of total wetland area in the country) mainly due to vast stretches of intertidal mudflats and saltpans. Gujarat is followed by Andhra Pradesh (14,500 km^2 or 9.31%), Uttar Pradesh (12,400 km^2 or 8.13%), West Bengal (11,100 km^2 or 7.28%) and Maharashtra (10,100 km^2 or 6.62%). In terms of percentage of geographical area of the respective regions (state/union territory), Lakshadweep islands rank first (96.12%) mainly due to the presence of corals and mangroves. The other major states/union territories having more than 10% area are Andaman and Nicobar Islands (1528 km^2, i.e. 18.52% of their geographical area),

Table 1.6 Area under different wetlands types in India

Sr No.	Wetland type	Area (km^2) of wetlands	Number of wetlands
1	Inland wetlands – natural	66,231	45,658
2	Inland wetlands – man-made	39,418	142,812
3	Total – inland wetland	105,649	188,470
4	Coastal wetlands – natural	37,039	10,204
5	Coastal wetlands – man-made	4362	2829
6	Total – coastal wetland	41,401	13,033
Total (of coastal and inland wetlands, each having area of at least 0.0225 km^2)		147,050	201,503
Total (of coastal and inland wetlands, each having area of less than 0.0225 km^2 that could not be mapped due to excessively small size)		5555	5555
Total wetland area and numbers in India		152,605	207,058

Source: SAC (2011)

Daman-Diu (20.68 km^2, i.e. 18.46% of the U.T.'s geographical area), Gujarat (34,700 km^2, i.e. 17.56%, of its geographical area), Puducherry (63.35 km^2, i.e. 12.88% of its geographical area) and West Bengal (11,079 km^2, i.e. 12.48% of its geographical area) (Panigrahy et al. 2012).

1.6 Threats to Wetlands and Wetland Losses

Wetlands around the world are under threat due to man (Mitsch and Gosselink 2000). In the South Asian region, rapid deterioration and decline in all types of wetlands has occurred during recent decades due to the rapid increase in human population and demand for natural resources for food, fuel and fodder (Gopal and Krishnamurthy 1992). Scientific estimates show that 64% of the world's wetlands have disappeared since 1900 (Ramsar Fact Sheet 2014). In some regions (especially, Asia) the loss is even higher. Inland wetlands are disappearing at a faster pace than coastal ones (Ramsar Fact Sheet 2014). In addition to loss in area of wetlands, wetland degradation due to contamination of waters is also a major issue. Vijayan et al. (2004) have reported their findings of fish toxicity investigations after examining 1249 individuals of 20 fish species from 114 wetlands of India spread over 15 states. They reported that none of the fishes examined were free from heavy metals and organochlorine pesticides, and in some cases, their concentration exceeded the permissible limit for human consumption. Of all the heavy metals studied (Pb, Zn, Cu, Cr and Cd), Pb was the most prevalent and significant contaminant followed by Zn. The wetlands of Uttar Pradesh, Bihar and Haryana were most contaminated. The levels of Pb in many fish species were closer to the permissible levels suggested for human consumption by the WHO, but in some species, its concentration was above permissible limits (Vijayan et al. 2004). In India, the threats and conservation issues identified for the wetlands in different states seem to be remarkably similar across the country (Vijayan et al. 2004). A review of "Directory of Indian Wetlands" indicates the following to be the major threats (Roy and Hussain 1993):

- Siltation of wetlands due to soil erosion in their respective catchments and watersheds
- Shrinking of wetland (especially lakes) due to siltation
- Pollution due to sewage, industrial effluents and rainwater runoff from agricultural land
- Cultural eutrophication due to domestic sewage, industrial pollutants (e.g. effluents from dying units) and agricultural pollutants (e.g. fertilizers)
- Choking of water spread due to excessive growth of aquatic macrophytes (hydrophytes) as a result of cultural eutrophication
- Encroachment of shores and basins for agricultural practices that further leads to accelerated sedimentation as ploughing and tilling near shore and in dried basins of wetlands without adequate soil conservation measures accelerates soil erosion
- Grazing on shores and increasing numbers of grazing livestock
- Construction of roads right up to the wetlands for tourism and economic activities.
- Solid waste (including garbage) dumping
- Filling and draining of wetland areas for converting them into built-up areas (roads and residential/commercial/industrial complexes)
- Filling and draining of wetland areas for developing into additional agricultural land.
- Dredging of wetlands to increase their depth for irrigation purpose
- Unregulated extraction of water for irrigation by means of diesel engines
- Auctioning of wetlands (especially irrigation reservoirs) on contract or leasing them out for commercial fishing without any effective regulation (e.g. control on mesh size to avoid fishing of fingerlings) that may lead to overfishing and scarcity of fish resource for piscivorous birds
- Poaching and trapping waterbirds
- Illegal burning and overextraction of macrophytes
- Unregulated tourism and improperly oriented tourists causing disturbance to wetland wildlife
- Irregular and unregulated (from wildlife view point) release of waters from dams into irrigation reservoirs through canal systems and release of waters from irrigation reservoirs to agricultural fields that make the irrigation reservoirs unsuitable as waterbird habitats due to unsuitable water levels

1.7 Wetland Conservation

For centuries, humankind had viewed wetlands as places to be drained and converted for more obvious uses such as agriculture. The process had gone so far in the developed countries that the disappearance of wetlands led to undesirable consequences (Matthews 1993). Such undesirable consequences included flash floods, shoreline destruction, accumulation of pollutants and disappearance of many useful plants and animals dependent on wetlands and the loss of groundwater reserves and the consequent need for irrigation. The developing countries too have been making the same mistakes leading to a variety of threats to wetlands. Our negligence towards wetland conservation would reduce if our masses and planners, policy-makers and developers are made aware about the ecological functions of wetlands and the goods and services that wetlands provide to the humankind.

Some important ecological functions performed by wetlands are as follows (US EPA 2015):

- Wetlands are like "biological supermarkets". Owing to their high productivity, they produce great quantities of food that attract many animal species to forage.
- Many animals, like certain amphibians and fishes, need specific types of wetlands for successful completion of their breeding. On the other hand, for many aquatic animals like waterbirds, otters and crocodiles, wetlands are necessary life-support system. Numerous species of aquatic reptiles, waterbirds and mammals rely on wetlands for food, water and shelter, especially while migrating and breeding.
- Wetlands support numerous aquatic invertebrates.
- Several hydrophytes rely on wetlands for survival, growth and development.
- Wetlands are very important in biogeochemical cycles (e.g. carbon cycle, nitrogen cycle, phosphorus cycle, hydrological cycle).
- Wetlands maintain ecological stability of landscapes by acting as buffers against floods.
- Wetlands act as traps for nutrients which otherwise may get "wasted" with flowing waters of rivers/streams or rainwater runoff.

Some important functions or ecosystem services performed by wetlands (Mitsch and Gosselink 2000; MoEF 2007; Ramsar Fact Sheet 2014) are as below:

- Wetlands satisfy domestic water needs (including drinking water) of people and help replenish the groundwater aquifers that are important source of freshwater for humanity.
- Fish and rice constitute major food items for millions of people of the world including those of India and other countries of South Asia. Coastal wetlands and several types of inland wetlands (e.g. irrigation reservoirs, dams and even rice paddies) provide fish, whereas rice paddies supply rice.
- About 2 billion people of South Asia depend on groundwater for getting their daily water supply. Wetlands keep this water pure and safe from toxic heavy

metals and other toxic pollutants as wetland sediments absorb such elements and prevent them from entering the groundwater aquifer.

- Forested wetlands or swamps supply timber (e.g. 220,000 km^2 in the USA), whereas marshes supply herbaceous vegetation that cater to the needs of grass-root or ecosystem people (e.g. for roof-thatch material, fodder for livestock, etc.). In India, mangrove swamps have fodder value too.
- Wetlands act as sponges or buffers against floods or other substantial flowing/moving water action and in turn reduce the amount of soil erosion and damage to human life and property.
- Wetlands support recreational needs of modern society (swimming, diving, tourism and waterbird-oriented recreation including photography).
- Wetlands support educational and scientific (research) requirement of the modern society.
- Wetlands play a vital role in climate change adaptation and mitigation.

Due to all these ecological functions and socio-economic values of wetlands, their conservation is considered important throughout the world.

1.8 Ramsar Convention: A Global Effort for Wetland Conservation

The Convention on Wetlands of International Importance, popularly known as the Ramsar Convention 1971, is a global intergovernmental treaty that facilitates the framework for national action and international cooperation for conservation and wise use of wetlands and their resources. It is the only global treaty that focuses exclusively on wetland ecosystem. The Convention was held in the Iranian city named Ramsar in 1971 (and therefore it is called “Ramsar Convention 1971”), and it came into force in 1975.

This Convention is the oldest of the modern global intergovernmental environmental agreements. The agreement/treaty was negotiated during the 1960s by countries and non-governmental organizations concerned about the increasing disappearance and dilapidation of wetland habitats for migratory waterbirds. Thus, in its early period, the Convention was known as Convention on Wetlands of International Importance especially as Waterfowl Habitat, but later, the last four words were dropped. Ramsar Convention promotes “wise use” of wetlands apart from their conservation. Here, the “wise use” of wetlands refers to their sustainable utilization for the benefit of mankind in a way compatible with the maintenance of the natural properties of the ecosystem (Davis 1993). The countries that have signed this Convention are committed to the following (WWF 1995):

- Work towards the wise use of their wetlands through country-level land-use planning, implementing appropriate policies and legislation, management actions and public education

- Propose significant wetlands for their inclusion in the list of Ramsar Sites (or the List of Wetlands of International Importance) and making sure they are effectively managed
- Cooperate internationally regarding trans-boundary wetlands, mutually common wetland systems, mutually common species and development projects that may affect wetlands

1.8.1 Salient Points on Working Machinery of Ramsar Convention (WWF 1995)

- The *Ramsar Secretariat* manages the day-to-day activities of the Convention.
- The *Conference of the Contracting Parties* (COP) meets every 3 years and promotes policies and guidelines to facilitate the application of the Convention.
- The *Standing Committee* meets annually to guide the Convention between meetings of COP.
- The *Scientific and Technical Review Panel* provides guidance on key issues for the Convention.
- Countries are encouraged to establish *National Wetland Committees*, involving all government sectors dealing with development planning, water resources, protected areas, biodiversity, education, tourism and development assistance. Non-governmental organizations and civil societies are also encouraged to participate.
- Nationally, each contracting party designates an administrative authority for implementation of the Convention.
- Ramsar Sites facing problems in maintaining their ecological character can be placed (in consultation with the contracting party) on a special list called *Montreux Record* and technical assistance to help solve the problems can be provided.
- Eligible countries can apply to the "Ramsar Small Grants Fund" and "Wetlands for the Future Fund" for financial assistance to implement wetland conservation and wise use projects.

As of now, there are 168 contracting parties (signatory countries) and 2186 Ramsar Sites covering an area of over 2,084,493 km^2. India, as a contracting party, has 26 Wetlands of International Importance (Ramsar Sites) covering an area of 12,119.03 km^2 (Source: Ministry of Environment, Forests and Climate Change, New Delhi, India). Details of Ramsar Sites in India are given in the Table 1.7. A brief account of Ramsar Sites in other countries in South Asia is presented in Table 1.8.

Table 1.7 Ramsar sites in India and important information regarding them[a]

Sr. No.	Ramsar site	Area (km^2)	State	Designated as Ramsar site on	Ramsar site No.
1.	Vembanad-Kol	1512.5	Kerala	19-8-2002	1214
2.	Chilika Lake	1165	Odisha	1-10-1981	229
3.	Deepor Beel	40	Assam	19-8-2002	1207
4.	Kolleru Lake	901	Andhra Pradesh	19-8-2002	1209
5.	Sasthamkotta Lake	3.73	Kerala	19-8-2002	1212
6.	Tsomoriri	120	Jammu and Kashmir	19-8-2002	1213
7	Hokera Wetland	13.75	Jammu and Kashmir	8-11-2005	1570
8.	Renuka Wetland	0.2	Himachal Pradesh	8-11-2005	1571
9.	Rudrasagar Lake	2.4	Tripura	8-11-2005	1572
10.	Upper Ganga River	266	Uttar Pradesh	8-11-2005	1574
11.	Bhoj Wetland	32	Madhya Pradesh	19-8-2002	1206
12.	East Calcutta Wetlands	125	West Bengal	19-8-2002	1208
13.	Point Calimere Wildlife Sanctuary	385	Tamil Nadu	19-8-2002	1210
14.	Ashtamudi Wetland	614	Kerala	19-8-2002	1204
15.	Nalsarovar Bird Sanctuary	120	Gujarat	24-9-2012	2078
16.	Kanjli	1.83	Punjab	22-1-2002	1160
17.	Ropar	13.65	Punjab	22-1-2002	1161
18.	Pong Dam Lake	156.62	Himachal Pradesh	19-8-2002	1211
19.	Keoladeo National Park	28.73	Rajasthan	1-10-1981	230
20.	Wular Lake	189	Jammu and Kashmir	23-3-1990	461
21.	Harike Lake	41	Punjab	23-3-1990	462
22.	Loktak Lake	266	Manipur	23-3-1990	463
23.	Sambhar Lake	240	Rajasthan	23-3-1990	464
24.	Chandertal Wetland	0.5	Himachal Pradesh	8-11-2005	1569
25.	Surinsar-Mansar Lake	3.5	Jammu and Kashmir	8-11-2005	1573
26.	Bhitarkanika Mangroves	650	Odisha	19-8-2002	1205

[a]Source: www.ramsar.org

Table 1.8 Number and area of Ramsar sites in some countries of South Asia[a]

Sr. No.	Country	No. of Ramsar sites	Area (km^2)
1.	Bangladesh	2	6112.00
2.	Bhutan	3	12.26
3.	Sri Lanka	6	1981.72
4.	Nepal	10	605.61
5.	Pakistan	19	13,438.07

[a]Note: Source of the information in the table: www.ramsar.org

1.9 Conclusion

A student or a researcher who is new to wetland science may initially feel perplexed over the multiple definitions of the term "wetland". From a baffling pool of numerous definitions of wetlands used in the world, a South Asian researcher/student can rely on the international definition coined and propagated by the Ramsar Convention. However, ideally, this "wetland typology-oriented" definition should be relied upon in combination with the understanding of "hydrobiological characteristics-oriented" definition by the US Fish and Wildlife Service as this definition is indeed ecological in nature.

Hydrology, hydric soil and hydrophytic vegetation play important roles in establishment and maintenance of wetlands on one hand, and on the other hand, they are also important for wetland delineation, management and conservation. Though wetlands globally cover 5–8% of land surface area of the world, they are under threat. Rapid deterioration and decline in all types of wetlands has occurred in the South Asian region due to the rapid human population rise and increased demand for natural resources for food, fuel and fodder. Wetlands are facing problems like siltation, pollution, cultural eutrophication, choking of open waters by excessive hydrophytic vegetation, encroachment of shores and basins for commercial agriculture and degradation due to filling, dredging and draining. This is happening despite the fact that wetlands provide numerous ecological and socio-economic functions that benefit humankind. Therefore, conservation of wetlands is extremely important. Ramsar Convention is an international effort for wetland conservation. It is a global intergovernmental treaty that facilitates the framework for national action and international cooperation for conservation and wise use of wetlands and their resources.

References

Akonda AW (1989) Bangladesh. In: Scott DA (ed) A directory of Asian wetlands. IUCN (The World Conservation Union), Gland, p 1181

Anderson JT (2012a) Exploring wetlands with the wetland guru..! Jalaplavit 3(2):7–9.

Anderson JT (2012b) A defining moment for wetlands: is it a wetland or is it not a wetland? Jalaplavit 3(1):5–9

Anonymous (1989a) Bhutan. In: Scott DA (ed) A directory of Asian wetlands. IUCN (The World Conservation Union), Gland, p 1181

Anonymous (1989b) Nepal. In: Scott DA (ed) A directory of Asian wetlands. IUCN (The World Conservation Union), Gland, p 1181

Baldassarre GA, Bolen EG (1994) Waterfowl ecology and management. Wiley, New York, p 609

Byomkesh T, Nakagoshi N, Md. Shahedur R (2009). State and management of wetlands in Bangladesh. Landsc Ecol Eng 5: 81–90. doi:10.1007/s11355-008-0052-5

Cowardin LM, Carter V, Golet FC, LaRoe ET (1979) Classification of wetlands and deepwater habitats of the United States. FWS/OBS-79/31. U. S. Fish and Wildlife Service, Washington, DC, p 103

Daubenmire R (1968) Plant communities: a textbook of plant synecology. Harper and Row publishers, New York

Davis TJ (ed) (1993) Towards the wise use of wetlands. Wise use Project. Ramsar Convention Bureau, Gland

DERM (2010) Queensland wetland definition and delineation guideline. DRAFT Queensland Government, Department of Environment and Resource Management, Brisbane

Environmental Laboratory (1987) Corps of Engineers wetlands delineation manual. U.S. Army Corps of Engineers Wetlands Research Program Technical Report Y-87-1. http://www.fws.gov/habitatconservation/delineation%2087.pdf. Accessed 9 Nov 2015

European Commission (2003).The role of wetlands in the water framework directive. Guidance Document 12, Luxembourg https://circabc.europa.eu/sd/a/47ac25cc-3b7f-4498-a542-afd9e3d-c3a4b/Guidance%20No%2012%20-%20Wetlands%20(WG%20B).pdf. Accessed 5 Nov 2015

Faria M (2015) Wetlands day 2015 in Maldives.https://www.linkedin.com/pulse/wetlands-day-2015-maldives-marialejandra-faria. Accessed 15 Nov 2015

Finlayson CM, Davidson NC (1999) Global review of wetland resources and priorities for wetland inventory. Ramsar Bureau Contract 56. Ramsar Convention Bureau, Gland, p 26

Gopal B, Krishnamurthy K (1992) Wetlands of South Asia. In: Wigham DF, Dykyjova D, Hejny S (eds) Handbook of vegetation science-wetlands of the world I. Inventory, ecology and management. Kluwer Academic Publishers, Dordrecht, pp 345–414

HMGN/MFSC (2002) Nepal biodiversity strategy. His Majesty's Government of Nepal, p 117

Kotagama SW, Pinto L, Samarakoon JL (1989) Sri Lanka. In: Scott DA (ed) A directory of Asian wetlands. IUCN (The World Conservation Union), Gland, p 1181

Leibowitz SG (2003) Isolated wetlands and their functions: an ecological perspective. Wetlands 23(3):517–531

Maltby E (1986) Waterlogged wealth: why waste the world's best wet places? Earthscan Publications, London, p 200

Maltby E, Turner RE (1983) Wetlands of the world. Geol Mag 55:12–17

Matthews GVT (1993) The Ramsar convention on wetlands: its history and development. Ramsar Convention Bureau, Gland, p 87

Matthews E, Fung I (1987) Methane emissions from natural wetlands: global distribution, area, and environmental characteristics of sources. Glob Chem Cycles 1:61–86

Mitsch WJ, Gosselink G (1986) Wetlands. Van Nostrand Reinhold, New York, p 539

Mitsch WJ, Gosselink G (2000) Wetlands. Wiley, New York, p 920

Mitsch WJ, Gosselink JG (2007) Wetlands. Wiley, New York, p 582

MoEF (2007) Conservation of wetlands in India: a profile (approach and guidelines). Ministry of Environment and Forests, New Delhi, p 42

National Wetlands Working Group (1988) Wetlands of Canada, Ecological land classification series, No. 24. Environment Canada and Polyscience Publications Inc., Ottawa, p 452

Navid D (1989) The international law of migratory species: the Ramsar Convention. Nat Resour J 29:1001–1016

NRC (National Research Council) (1995) Wetlands: characteristics and boundaries. National Research Council Committee on characterization of wetlands. National Academy Press, Washington, DC, p 328

Panigrahy S, Murthy TVR, Patel JG, Singh TS (2012) Wetlands of India: inventory and assessment at 1: 50,000 scale using geospatial techniques. Curr Sci 102:852–856

Ramsar Convention Secretariat (2013) The Ramsar convention manual: a guide to the Convention on Wetlands (Ramsar, Iran, 1971), 6th edn. Ramsar Convention Secretariat, Gland, p 109

Rao AL (1989) Pakistan. In: Scott DA (ed) A directory of Asian wetlands. IUCN (The World Conservation Union), Gland, p 1181

Rosenberry DO, Hayashi M (2013) Assessing and measuring wetland hydrology. In: Anderson JT, Davis CA (eds) Wetland techniques: vol. 1: foundation. Springer, New York, p 459

Roy R, Hussain SA (1993) Directory of Indian wetlands. Worldewide Fund for Nature-India, New Delhi and AWB Kuala Lumpur, p 264

SAC (2011) National wetland atlas. SAC/EPSA/ABHG/NWIA/ATLAS/34/2011. Space Applications Centre (ISRO), Ahmedabad, p 310

Scott DA (ed) (1995) A directory of wetlands in the Middle East. IUCN, Gland, and IWRB, Slimbridge, p 560

Scott DA, Jones TA (1995) Classification and inventory of wetlands: a global overview. Vegetatio 118:3–16

Ramsar Fact Sheet (2014) Wetlands-why should I care? http://www.ramsar.org/sites/default/files/ramsar_factsheets_1-4_en.pdf. Accessed 16 Feb 2015

Smith RL (1980) Ecology and field biology, 3rd edn. Harper & Row, New York, p 835

Stewart, RE, Kantrud, HA (1971) Classification of natural ponds and lakes in the glaciated prairie region. U.S. Fish and Wildlife Service, Resource Publication 92, Washington, DC, p 26

Tarnocai C, Adams GD, Glooschenko V, Glooschenko, WA, Grondin P, Hirvonen HE, Lynch-Stewart, P, Mills, GF, Oswald ET, Pollett FC, Rubec CDA, Wells ED, Zoltai, SC (1988) The Canadian wetland classification system. In National Wetland Working Group, ED. Wetlands of Canada. Ecological Land Classification Series 24, Environment Canada, Ottawa, Ontario and Polyscience Publications, Montreal, Quebec, pp. 413–427

Tiner RW (1991) The concept of a hydrophyte for wetland identification. BioScience 4:236–247

Tiner RW (2003) Geographically isolated wetlands of the Unites States. Wetlands 23(3):494–516

USEPA (2015) Wetlands-functions and values. http://cfpub.epa.gov/watertrain/pdf/modules/wetlandsfunctions.pdf. Accessed 15 Nov 2015

USGS National Wetlands Research Center (2014) Wetlands http://www.nwrc.usgs.gov/topics/wetlands/wetlandsInfo.htm. Accessed 15 Nov 2015

Vijayan VS, Prasad SN, Vijayan L, Muralidharan S (2004) Inland wetlands of India- conservation priorities. Sálim Ali Centre for Ornithology and Natural History, Coimbatore, p 532

Weaver JE, Clements E (1929) Plant ecology. McGraw-Hill Publication, New York, p 520

Wolstencroft JA, Hussain SA, Varshney CK (1989) India. In: Scott DA (ed) A directory of Asian wetlands. IUCN (The World Conservation Union), Gland, p 1181

WWF (1995) Ramsar convention on wetlands. http://wwf.panda.org/what_we_do/how_we_work/policy/conventions/ramsar/. Accessed 15 Nov 2015

Wetlands of Small Island Nations in South Asia vis-à-vis the Mainland and Island Groups in India: Status and Conservation Strategies

2

S. Dam Roy, P. Krishnan, Shesdev Patro, Grinson George, A. Velmurugan, R. Kiruba Sankar, and Purvaja Ramachandran

Abstract

The wetlands of small island nations in South Asia such as Sri Lanka and the Maldives are compared with that of India with respect to their status, biodiversity, threats and conservation measures. Sri Lanka has diverse coastal habitats, which are known to support fishes (1800 species), marine turtles (5 species), marine mammals (38 species), corals (183 species), mangroves (40 species), birds (100 species), reptiles (33 species) and seagrasses (10 species). The Maldives boasts one of the world's richest marine biodiversity comprising 250 species of corals, over 1200 of reef fishes, 200 species of sponges, over 1000 species of crustaceans and over 100 species of echinoderms. Marine biodiversity of India comprises 12,913 species, of which more than 5800 species are reported from Andaman and Nicobar Islands. Marine biodiversity of Lakshadweep islands is represented by corals (172 species), fishes (396), sponges (95), molluscs (260), echinoderms (84), crustaceans (80), turtles (04),

S. Dam Roy (✉) • A. Velmurugan • R. Kiruba Sankar
ICAR – Central Island Agricultural Research Institute (CIARI), Port Blair, Andaman, India
e-mail: sibnarayan@gmail.com; vels_21@yahoo.com; rkirubasankar@gmail.com

P. Krishnan • S. Patro • P. Ramachandran
National Centre for Sustainable Coastal Management (NCSCM), Ministry of Environment Forest & Climate Change, Anna University Campus, Chennai 600 025, Tamil Nadu, India
e-mail: krishnanars@yahoo.com; shesdevpatro@yahoo.com; purvaja.ramachandran@gmail.com

G. George
ICAR-Central Marine Fisheries Research Institute (CMFRI), Kochi, Kerala, India
e-mail: grinsongeorge@gmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_2

birds (142), marine mammals (6), seagrasses (07) and mangroves (03). The major threats to these wetlands of South Asian countries are climate change, extreme events like tsunami, coastal erosion, population pressure, habitat destruction and over-exploitation. The chapter emphasises the need for adopting frontier tools for biodiversity documentation and innovative strategies for their conservation.

Keywords
Biodiversity • Small island nations • Threats • Wetlands

2.1 Introduction

Ramsar Convention of 1971 defines wetlands as '*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six meters*' (Navid 1989). Wetlands are among the most productive ecosystems in the world, which have for thousands of years supplied human communities with food, drinking water, building materials and countless other benefits. They also play a critical role in maintaining global biodiversity, partly through their rich productivity, which helps to support food chains, and partly through provision of habitats for specially adapted plant and animal species (IUCN Sri Lanka 2004).

Following the Ramsar Convention and increased human pressure imposed on wetland ecosystems, considerable attention is given for promotion of wetland conservation in Asia. Based on the investigation by a number of organisations (such as Asian Wetland Bureau, World Wide Fund for Nature, IUCN – The World Conservation Union, and the International Council for Bird Preservation), the number of wetlands of high importance is 947, and the total area covered by them is 120 Mha (Van Zon 2004).

Small island nations of South Asia are represented by Sri Lanka and the Maldives. While Sri Lanka has an approximate wetland area of 274,000 ha (Van Zon 2004), that of the Maldives is still unreported. The wetlands of Sri Lanka are of 03 categories, namely, inland wetlands, coastal wetlands and man-made wetlands. Many of the wetlands in Sri Lanka are today being recognised as important, both regionally and globally, and two have been declared as wetlands of international importance under the Ramsar Convention (Van Zon 2004). The Maldives enjoy some of the richest marine biodiversity in the world. As per the available reports, the coral reefs (21,000 km^2) of the Maldives are the seventh most extensive in the world, representing about 3% of global coral reef area and is home to 250 species of corals teaming with over 1000 species of fish (Anon 2013). The wetlands of the Maldives and Sri Lanka

Table 2.1 Wetland classification of India, Sri Lanka and the Maldives

India[a]	Sri Lanka[b]	Maldives[c]
A. Inland wetlands *Natural* Lake, oxbow lake/cutoff meander, high altitude wetland, riverine wetland, waterlogged, river/stream *Man-made* Reservoir/barrage, tank/pond, waterlogged, salt pan **B. Coastal wetlands** *Natural* Lagoon, creek, sand/beach, intertidal mudflat, salt marsh, mangrove, coral reef *Man-made* Salt pan, aquaculture ponds	**A. Inland wetlands** Rivers, streams, marshes, swamp forests and 'villus' **B. Coastal wetlands** Lagoons, estuaries, mangroves, seagrass beds and coral reefs **C. Man-made** Tanks, reservoirs, rice fields and salterns	No classification available Wetlands are locally known as 'Kulhi' and situated within or partly along the coast. Linked to lagoons and contains mangroves

[a]Source: SAC (2011)
[b]Van Zon (2004)
[c]Anon (2012)

also serve as the major sources of foreign income for these island nations (Anon 2013; Fernando and Shariff 2013). The flourishing tourism sector in these islands is due to their unique biodiversity. Similarly, in the case of India, compared to the biodiversity of mainland, that of islands, such as Andaman and Nicobar Islands (ANI) and Lakshadweep islands, is furthermore unique. Mostly because of the insular nature, habitats on oceanic islands are often different from those on the nearest mainland even when latitudes (climates) and the sizes (areas) are the same. Islands often support unique species that are rare and endemic, but with small population sizes (e.g. reduced body size or the so-called insular dwarfism, and dispersal). Partly because of their unique features (e.g. isolation) and conservation values, islands are extremely attractive for intensive efforts in exploration, research and conservation (Kalmar and Currie 2006).

The spread and classification of wetlands of India and two island nations (Sri Lanka and the Maldives) are tabulated in Table 2.1, and it suggests that the wetland classification is almost similar in India and Sri Lanka, except that creek, sand/beach and intertidal mudflats are considered as wetlands in India. There is no report on classification of wetlands in the Maldives. The wetlands in the Maldives, locally called 'Kulhi', are located along the coast, sometimes linked to lagoons and usually supporting mangroves. In the Maldives, coral reef is not considered as a wetland (Anon 2012).

2.2 Wetland Ecosystems and Associated Biodiversity

2.2.1 Status of Wetlands in Small Island Developing States: An Overview

Majority of the 'Small Island Developing States (SIDS)' are situated in the tropics. Thus, many of these islands are bestowed with vast extent of coastal wetland ecosystems that include coral reefs, mangrove forests and seagrass beds rich in marine biodiversity. Mangroves and corals protect shorelines and contribute significantly to the fisheries by acting as nursery grounds to fish seeds and fingerlings. Apart from raising the shores of the islands and protecting them against sea level rise (SLR), the coral reefs and mangroves act as barriers and natural breakwater and protect small islands against storm surges and tsunamis, as observed during the 2005 tsunami in the Indian Ocean. By providing shelter to fish stock, they also support the fishery industry and help in revenue generation for these small islands. Coral reefs also generate revenue from tourism and recreational activities such as diving and snorkelling. Thus, these ecosystems are significant in sustaining the economy of these small island states.

2.2.2 Wetlands of India and the Small Island Nations in South Asia

2.2.2.1 Sri Lanka

Sri Lanka is an island country, south of India in the Indian Ocean with a land area of 65,610 km^2. It has a coastline of 1340 km. The country's jurisdictional area that extends up to the Exclusive Economic Zone (EEZ) is 530,684 km^2. Sri Lanka is divided into nine provinces, which are subdivided into 25 states. The coastal boundary of Sri Lanka stretches across 14 districts. The coastal regions in Sri Lanka are fast developing and have seen remarkable changes for the ongoing economic reforms. One of the major factors to this economic boom is the resources, such as flora and fauna, and wide-ranging habitats such as coral reefs, mangroves, seagrass beds, tidal flats, lagoons, peatlands, beaches, cliffs and spits. These habitats play a critical role in the economy of the coastal regions.

Wetlands of Sri Lanka are of three main categories (*viz.* inland, coastal and man-made) and 14 types, namely, rivers, streams, marshes, swamp forests, villus, lagoons, estuaries, mangroves, seagrass beds and coral reefs, tanks, reservoirs, rice fields and salterns. Inland wetlands are represented by streams, rivers, villus wetlands, fresh water marsh and swamps. Sri Lanka has an extensive network of rivers and streams and 103 natural river basins. The largest river basin is Mahaweli, covering 16% of the island and has high ecological and socio-economic value. Villus are the floodplain lakes, covering an area of 12,500 ha and mostly located in the Mahaweli floodplains in the east. Freshwater marshes are inland depressions, which have a source of water, peat and waterlogged sticky soil. In Sri Lanka, the largest freshwater marsh is located in Muthurajawela. Freshwater swamp forest, which is seasonally inundated with river water, is the most rare wetland type in Sri Lanka, and it comprises trees that are adapted to shallow stagnant water (Van Zon 2004).

Coastal wetlands are an integral part of Sri Lanka, having 45 estuaries, 42 coastal lagoons and a mangrove cover of less than 1000 ha. The Gulf of Mannar region, the stretch between Trincomalee and Kalmunai on the east coast and several areas in the south and south-western coasts are rich with coral reef habitats. Seagrass beds are present in the northwest coast of the country. The coastal wetlands of Sri Lanka harbour nearly 1000 species of fishes and many other marine species, and they attract migrant birds and marine turtles for nesting.

Man-made wetlands are represented by tanks, reservoirs and rice fields. The major irrigation reservoirs cover an area of 7820 ha, and seasonal/minor wetlands account for 52,250 ha. The rice fields account for an area of 780,000 ha, accounting for approximately 12% of the total land area.

The coastal wetlands are the most exploited resources and hence face serious threats. Most of the threats faced by these wetlands are due to the upstream activities such as agriculture and residential and industrial projects, but the most damaging impact is when these wetlands are considered as wastelands for dumping garbage. The coastal wetlands are also being used for prawn farming and other aquaculture activities. In order to conserve and protect these wetlands, the government of Sri Lanka has gone ahead with a series of legislations to regulate and keep the threats away from damaging the wetland ecosystems and its biological diversity.

2.2.2.2 The Maldives

The Maldives is a group of small islands in the Indian Ocean that lies southwest of Sri Lanka. It comprises 1190 islands grouped into 26 atolls and has a landmass area of 298 km^2, whereas the overall area of the country inclusive of the marine waters between island masses is more than 90,000 km^2. The Maldives has a coastline of 644 km, and being an island group, its area under EEZ is 916,189 km^2, second only to India. The coastline of the Maldives is gifted with numerous ecosystems and, most importantly, with the coastal wetlands, *viz.* mangroves. The Maldives has the seventh largest coral reef system in the world. The Maldivian wetlands are said to be highly productive, which serve as a source of food and other ecological services for the people. As the Maldives is not a heavily populated country, there is not much pressure on the coastal ecosystems, but still there is a gradual deterioration due to the effects of climate change and dumping of waste in the sea and along the coast areas. The pressure from land reclamation, timber harvest, aquaculture and tourism also results in loss of coastal biodiversity.

The wetlands of the Maldives are mostly located within or partly along the coast (Anon 2012) and are either fresh or brackish water. Of the 1190 Maldivian islands, only 41 islands have wetlands. In the Maldives, coral reefs are not classified as wetlands. The wetlands and coral reef ecosystem of the Maldives are the major contributors to the economy of the country. An earlier study showed that 71% of national employment, 49% of public revenue, 62% of foreign exchange, 98% of exports and 89% of gross domestic product (GDP) are biodiversity dependent in the country (Anon 2012).

2.2.2.3 India

2.2.2.3.1 Mainland India

The wetland inventory of India prepared by the Space Applications Centre (2011) and published as ‘National Wetland Atlas’ categorises the wetlands of India into two: inland and coastal. There are 188,470 inland wetlands, which spread over 10,564,899 ha in the country. Similarly, the coastal wetlands are 13,033 in number and are spread over 4,140,116 ha. The area of inland wetlands (69.23%) is much more than coastal wetlands (27.13%). These wetlands encompass numerous varieties of flora and fauna and are the hotspots of biodiversity (Venkataraman 2008).

The country has a landmass area of 3,287,590 km^2 and has a long coastline of 5422 km that spreads across nine states and two union territories (Venkataraman 2008). The coastline of India is resourced with mangroves, coral reefs, sand dunes, mudflats, salt marsh, seagrass beds, turtle nesting sites and bird nesting grounds. The country’s seaward jurisdictional area, which extends to the EEZ, is about 2,290,278 km^2. The coastal wetland spread along the coast of India accounts to about 3,703,971 ha that comprises lagoons, creeks, sand/beach, intertidal mudflat, salt marsh, mangroves and corals. These wetlands serve as habitats for several migratory and resident birds, thousands of coastal aquatic vertebrates and invertebrates.

India has 26 wetlands, declared as Ramsar Sites, of which five are coastal wetlands, *viz*. Ashtamudi Wetland and Vembanad-Kol Wetland of Kerala, Point Calimere Wildlife and Bird Sanctuary of Tamil Nadu, and Chilika Lagoon and Bhitarkanika Mangroves of Odisha (Sarkar 2011). The coastal wetlands of India are witnessing steady depletion of their ecosystems, leading to decline in a wide variety of species, few of which are ‘threatened’. India has put in force a number of policies and legislations to govern and regulate the coastal wetlands for the purpose of restoring and protecting the ecosystems.

2.2.2.3.2 Island Groups in India

India is surrounded by water on all three sides with the Bay of Bengal Sea in the East, the Arabian Sea in the West and the Indian Ocean in the South. The major island groups of India are the Andaman and Nicobar Islands and the Lakshadweep group of islands.

Andaman and Nicobar Groups of Islands

The Andaman and Nicobar Islands in the Bay of Bengal form an archipelago of 1382 islands, islets and rocks. The islands are home to highly diverse terrestrial and marine ecosystems, with a variety of habitats ranging from densely forested hills to sandy beaches and some of the intact coral reefs. Mangroves occupy an area of 614 km^2 in Andaman Islands and 3 km^2 in Nicobar Island (Ragavan et al. 2014). The mangroves of Andaman and Nicobar Islands are recognised as the best in the country in terms of density and growth (Dagar et al. 1991).

Lakshadweep Islands

The Union Territory of Lakshadweep, a group of 11 inhabited and 25 uninhabited tiny islands, is geographically isolated and segregated at 200–400 km from the Malabar Coast along the west coast of India. The only atolls in the Indian Union, they attract the attention of naturalists for centuries. The archipelago consists of 12 atolls, three reefs and five submerged banks. Except Androth, the biggest island, all other islands have a lagoon. Bitra is the smallest island with a large and magnificent lagoon. Pitti or the bird island, which is designated a bird sanctuary, is a small reef with a sand bank visited by thousands of birds for nesting (James 2011). The islands range in area up to 440 ha. Seagrass zones are conspicuous in the lagoons of all atolls except Bitra and Kiltan. They form dense beds alongside the islands in calm zones (0.5–3.0 m depth). Mangroves are limited to Minicoy Island on its south-eastern and south-western sides, of which one site is landlocked and the other opens to seawater (Nasser et al. 1999).

2.2.3 Wetland Biodiversity of the Small Island Nations in South Asia

2.2.3.1 Sri Lanka

Sri Lanka's varied coastal habitats include estuaries and lagoons (126,989 ha), mangroves (6083 ha), seagrass beds, salt marshes (23,797 ha), coral reefs and large extent of beaches including barrier beaches, spits (5621 ha) and dunes (15,546 ha). These habitats contain a significant part of the country's biodiversity (Table 2.2).

Sri Lanka's tidal variation being low (rarely exceeding 75 cm), mangroves generally occur as a narrow belt in intertidal areas of lagoons, estuaries or associated islands and river mouths. However, they do not occur in all intertidal areas, and they are confined to the areas with low wave action. Although mangroves rarely extend beyond 1 km landwards from the mean low tidal level (Amarasinghe 1996), they may spread to the upper limit of brackish water intrusion areas in some riverine

Table 2.2 Major coastal and marine biodiversity of Sri Lanka

Group	Number of species
Freshwater fish (riverine or marsh dwelling)	65
Marine fish	1800
Marine turtles	5
Marine mammals	38
Corals	183
Mangroves	40
Mangrove fishes	53
Birds	100
Reptiles	33
Seagrass	10

Source: MOFE (1999), Ekaratne (2000) and CZMP (2003) estuaries, extending even up to a distance of 20 km (e.g. Galatara in the Kalutara district, CRMP 2002).

Reefs in Sri Lanka are categorised under coral reefs, sandstone reefs and rocky reefs. All three habitats are distinct, but may be found mixed together (Rajasuriya and White 1995). It has been estimated that about 2% of the coastline contains fringing coral reefs (Swan 1983). Barrier coral reefs, consisting of ridges of coral lying some distance from the shore, parallel with it and forming a broad 'reef lagoon', are rare in Sri Lanka; but some are found at Vankalai and Silavathurai in the north-western coast (Rajasuriya and White 1995). Seagrass beds often occur in association with coral reef ecosystems or estuaries and lagoons such as the basin estuaries and lagoons of Puttalam, Negombo, Mawella, Koggala, Kokilai, Jaffna and Batticaloa (CRMP 2002).

Around 23,797 ha of salt marshes exist in the country (CRMP 2002). While the conditions under which salt marshes occur vary, they are often close to landward margin of the intertidal zone where the soil salinity is relatively high due to insufficient freshwater runoff to flush out the accumulated salts. Extensive salt marshes occur in the Mannar area (mainly on tidal flats containing about 56 species of marsh vegetation) in the coastal belt from Mantai to Vankalai. Patchy salt marshes occur mainly in sediment lagoon/estuarine areas such as Hambantota, Puttalam, Kalpitiya and Mundel (Samarakoon and Pinto 1988).

2.2.3.2 The Maldives

In contrast to the relatively impoverished terrestrial biological diversity, marine biological diversity in the Maldives is outstanding in richness. Indeed, the marine biodiversity of the archipelago is among the richest in the entire region, and the Maldives have been recognised as having one of the world's most diverse marine ecosystems. More than 250 different species of hermatypic corals have been reported from the Maldives. Over 1200 species of reef fishes, as many as 5000 different shell species, around 200 sponge species, more than 1000 species of marine crustaceans and over 100 species of echinoderms are reported from the Maldives. Large ranges of different types of marine algae have been documented. Different species of sharks, eels, rays, dolphins, whales and aquarium fish are commonly observed throughout the archipelago. Five species of endangered turtles, namely, loggerhead turtles, green turtles, hawksbill turtles, olive ridley turtles and leatherback turtles, are known to inhabit Maldivian waters (Kalvinde 1999).

2.2.3.3 Island Groups in India

2.2.3.3.1 Andaman and Nicobar Islands

Flora

From the islands, 2426 species of angiosperms, 8 species of gymnosperm, 300 species of medicinal plants, 130 species of orchids, 150 species of fruits and vegetables, around 10 species of oil-yielding plants and 34 species of mangroves are reported (George 2015). There are also several introduced species, besides agricultural crops and fruit trees, including Australian trees such as *Acacia auriculiformis* and *Eucalyptus* sp. Other introduced species include large palms, bamboos, fence plants and ornamental garden plants.

Fauna

Andaman and Nicobar Islands are considered as paradise of faunal diversity (both terrestrial and marine), with 8425 species of fauna, of which 846 species are endemic (Chandra et al. 2012), nearly 67% of them belonging to the marine habitat. It is known that 12 out of 22 animal phyla found in these islands exist in sea. Of these, 5 species of sponges, 6 species of Gastrotricha, 56 species of crustaceans, 2 species of marine molluscs and 2 species of echinoderms are endemic to these islands. The coral reefs of the islands, with an estimated area of 12,000 km^2, rank next only to the Australian Great Barrier Reef, in terms of biodiversity, in the world. Seagrass beds occur in shallow coastal waters and sheltered bays where clear water allows light penetration. Raghunathan et al. (2013) compiled the marine biodiversity of ANI based on the surveys conducted by researchers elsewhere and concluded the presence of more than 5846 species belonging to 13 major groups (Table 2.3).

Table 2.3 Marine biodiversity in ANI in relation to those in India and the world

Category	Number of species World	India	ANI
Porifera (sponges)	5100	519	146
Platyhelminthes	11,690	42	38
Cnidaria	10,211		789+
Scleractinian corals	1574	478	424
Gorgonians			51
Antipatharians			8
Sea anemones			31
Others			275
Polychaeta	12,632	428	191
Crustacea	24,375	2970	837
Mollusca	56,235	3751	1586
Polyplacophora			12
Gastropoda			888
Ophisthobranchia	6500	456	296
Cephalopoda			332
Bivalvia			350
Scaphopoda			7
Echinodermata	7291	765	430
Fishes	16,733	2546	1485
Marine reptiles	110	35	30
Marine mammals	135	25	
Seaweeds	7450	844	300+
Seagrasses	68	16	9
Mangroves	75	40	35
Total	**160,179**	**12,913**	**5846+**

Source: Raghunathan et al. (2013)

The small island conglomerations are often hotspots in terms of biodiversity and have a great probability of having endemic fauna due to their remote locations and isolation from other landmasses, which calls for protection of the organisms and their habitats from over-exploitation, pollution, destructive fishing techniques and habitat loss.

Parks and Sanctuaries

The archipelago has four national parks: Mahatma Gandhi Marine National Park, Mount Harriet National Park, Rani Jhansi Marine National Park and Saddle Peak National Park, all in the Andaman Islands. The Nicobar group of islands have two national parks and a biosphere reserve.

2.2.3.3.2 The Lakshadweep Islands

Marine Diversity

Marine biodiversity of Lakshadweep islands is very rich with 95 species of sponges, 172 species of corals, 80 species of crustaceans, 260 species of molluscs, 84 species of echinoderms, 396 species of fishes, 4 species of turtles, 142 species of birds, 6 species of marine mammals, 7 species of seagrass and 3 species of mangroves.

Seaweeds and Seagrasses

Marine algal distribution is generally sparse and heterogeneous. Sixty-two genera and 114 species of seaweeds have been recorded from Lakshadweep (Kaliaperumal et al. 1989). Among them, the most abundant species are the *Gracilaria edulis*, *Sargassum duplicatum* and *Turbinaria ornata* that grow luxuriantly on the lagoon beds of many islands. Seagrasses are found in all the islands of Lakshadweep, and seven species (*viz. Cymodocea rotundata*, *C. serrulata*, *Halodule uninervis*, *Halophila ovata*, *Halophila ovalis*, *Syringodium isoetifolium* and *Thalassia hemprichii*) have been recorded from the islands. The most common of these are the *C. rotundata* and *T. hemprichii*, which the green turtles predominantly forage upon in the lagoon (Jagtap 1987). The major reasons for destruction of seagrass beds were anthropogenic activities and grazing by turtles and sea urchins.

Mangroves

Mangroves have been recorded in Minicoy and Kalpeni. The extent of mangrove area in Minicoy is 13 ha, while in Kalpeni, it is in the emerging stage. *Avicennia marina*, *Bruguiera cylindrica* and *Ceriops tagal* have been reported from Minicoy (Nasser et al. 1999).

Corals

In total 172 species of corals have been reported from the islands of Lakshadweep (Pillai 1971; Suresh 1991; Navas 1993; Jeyabaskaran 2009; Balasubramanian and Ajmal Khan 2010). *Acropora*, *Porites*, *Montipora* and *Heliopora* are the widely distributed genera of corals in Lakshadweep group of islands (Wafar 1986; Pillai and Jasmine 1989). Besides, *Fungia* and *Favia* are also reported from the island lagoons (Wafar 1986; Pillai 1989). Various anthropogenic activities like quarrying corals, removal of surface soil (Pillai 1986), domestic pollution, destructive fishing activities and other factors like coral predators, cyclones and elevated sea surface temperature impact the island reefs (Arthur et al. 2006; Arthur 2008).

Mollusca

In total 260 species of molluscs have been reported from Lakshadweep. The giant clam Tridacna (*Tridacna maxima*) is found on the reef flat of many islands, while octopuses (*Octopus vulgaris*, *O. membranaceus* and *O. cyaneus*) are common in the lagoon bottom. In addition to this, 48 species of gastropods and 12 bivalves have also been documented from the Lakshadweep archipelago (George et al. 1986; Appukuttan et al. 1989). Among the gastropods, cone shells (*Conus leopardus* and *C. litteratus*) and cowries (*Cypraea caputserpentis* and *C. tigris*) are the commonly found molluscs in the island reef bottom.

Sponges

Ninety-five species of sponges are identified from the Lakshadweep group. Only the class Demospongiae is documented from this area. Being the earliest metazoans, sponges are known for their survival instincts since the beginning of metazoans in the history of life. They support diverse groups of associated bacteria, because of which sponges are looked upon as the major targets for 'drugs from the sea' programmes globally. Tropical islands such as Lakshadweep and Andaman are rich sources of sponges and can play a big role in marine bioprospecting and conservation mariculture programmes.

Marine Turtles

Four species of turtles, namely, *Chelonia mydas* (green turtle), *Lepidochelys olivacea* (olive ridley), *Eretmochelys imbricata* (hawksbill) and *Dermochelys coriacea* (leatherback), have been reported in Lakshadweep islands (Bhaskar 1978). The green turtle (*Chelonia mydas*) is the common species that nests in inhabited islands, whereas hawksbill (*Eretmochelys imbricata*) and leatherback nest more frequently in the uninhabited islands. The major threats of the turtles include degradation of nesting habitats, disturbances to nesting habitats due to beach lighting, recreational activities and incidental catching. The conservation measures for marine turtles include monitoring nesting sites, avoiding infrastructure development close to the shore and tracking their migration through tagging initiatives.

Birds

Over 140 sea/shorebirds have been reported from these islands including one endangered species, Barau's Petrel (*Pterodroma baraui*), seven near-threatened species (Swinhoe's Storm Petrel, *Oceanodroma monorhis*; Jouanin's Petrel, *Bulweria fallax*; Black-tailed Godwit, *Limosa limosa*; Eurasian Curlew, *Numenius arquata*; Ferruginous Duck, *Aythya nyroca*; Pallid Harrier, *Circus macrourus*; and Lesser Flamingo, *Phoeniconaias minor*) and one vulnerable species (Great Knot, *Calidris tenuirostris*) (Avibase 2016). Sooty Tern (*Sterna fuscata*) and Brown Noddy (*Anous* *stolidus*) breeding have been reported from these islands (Pande et al. 2007). The Pitti island of Lakshadweep is inhabited by three species of terns, namely, the Noddy Tern (*Anous stolidus pileatus*), Sooty Tern (*Sterna fuscata nubilosa*) and the Brown-winged Tern (*Sterna anaethetus*). Besides, there are Grey plovers, Golden plovers, Crab plovers, whimbrels, curlews and Common sandpipers around the islands (Betts 1938; Mathew and Ambedkar 1964; Daniels 1999).

Marine Ornamental Fishes

Over 160 marine ornamental fishes, belonging to 20 families, have been reported from nine islands in Lakshadweep (Murty 2002). Among them, Labridae (wrasses, 32 species) has the largest number of species, followed by Pomacentridae (damselfishes, 26 species), Serranidae (groupers, 09 species), Acanthuridae (surgeonfish, 17 species), Chaetodontidae (butterfly fish, 14 species), Scaridae (parrotfish, 12 species), Mullidae (goatfish, 10 species), Balistidae (triggerfish, 6 species), Holocentridae (squirrelfish, 11 species), Apogonidae (cardinal, 9 species), Siganidae (rabbitfish, 3 species), Scorpaenidae (lionfish, 3 species), Canthigasteridae (putter fish, 2 species), Pomacanthidae (angelfish, 2 species), Tetraodontidae (puffer/porcupine fish, 2 species), Synodontidae (lizard fish, 1 species), Ostraciontidae (boxfish, 1 species) and Zanclidae (Moorish idol, 1 species).

2.3 Challenges to the Island Wetland Ecosystems vis-a-vis Biodiversity

The major challenges of the UN classified SIDS include economic dependence on import of various commodities, communication and connectivity, hiked prices, unemployment, loss of land due to subsidence and erosion and vulnerability to natural calamities and oceanic changes. The challenges are not any different in the two island territories in India. Due to their small size, remote locations and growing human populations, the small islands have extremely fragile economies. Low availability of resources, high costs of living and high vulnerability due to natural disasters are common features. The 2004 tsunami caused enormous damage to the coastal ecosystems like coral reefs and mangroves, human life and material goods in these islands.

2.3.1 Climate Change

Climate change is emerging as one of the main challenges that humankind will have to face for years to come. It is projected to affect the lives of billions of people around the world in the next few decades. It is also expected that the extent of vulnerability may differ widely in different regions of the globe, but no region or country would be an exception to its impacts. It could become a major threat to world food security, as it has a strong impact on food production, access and distribution.

Developing and lesser developed island states/nations are more vulnerable to climate change (Anon 2007).

Island ecosystems are intrinsically linked to climate in many ways. Sea level rise is a climate-related phenomenon with a foremost impact on coastlines. It has now been reasonably established that the climate change is happening and the global average temperature has risen by about 0.6 °C over the twentieth century. Globally, the ten warmest years on record all occurred after 1991. A temperature rise of 1–2.5 °C will have serious effects, including increase in the severity and frequency of extreme weather, changes in rainfall patterns leading to severe water shortages and/or flooding, melting of glaciers resulting in flooding and soil erosion and an increased risk of extinction of plant and animal species (Dam Roy and George 2010). Further, SLR will lead to destruction of coasts worldwide with some islands possibly facing complete inundation. Small Island Developing States are highly dependent on the ocean; the fragile relationship of the environment and human population with the ocean makes the resident population vulnerable to natural calamities.

2.3.2 Extreme Events

Tsunami, tropical cyclones, floods and droughts are the most destructive severe weather and climate extreme events, which would affect countries in the South Asia. A classical example of extreme events in South Asia is the tsunami of 26 December 2004. On that day, a massive earthquake of magnitude 9.0 struck the coastal area of northern Sumatra in Indonesia. These earthquakes triggered tsunamis that affected Indonesia and neighbouring countries (India, Malaysia, the Maldives, Sri Lanka and Thailand) in Asia and the east coasts of Africa (Somalia and Yemen), causing serious damage to the coastal areas and small islands, loss of life to an extent of 250,000 persons. The reports indicate that natural ecological systems, such as coral reefs, mangroves and wetlands, had suffered extensive damages due to this (Ramachandran et al. 2005). Physical damages might affect the structure and function of coastal ecosystems and their ability to sustain marine life and support livelihood of coastal communities.

2.3.3 Coastal Erosion

Erosion of land or the removal of beach or dune sediments by wave action, tidal currents, wave currents or drainage due to natural or anthropogenic causes are the issues confronting the islands. While in the mainland, the littoral transport is interfered by coastal structures that include groynes, ports and jetties; the rise in sea level also plays a major role in coastal erosion in case of islands. Coastal erosion is a long-standing problem in Sri Lanka, aggravated in recent years due to human interferences in natural processes.

Over 80% of the land area in the Maldives is less than 1 m above mean sea level, and hence the islands of the Maldives are very vulnerable to inundation and beach erosion. If the sea level rises by 01 m, the Maldives will be submerged under water (Turner et al. 2001). Presently, 50% of all inhabited islands and 45% of tourist resorts face varying degrees of beach erosion. Climate change and projected SLR would aggravate the present problem of beach erosion.

2.3.4 Population Pressure

Most settlements in small islands with the exception of some of the larger Melanesian and Caribbean islands are located in coastal region. Rapid and unplanned movements of rural and outer island residents to the major centres are occurring throughout small islands, resulting in deterioration of urban conditions. High concentrations of people in urban areas create various social, economical, infrastructural and political stresses and make people more vulnerable to short-term physical and biological hazards, such as tropical cyclones and diseases. Anomalous sea surface temperature leads to stronger and frequent cyclones, which in turn upsets the food and drinking water sources, thus resulting in disease outbreaks. Population pressure increases the vulnerability to impacts of climate change and SLR, due to reduction in their adaptive capacity.

2.3.5 Habitat Destruction

Coastal and offshore developments including land reclamation, dredging and disposal, construction of ports and jetties, desalination plants, large-scale aquaculture, etc. adversely affect marine biodiversity. Though these issues are confronted by all coastal environments, the issue of land reclamation and unplanned development are particularly acute for the small island conglomerations.

The ecological systems of small islands and the functions they perform are sensitive to the rate and magnitude of climate change and SLR. Both terrestrial ecosystems on the larger islands and coastal ecosystems on most islands have been subjected to increasing degradation and destruction in recent decades. For instance, analysis of coral reef surveys has revealed that coral cover across reefs in the Caribbean has declined by 80% in just 30 years, largely as a result of continued pollution, sedimentation, marine diseases and overfishing (Gardner et al. 2003).

2.3.6 Over-exploitation

The most important resource of any small island is the freshwater. Most small islands have limited sources of freshwater. Atoll countries and limestone islands have no surface water or streams and are fully reliant on rainfall and groundwater harvesting. Many small islands are experiencing water stress at the current levels of rainfall input, and extraction of groundwater is often outstripping supply.

2.4 Conservation of Sensitive Wetlands and Habitats

In the year 2010, India passed the National Wetland Rules to protect and conserve the wetlands of the country. As many wetlands in India are seriously threatened by reclamation through drainage and landfill, pollution, hydrological alterations and over-exploitation of their natural resources resulting in loss of biodiversity, the government has taken action to protect the biodiversity and to retain the goods and services provided by the ecosystems. The Coastal Regulation Zone (CRZ) Notification, 2011, and the Island Protection Zone (IPZ), 2011, provide conservation of all the ecologically sensitive wetlands along the mainland coast and islands with stringent regulatory provisions.

The Asian Wetland Directory described 41 wetland sites of international importance in Sri Lanka, covering 274,000 ha. They could be divided into three broad categories (i) inland freshwater wetlands (e.g. rivers, streams, marshes, swamp forests and villus), (ii) salt water wetlands (e.g. lagoons, estuaries, mangroves, seagrass beds and coral reefs) and (iii) man-made wetlands (e.g. tanks, reservoirs, rice fields and salterns). Central Environmental Authority of Sri Lanka (CEA) formulated the Wetland Conservation Project in 1990 to protect the wetlands of Sri Lanka. Nearly 30% of the identified sites were under some form of protection, whereas 28% were completely protected (Derek 1989). A significant number of the internationally important sites in Sri Lanka were reported to be under moderate or high threat. Most of the low-lying wetlands are buffer zones for human dwelling too.

The Maldives has enabling policy for conservation of wetlands and coral reefs from the standpoint of biodiversity conservation and climate change adaptation. The National Biodiversity Strategy and Action Plan and the third National Environmental Action Plan (NEAP) stress the importance of protecting and restoring coral, wetlands and mangrove ecosystems. The Strategic Action Plan (SAP; also called National Framework for Development 2009–2013) stresses conserving and sustainably utilising biological diversity to ensure maximum ecosystem benefits.

2.5 Epilogue

The United Nations has been instrumental in recognising the environmental importance and economic fragility of the small island states. At the conference in Rio de Janeiro during 1992, 179 nations acknowledged that these islands were vulnerable to global warming and SLR. The United Nations has also been conducting awareness campaigns among the individual islands to explain the effects of overfishing, global warming and SLR to the local people apart from major efforts in policymaking and conservation of the natural resources. The United Nations Organization announced 2014 as the ‘International year of Small Island Developing States’, in order to garner the focus of different countries to the plight of small island nations under changing climate.

While legal frameworks and regulations contribute for checking over-exploitation and conservation of resources, community sensitisation and participation are crucial for the success of any conservation agenda. The first step towards conservation and management of coastal ecosystems is to map their boundaries. High-resolution mapping of all resources like coral reefs, mangroves and seagrasses is crucial as the services they provide are adversely affected by a wide variety of human activities. Besides ecologically sensitive ecosystems, sensitive coastal habitats like turtle nesting grounds, horseshoe crab habitats and bird foraging/breeding grounds have to be mapped. Turtles are known to migrate extensively, and frontier tools like satellite telemetry should be deployed to track their migratory patterns and map their nesting grounds. Species cataloguing is important in understanding the diversity within a region, country and collectively in the world. Besides, it is also essential for ascertaining the distribution and abundance of a particular species. While conventional methods are crucial, in order to fast-track the process and to bridge the wide gap between the estimated and actually documented species, frontier tools such as space technology (development of spectral signatures), biotechnology (development of DNA signatures) and information technology (development of digital database) are to be deployed for the purpose.

It is important to monitor, analyse and exchange lessons on the conservation of the coastal resources, and it is vital for securing the coastal livelihoods and preserving the biodiversity and habitats. Mapping of critically resilient ecosystems could help in restoration processes. Preserving nursery zones, nesting sites and foraging area could help in protecting and perpetuating various marine organisms. The key balance in the management of small island conglomerations lies in the possibility of allowing development with minimal impact on the environment. Integrated Coastal Zone Management (ICZM), a concept that is globally being used, holds the key for sustainable management of the fragile environs of the islands.

References

Amarasinghe MD (1996) Mangrove ecosystems in Sri Lanka – Flora, Fauna and their socioeconomic significance. Published by the Mangrove Information Centre, Small Fisher Federation, Pambala Sri Lanka, p 25

Anon (2007) The millennium development goal report, United Nations, p 36

Anon (2012) Wetland conservation and coral reef monitoring for adaptation to climate change. Climate change trust fund, Maldives, p 56

Anon (2013) Maldives as a biosphere reserve. Implementation Plan, Ministry of environment and Energy, Government of Maldives, p 26

Appukuttan KK, Chellam A, Ramdoss K, Victor ACC, Meiyappan MM (1989) Molluscan resources. In: Suseelan C (ed) Marine living resources of the union territory of Lakshadweep: an indicative survey with suggestions for development, Bulletin, 43. Central Marine Fisheries Research Institute, Kochi, pp 77–92

Arthur R (2008) Patterns of benthic recovery in the Lakshadweep Islands. In: Obura D, Tamelander J, Linden O (eds) Ten years after bleaching-facing the consequences of climate change in the

Indian Ocean. Coastal Oceans Research and Development in the Indian Ocean/Sida-SAREC, Mombasa, pp 39–44

Arthur R, Done TJ, Marsh H, Harriott V (2006) Local processes strongly influence post-bleaching benthic recovery in the Lakshadweep Islands. Coral Reefs 25:427–440

Avibase (2016) The world bird database. http://avibase.bsc-eoc.org/checklist.jsp?region=INld&list=clements. Accessed 20 June 2016

Balasubramanian T, Ajmal Khan S (eds) (2010) Bleached corals along with the reef fishes in Agatti Island, Lakshadweep. Seshaiyana 18(1): ISSN 0971-8656

Betts FN (1938) The birds of Laccadive islands. J Bombay Nat Hist Soc 40(3):382–387

Bhaskar S (1978) Turtles and other marine life in Lakshadweep. Hornbill (April–June): 21–26

Chandra K, Raghunathan C, Sivaperuman C, Devi K, Rajan PT, Shah SK, Sreeraj CR, Sadhukhan K, Mondal T, Yogesh Kumar JS, Raghuraman R, Kumaralingam S, Rajesh Kumar S (2012) Faunal diversity of Andaman and Nicobar Islands – threats and management. ENVIS Newslett, ENVIS Centre Faunal Divers, Zool Surv India, Kolkata 18(1&2):2–13

CRMP (2002) Coastal habitat survey. Coastal Resources Management Project/Coast Conservation Department, Colombo

CZMP (2003) Revised coastal zone management plan (Draft), Sri Lanka, 2003. Coast Conservation Department, Colombo

Dagar JC, Mongia AD, Bandyopadhyay AK (1991) Mangroves of Andaman and Nicobar Islands. Oxford and IBH Publishing Co., New Delhi, p 166

Dam Roy S, George G (2010) Marine resources of Islands: status and approaches for sustainable exploitation/conservation with special emphasis to Andaman and Nicobar. Indian J Anim Sci 80(4):57–62

Daniels RJR (1999) Island biogeography and the birds of the Lakshadweep Archipelago, Indian Ocean. J Bombay Nat Hist Soc 88:320–328

Derek SA (1989) A directory of Asian Wetlands. IUCN, p 1181

Ekaratne S (2000) A review of the status and trends of exported ornamental fish resources and their habitats in Sri Lanka, BOBP/REP/88. Bay of Bengal Programme, Chennai

Fernando SLJ, Shariff NM (2013) Wetland ecotourism in Sri Lanka; issues and challenges. Malays J Soc Space 9(4):99–105

Gardner TA, Cote I, Gill G, Grant A, Watkinson A (2003) Long-term region wide declines in Caribbean corals. Science 301:958–960

George G (2015) Ecological challenges of Island Biodiversity. Central Marine Fishery Research Institute, Cochin, pp 212–214

George KC, Thomas PA, Appukuttan KK, Gopakumar G (1986) Ancillary living resources of Lakshadweep. Mar Fish Inf Serv 68:46–50

IUCN Sri Lanka (2004) Wetland Conservation in Sri Lanka. Proceedings of the National Symposium on Wetland Conservation and Management, June 19th and 20th, 2003. iii + 75 pp.

Jagtap TG (1987) Distribution of algae, marine grasses and coral communities from Lakshadweep Island, Eastern Arabian Sea. Indian J Mar Sci 16(4):256–260

James PSBR (2011) The Lakshadweep: islands of ecological fragility, environmental sensitivity and anthropogenic vulnerability. J Coast Env 2(1):9–25

Jeyabaskaran R (2009) New records of corals from Lakshadweep Islands. Rec Zool Surv India 109(1):53–64

Kaliaperumal N, Kaladharan P, Kalimuthu S (1989) Seaweed and Seagrass resources: in marine living resources of the Union Territory of Lakshadweep. Bull Cent Mar Fish Res Inst 43:162–175

Kalmar A, Currie DJ (2006) A global model of island biogeography. Glob Ecol Biogeogr 15:72–81

Kalvinde HS (1999) Maldivian gender roles in bio-resource management. FAO; RAP Publication 1999/15

Mathew DN, Ambedkar VC (1964) A bird study trip to the Laccadive island. J Bombay Nat Hist Soc 61(1):188–190

MOFE (1999) Biodiversity conservation in Sri Lanka: a framework for action. Ministry of Forestry and Environment, Battaramulla

Murty VS (2002) Marine ornamental fish resources of Lakshadweep. CMFRI 72:134

Nasser AKV, Kunhikoya A, Aboobaker PM (1999) Mangrove ecosystems of Minicoy island. Lakshadweep. Marine Fisheries Information Service, Technical and Extension Series, CMFRI, No.1:8–10

Navas KA (1993). Present status of coral erosion in Lakshadweep with special reference to Minicoy. Ph.D. thesis submitted to Cochin University of Science and Technology, Cochin, India

Navid D (1989) The international law of migratory species: the Ramsar Convention. Nat Resour J 29:1001–1016

Pande S, Sant NR, Ranade SD, Pednekar SN, Mestry PG, Kharat SS, Deshmukh V (2007) An ornithological expedition to the Lakshadweep archipelago: assessment of threats to pelagic and other birds and recommendations. Indian Birds 3(1):2–12

Pillai CSG (1971) Composition of the coral fauna of the southeastern coast of India and the Laccadives. In: Yonge CM, Stoddart DR (Eds.) Regional variation in Indian Ocean coral reefs. Symp. Zool. Lond., Academic Press, p 301–327

Pillai CSG (1986) Status of coral reefs of Lakshadweep. Mar Fish Infor Serv, T&E Ser No 68:38–41

Pillai CSG (1989) The coral fauna of Lakshadweep. Cent Mar Fish Res Inst, Bul1 No 43:179–195

Pillai CSG, Jasmine S (1989) The coral fauna of Lakshadweep. Bull Cent Mar Fish Res Inst 43:179–195

Ragavan P, Saxena M, Saxena A, Mohan PM, Sachithanandam V, Coomar T (2014) Floral composition and taxonomy of mangroves of Andaman and Nicobar Islands. Indian J Mar Sci 43(6):1031–1044

Raghunathan C, Sreeraj CR, Raghuraman R, Venkataraman K (2013) Coral reef ecosystem of Andaman and Nicobar Islands: a hotspot for Indian marine biodiversity. In: Kathiresan K, Khan SA (Eds) Coastal ecosystems of India- Special publication. Envis Publication Series 1:67–114

Rajasuriya A, White A (1995) Coral reefs of Sri Lanka: review of their extent, condition and management status. Coast Manag 23:77–90

Ramachandran S, Anitha S, Balamurugan V, Dharanirajan K, Ezhil Vendhan K, Marie IPD, Senthil Vel A, Sujjahad Hussain I, Udayaraj A (2005) Ecological impact of tsunami on Nicobar Islands (Camorta, Katchal, Nancowry and Trinkat). Curr Sci 89(1):195–200

SAC (2011) National wetland atlas. Ministry of Environment and Forest, India, Space Application Centre, Ahmedabad, p 334

Samarakoon JI, Pinto L (1988) Synthesis report for information on critical habitats in the coastal zone: Workshop on Critical Habitats in the Coastal Zone, CCD/US AID/URI, p 106

Sarkar J (2011) Ramsar convention and India. Curr Sci 101(10):1266–1288

Suresh VR (1991) Studies on the coral reefs of Lakshadweep. Ph.D. thesis submitted to Cochin University of Science and Technology, p 218

Swan B (1983) An introduction to the coastal geomorphology of Sri Lanka. National Museum of Sri Lanka, Colombo

Turner JR, Yousden D, Klaus R, Satyanarayana CH, Fenner D, Venkataraman K, Rajan PT, Subba Rao NY (2001) GOI-UNDP GEF coral reef ecosystems of the Andaman Islands (Report)

Van Zon JCJ (2004) Wetland conservation and management in Sri Lanka: a status paper. In: Wetland conservation in Sri Lanka. Proceedings of the National Symposium on Wetland Conservation and Management: Sri Lanka*,* p 75

Venkataraman K (2008) Coastal and marine wetlands in India. In: Sengupta M, Dalwani R (eds.) Proceedings of Taal 2007 The 12th world lake conference. Ministry of Environment and Forests, 392–400

Wafar MVM (1986) Corals and coral reefs of India. Proc. Indian Acad. Sci, (Animal Sci/Plant Sci) Suppl Nov (1986): 19–43

Part II

Wetland Biodiversity

Digital Repositories for Coastal Wetland Biodiversity in South Asia: A Conceptual Framework from India

3

P. Krishnan, V. Deepak Samuel, C.R. Sreeraj, K.R. Abhilash, Shesdev Patro, R. Sankar, Margi Purohit, G. Dharani, Ahana Lakshmi, R. Purvaja, and R. Ramesh

Abstract

Wetlands support a variety of life forms, which are inextricably linked with the goods and services provided by them. Documentation of the biological resources of wetlands is essential in order to aid in their conservation. Digital repositories ensure wide and easy access to such complex biodiversity information and are gaining significance in conservation planning. However, such digital repositories are few at the regional level, especially in South Asia, an area of high coastal and marine biodiversity. This chapter provides an overview of digital repositories in general and the design and architecture of Coastal and Marine Biodiversity Integration Network (CoMBINe), a national Web portal on coastal biodiversity of India, designed to be scalable vertically to include data with respect to other taxonomic groups and horizontally to cover other countries.

Keywords

Biodiversity • Database • Digital repository • Taxonomy

P. Krishnan • V. Deepak Samuel • C.R. Sreeraj • K.R. Abhilash • S. Patro • R. Sankar
M. Purohit • A. Lakshmi • R. Purvaja • R. Ramesh (✉)
National Centre for Sustainable Coastal Management (NCSCM), Ministry of Environment Forest & Climate Change, Anna University Campus, Chennai 600 025, Tamil Nadu, India
e-mail: krishnanars@yahoo.com; deepakocean@gmail.com; crsreeraj@gmail.com; abhilaashkr@gmail.com; shesdevpatro@yahoo.com; sankarncscm@yahoo.com; margicmr@gmail.com; ahanalakshmi@gmail.com; purvaja.ramachandran@gmail.com; rramesh_au@yahoo.com

G. Dharani
National Institute of Ocean Technology (NIOT), Ministry of Earth Sciences, Chennai 600 100, India
e-mail: dhara@niot.res.in

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_3

3.1 Introduction

Wetlands are productive aquatic systems that support a variety of life forms. The biodiversity in wetlands has to be documented to plan for conservation mainly because of their rapid decline due to various natural and anthropogenic stressors. Digital repositories are thus essential to ensure a wide and easy access to such information. While several digital repositories exist at the global level, there are very few at the regional level, especially in South Asia.

Biological data are complex (e.g. hierarchical structures of gene ontology), heterogeneous (composed of different types) and highly dynamic (revision and addition) (Ozsoyoglu et al. 2006), thus offering challenges in choosing technologies and designing database schema for data reliability. Most of the frequently used biodiversity databases are supported by a conglomeration of academic and research institutions in order to provide wholesome results, which indicate the need for a high order of cooperation among institutions. A *Content Needs Assessment* survey conducted by Global Biodiversity Information Facility (GBIF) indicated that if the basic primary data are linked with other related data, it could provide diverse information and will be useful to other branches of science like ecology, molecular biology and pharmacology (Morris et al. 2008). Information gap is another issue with records found missing for various reasons like inadequate funds for digitizing old records or damage and destruction due to poor maintenance of records (Morris et al. 2008) due to social, cultural or natural disturbances, etc. (Fonselius 2001). Many organizations, which share information related to biodiversity and knowledge relevant to conservation, rely heavily on donor funding to support their activities (UNEP 2012) as it is expensive to maintain larger storage and advanced servers to preserve the collected information.

3.2 Repositories of Wetland Biodiversity

3.2.1 Significance

A major goal of the Convention of Biological Diversity (CBD 1992) is to conserve biological diversity, world over. In 2002, the Indian government passed the Biological Diversity Act to meet the obligations under the convention. It is well known that coastal wetlands are under threat worldwide. Between 2002 and 2009, about 2500 species in Asia and the Pacific were recorded in the Red List of International Union for Conservation of Nature (IUCN) and categorized as 'endangered' or 'vulnerable' (UNEP 2010). Evaluation of the species status is possible only if detailed inventories are available for monitoring the species. Also, biodiversity is inextricably linked with the goods and services provided by ecosystems. The Millennium Ecosystem Assessment (MEA 2005) concluded that the ecosystem goods and services provided by wetlands are extremely valuable to people all over the world. Hence, complete documentation of the biological resources of wetlands is essential.

3.2.2 Approaches

Repositories form an intersection of interest for different communities of practice: digital libraries, research, learning, e-science, publishing, records management, preservation, etc. As part of a larger set of strategies emerging across academic institutions, institutional repositories will contribute to the stewardship and mobilization of scientific research data for e-Research and learning.

While live repositories such as zoos and aquaria and preserved repositories, such as museums, can make a difference in the conservation of knowledge and attitudes of visitors through special awareness programmes, they are limited in their outreach because of their inherent nature. On the other hand, digital repositories (institutional repositories, digital archives) can be used by diverse stakeholders, in many forms. The contemporary understanding of the term 'digital repository' has broadened from an initial focus on software systems. This requires not just the software and hardware but also policies, processes, services and people, as well as, content and metadata (Semple 2006).

3.3 Digital Repositories on Wetland Biodiversity

3.3.1 Evolution of the Digital Repository

Globally, there are many databases, both general and group specific. The timeline of the evolution of digital repositories for documenting biodiversity data is depicted in Fig. 3.1. The first taxonomic database was established by Swartz et al. (1972) of the Virginia Institute of Marine Science (VIMS), Virginia, USA. The first working group meeting for taxonomic database was held in 1985 in Geneva where the structures of database and the protocols to be followed were discussed.

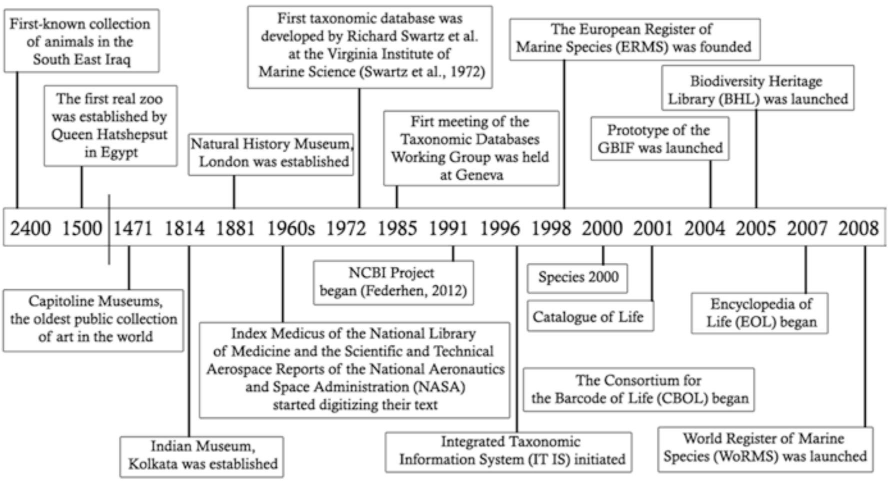


Fig. 3.1 Significant milestones in the evolution of digital repositories for biodiversity data

The International Conferences on Hypermedia and Interactivity in Museums (ICHIM), which started in 1991, established interest in the application of interactivity and multimedia in the museum community. Instead of only presenting objects, museums had to create the description and establish context. This emphasized the importance of *connectedness*, the basic feature of the 'virtual museum' (Hoptman 1992), as it seeks to describe the interrelated and interdisciplinary presentation of museum information with the help of integrated media. From the concept of virtual museum evolved the basic idea of digital repositories, and a step ahead of the virtual museum is the digital database where cyber infrastructure plays a major role, principally how to get, share, store and leverage data for scientific discovery and learning (Edwards et al. 2007).

3.3.2 Scope of Biodiversity Databases

Extensive databases serve as primary tools in ecological research (Porter 2000; Michener and Brunt 2009). There are global efforts such as the GBIF, an intergovernmental organization providing an Internet accessible, interoperable network of biodiversity database and information technology tools (Edwards 2004), with a mission to make the world's biodiversity data freely and universally available via the Internet (Lane 2007). The Tree of Life Web is another project involved in the collection of information about biodiversity compiled collaboratively by hundreds of expert and amateur contributors. Other important databases at the global level include Encyclopedia of Life (EoL), uBio project, UK species inventory, Zoobank, Zoological-Botanical Database (ZOBODAT), Australian faunal discovery, Global Registry of Migratory Species (GROMS) and International Species Information System (ISIS).

Taxonomy is the most important content in all biodiversity databases. Besides taxonomy, a number of other characteristics have been integrated depending upon the scope of the database. The World Register of Marine Species (WoRMS) is a taxonomic database, which plans to integrate information on ecology. FishBase is specifically designed for fish and important shellfish (Froese and Pauly 2016). Ocean Biogeographic Information System (OBIS) provides geo-referenced biodiversity data. GBIF covers all life forms on earth providing diverse species information. The Korean Natural History Research Information System (NARIS) was built for biodiversity data recorded in Korea, but information from other databases like GBIF have also been shared.

There are a number of dedicated databases that are specific in function and may be broadly classified as species-centric, ecosystem-centric or spatial/regional databases.

3.3.2.1 Species-Centric Databases

These are taxon-specific databases that are built for major groups with specific information covering basic aspects of the taxa, such as FishBase (www.fishbase.org), AlgaeBase (hwww.algaebase.org), Reptile database (www.reptile-database.

org), Nudipixel (NudiPixel 2015, www.nudipixel.net) for nudibranchs and Turbellarian Taxonomic Database (turbellaria.umaine.edu) for flatworms.

3.3.2.2 Ecosystem-Centric Databases

These are databases with specific focus on the select ecosystems. ReefBase (www.reefbase.org) is the official database of the Global Coral Reef Monitoring Network (GCRMN) that provides data and information on the status and trends in coral reefs to the international community to improve conservation. GLOMIS (Global Mangrove Database and Information System – www.glomis.com) consists of a searchable database of scientific literature relating to mangroves, institutions and scientists working on all aspects of mangroves, as well as regional projects and programmes related to mangroves. Ramsar database contains information on wetlands designated as internationally important under the Convention on Wetlands.

3.3.2.3 Spatial Databases

Spatial databases focus on assembling region-specific data and are generally hosted by state agencies, e.g. biodiversity of Pakistan (www.pmnh.gov.pk/htm/bgn.html) hosted by Pakistan Museum of Natural History (PMNH 2015), marine biodiversity database of India (www.biosearch.in) hosted by the National Institute of Oceanography, IndoBioSys – Indonesian biodiversity discovery and information system (www.indobiosys.org) and Marine Biodiversity Informatics for Kerala (www.keralamarinelife.in) hosted by University of Kerala.

While most of the databases are state sponsored, some databases hosted by NGOs or private agencies such as Project Noah (www.projectnoah.org), India Biodiversity Portal (www.indiabiodiversity.org) and Gharial database (Nair et al. 2012, www.gharial-info.com) also serve as open-access repositories for species information and literature that are useful to the diverse end users.

3.3.3 Data Architecture of Global Databases

Data architecture is composed of models, policies, rules or standards that govern on how data are collected, stored, arranged, integrated and put to use in data systems and in organizations (Business Dictionary 2015). It describes the data structures used by a setup and the application software. The system architecture adopted by some of the popular biodiversity databases, across the globe, is provided in Table 3.1.

While Darwin Core metadata standard is used by NARIS and GBIF, an extended format of the same is used in OBIS database. World Register of Marine Species (WoRMS) system has MS SQL 2008 Aphia architecture with an Apache 2 windows server, but FishBase and SeaLifeBase operate in MySQL and PostgreSQL. Except the WoRMS database which has Simple Object Access Protocol (SOAP) for accessing web services, the other databases have Distributed Generic Information Retrieval (DiGIR) protocol. SOAP is based on XML and acts as a communication protocol for sending messages via the Internet. SOAP provides a way to communicate between applications running on different operating systems with different

Table 3.1 Key features of selected global databases

Global databases	NARIS	WoRMS	FishBase	GBIF	OBIS	SeaLifeBase
System architecture	Darwin Core 2.0 metadata standard	MS SQL 2008 Aphia	MySQL, PostgreSQL	Darwin Core, ABCD Schema, Taxon Concept Schema, SDD Schema	OBIS Schema Version 1.1 (an extension of Darwin Core 2)	MySQL, PostgreSQL
		Apache 2 windows server	Web server: MS Internet Info Services (IIS) or Apache			Web server: MS Internet Info Services (IIS) or Apache
Protocol	DiGIR	SOAP	DiGIR	DiGIR, BioCASe	DiGIR	DiGIR
User interface	Search page and an integrated search result page	Search interface is incorporated	Search interface is incorporated	Search interface is incorporated	Search interface is incorporated	Search interface is incorporated
Types of information provided	Specimen and ecological information, observed information, images and videos	Taxonomy	Comprehensive data on Finfish including taxonomy, biometrics, behaviour, distribution, habitats, photos, conservation and onward links to information in many other database	Data on all types of life on earth, shared across national boundaries via the Internet	Global database on all groups of organisms associated with marine or estuarine habitats, shorelines, atmosphere above ocean, including marine bacteria	Taxonomy, distribution and ecology of all marine species globally apart from finfish
		Some pages contain additional information like images and biology				
		Photo gallery				
Total records	1,324,761 entries	227,979 valid marine species (218,759 checked)	33,100 species, 305,600 common names, 56,100 images, 51,800 references, 2,200 collaborators	1,605,262 species, 891,852 species (under review)	147,881 valid species, 158,728 valid marine taxa, 1801 datasets	66,300 species, 31,100 common names, 12,200 images, 22,100 references
Database access	Free open access	Free open access	Free open access	Free open access	Free open access – geo – referenced data	Free open access

technologies and programming languages. DiGIR is for developing and testing a protocol for single-point access to the distributed data sources, based on HTTP, XML and UDDI.

3.4 Biodiversity Database in South Asia

South Asia has numerous wetlands with great ecological and socio-economic importance. The coastal wetlands, such as mangrove forests, play an important role in maintaining coastal integrity, securing water supplies and providing many other essential services. Though the support from international agencies has been constant, the development of digital databases in South Asia has been minimal with the exception of India and Sri Lanka, which could be attributed to lack of unified national architecture for collection and maintenance of marine biodiversity data, inadequate studies on marine realm and lack of comprehensive information on the biodiversity and innovative modes of using them for research and policy-making.

India has a few marine biodiversity databases that provide information on coastal biodiversity from unicellular forms to mammals. The Indian Ocean Biogeographic Information System (IndOBIS) hosted by Centre for Marine Living Resources and Ecology (CMLRE) with the support of OBIS and Census of Marine Life (CoML) under the GBIF provides spatial and temporal details of coastal, ocean and deep-sea organisms, along with physicochemical attributes. The India Biodiversity Portal (IBP) intends to offer information on biodiversity in India for both terrestrial and marine life. IBP is designed to harness the collective knowledge by seeking voluntary participation of users and by establishing a participatory platform for content generation, its verification and usage. It facilitates participation by citizens in contributing and accessing information on Indian biodiversity that benefits science and society.

The Maldives accords high significance on its coastal and marine resources and recognizes the need to establish a central database for information relating to all aspects of the environment of the Maldives. The Maldives Conservation Portal is part of Project REGENERATE, a joint initiative of IUCN Marine Maldives Projects, Ministry of Environment and Energy, Ministry of Fisheries and Agriculture, Marine Research Centre and Environmental Protection Agency funded by the USAID. It aims at generation of knowledge and science associated with marine resources of the Maldives to apply resilience-based management and to facilitate access to information for all people interested in conservation activities in the Maldives.

Sri Lanka and Bangladesh have their national biodiversity databases such as Wetland Advocacy and Resource Centre (WARC) in Bangladesh, National Wetland Directory of Sri Lanka and Wildlife in Sri Lanka. They also host regional content in the global databases such as IUCN Mangroves for the Future (IUCN-MFF), Global Invasive Species and Mangrove Reference Database and Herbarium (MRDH).

Table 3.2 Regional databases in the South Asia region

Country	Database	URL
South Asia	Wetlands International South Asia	http://south-asia.wetlands.org/
	Ramsar Sites Information Service	https://rsis.ramsar.org/
	IUCN Mangroves for the Future	https://www.mangrovesforthefuture.org
India	India Biodiversity Portal	http://www.indiabiodiversity.org/
	BioSearch – *Marine Biodiversity Database of India*	http://www.biosearch.in/
	Indian Biodiversity Information System	http://www.indianbiodiversity.org/
	IndOBIS – *Ocean Biogeographic Information System for Indian Ocean*	Hosted by National Institute of Oceanography, Goa; *(site temporarily unresponsive)*
Bangladesh	Bangladesh Water Development Board	http://www.bwdb.gov.bd
	Wetland Advocacy and Resource Center – WARC	http://www.warc-cdp.org/
Pakistan	Pakistan Wetland Programme	http://www.pakistanwetlands.org
	Wildlife of Pakistan	http://www.wildlifeofpakistan.com
Maldives	Maldives Conservation Portal	https://maldivesconservationportal.org
	Coral Database	https://coraldatabase.gov.mv
Sri Lanka	Wildlife in Sri Lanka	http://www.wildlifesrilanka.com/index.php
	National Wetland Directory of Sri Lanka	http://203.115.26.10/wetland/conservation.php

The digital repository for Pakistan's biodiversity, hosted by the Pakistan Museum of Natural History (PMNH 2015), has a collection of animals, plants, fossils, rocks, minerals, etc. The Database and Global Networking (BGN) project is one of the most important IT projects of PMNH funded by Ministry of Science and Technology (MoST) and is part of the GBIF. A list of significant regional databases of South Asian countries is provided in Table 3.2.

However, advancements in informatics capabilities for biological sciences (in data management, in network connections and in data content) are still needed (Shanmughavel 2007) especially for South Asian countries. Though the intellectual wealth in biology is abundant in these countries, it has to be appropriately presented to aid in policy-making and popular use by the society.

As for species repositories, they usually hold only basic information about the various species present in the region. The structure and functionalities of the local database vary within the same country, and, thus, their usage is low and end users have to seek more information elsewhere. A list of the significant species repositories in India is provided in Table 3.3.

Table 3.3 Species repositories in India

No	Institution	Category of biological resources	URL
1	Biodiversity Information System, Indian Space Research Organisation	Flora and coastal landscape and phytosociological database for 16,000+ sample plots for entire India	http://bis.iirs.gov.in/
2	Indian Bioresource Information Network	Flora, fauna and landscape	http://www.ibin.gov.in/
3	Botanical Survey of India, Kolkata	Flora	http://www.bsi.gov.in
4	National Bureau of Plant Genetic Resources, New Delhi	Plant genetic resources	http://www.nbpgr.ernet.in
5	National Botanical Research Institute, Lucknow	Flora	http://www.nbri.res.in
6	Indian Council of Forestry Research and Education, Dehradun (12 institutes under ICFRE)	Flora and fauna (termites, butterflies, moths)	http://www.icfre.org/
7	Zoological Survey of India, Kolkata	Fauna	http://zsi.gov.in/
8	National Bureau of Animal Genetic Resources, Karnal, Haryana	Genetic resources of domestic animals	http://www.nbagr.res.in/
9	National Bureau of Fish Genetic Resources, Lucknow	Fish genetic resources	http://www.nbfgr.res.in/
10	National Institute of Oceanography, Goa	Marine flora and fauna	http://www.nio.org/
11	Wildlife Institute of India, Dehradun	Faunal resources in protected areas	www.wii.gov.in
12	National Bureau of Agriculturally Important Microorganisms, Mau Nathan, Bhanjan, UP	Agriculturally important microorganisms	http://www.nbaim.org.in/
13	Institute of Microbial Technology, Chandigarh	Microorganisms	http://www.imtech.res.in/
14	National Institute of Virology, Pune	Viruses	http://www.niv.co.in/
15	Indian Agricultural Research Institute, New Delhi	Microbes/fungi	http://www.iari.res.in/
16	National Bureau of Agriculturally Important Insects, Bangalore	Insects	http://www.nbaii.res.in/
17	National Facility for Marine Cyanobacteria, Bharathidasan University, Tiruchirappalli	Marine cyanobacteria	http://www.nfmc.res.in/

3.5 Conceptual Framework for Regional Wetland Database

3.5.1 Regional Database: Context and Relevance

A scientifically well-planned regional database will ensure an integrated management approach to incorporate scattered data that are multi-thematic at different levels. A database of this sort will function as an initiative for data sharing and for the effective usage of biodiversity data, which otherwise remain scattered. Despite the high coastal and marine biodiversity in the South Asian countries, they are documented/deposited only in federal and state museums or national/private collections with limited access to wider users. A meaningful approach for a regional database would be to collate data from all organizations responsible for storing biodiversity information onto a common platform to enable wider access.

3.5.2 Challenges and Strategies

The common barriers with respect to data sharing include (1) psychological and behavioural barriers (unwillingness to share data), (2) barriers relating to describing information data (lack of complete datasets or varied classification systems), (3) practical barriers (knowledge of existing data and acquired data) and (4) inadequate strategies and resources (data made available in an opportunistic manner which is not need based) (UNEP 2012).

A complete database would have all the available information on the species and provide opportunity for the end users to seek the same through a user-friendly query. Shorter (2016) reviewed the barriers in accessing and sharing data. The challenges in the integration of scattered biodiversity data could be effectively overcome by forging knowledge networks, technical collaborations, strengthening communication between experts and expert agencies, formal data sharing agreements, institutionalization of biodiversity data documentation and most significantly effective use of the bioinformatics and information technology tools.

3.6 Coastal and Marine Biodiversity Integration Network (CoMBINe): A Prelude to Regional Wetland Database

3.6.1 Scope and Capabilities

In view of the growing concerns on the progressive environmental deterioration of sensitive coastal and marine ecosystems of India, the National Centre for Sustainable Coastal Management (NCSCM), Chennai, under the Ministry of Environment, Forest and Climate Change (MoEF & CC) has undertaken the task of developing a national Web portal on coastal and marine biodiversity under the aegis of Coastal and Marine Biodiversity Integration Network (CoMBINe). The CoMBINe portal provides a framework for collating comprehensive species data from published literature and also across various research agencies and databases.

As biodiversity research and documentation are becoming a data-intensive science (Kelling et al. 2009), growth along with technological breakthroughs in the field of bioinformatics is important. It also calls for maintaining a cyber infrastructure for open access, delivery and data-intensive collaborative research (Borgman et al. 2007). It is envisaged to take advantage of the power of bioinformatics tools for integrating character-based field identification protocol in its architecture.

CoMBINe aims to integrate biological, spatial and genetic information of organisms inhabiting sensitive ecosystems and provides advanced tools for querying, analysing, modelling and visualizing patterns of species distribution for researchers in India and abroad. It envisages broadening interdisciplinary linkages of primary biodiversity data, whereby the initiatives in the fields of genetics, ecology and climate change or impact assessment can be integrated to support scientific enquiry.

CoMBINe portal uses the Darwin Core 2.0 metadata standard, along with DiGIR protocol, which is a request and response message format for communication between the data provider, portal engine and applications. Darwin Core is evolved and developed as a data standard for publishing and integrating biodiversity information (Wieczorek et al. 2012). The philosophy for Darwin Core development has been to keep the standard as simple and open as possible and to develop terms only when there is shared demand. DiGIR specifies the messaging system that allows questions to be asked and answered across the network of primary data sources (Constable et al. 2010). The adoption of the DiGIR protocol provides for data sharing between national and international databases built as per international codes.

3.6.2 Utility Features

CoMBINe database will have both Web and mobile interface in order to facilitate easy access for the potential end users. Apart from taxonomic details, CoMBINe provides a platform for species identification by diverse users, *viz.* school students, wildlife enthusiasts, researchers, policy-makers, etc.

3.6.2.1 Species Data Sheets with Geospatial Data

The CoMBINe dataset format includes more than 60 fields representing taxonomy, biology, anatomy, distribution, spectral, molecular, etc. The set of data management processes for ensuring the quality of data include digitization of data, documentation, data storage and archiving, data presentation and dissemination and application of the data (Chapman 2005). CoMBINe database comprises of secondary information collected from various sources like research institutions, federal agencies, museums and published literature. The spatial data are stored in the form of geo-coordinates and can be used for analysis through geographic information systems (GIS).

3.6.2.2 Character-Based Identification

The portal supports identification of common coastal and marine organisms based on general characteristics like colour, appearance, shapes, etc. thus helping diverse end users. The database serves as the backbone for this character-based identification protocol. This approach departs from the conventional dichotomous key approach in order to aid in quick field identification. Based on these taxonomic characters, an interactive user-friendly Web interface is set up, which can be updated by users after suitable validation. An example of using simple characters and attributes for identification is illustrated for the birds in Table 3.4.

3.6.2.3 Updated Species Checklists

Taxonomic checklists contain a summarized list of species from a particular region or area used for documenting biodiversity. Species checklists are updated for all major groups of coastal and marine flora and fauna of India, which involves identification of the most recent published checklist for a particular group, to which the subsequent species distributional records are integrated. The updated checklist is validated against WoRMS Database in order to eliminate taxonomic inconsistencies such as synonyms, emendations, alternate representations, status unknown, *nomen nudum*, *nomen dubium*, etc.

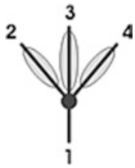
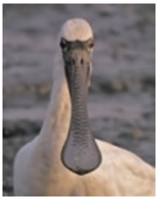
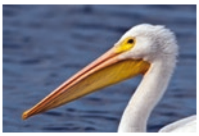
3.6.2.4 Interoperability Between Databases

CoMBINe database architecture provides for integration, scalability and interoperability within and between national and international databases. The primary purpose is to create a common language for sharing biodiversity data that are complementary and reuse metadata standards from other domains wherever possible. CoMBINe dataset envisages constituting a new standard across biodiversity for storing and exchanging knowledge related to various species. It will be an extension of Darwin Core and have a special customization to adapt to the Indian biodiversity practices (taxonomy/specimen centric) and to the global practices of storing biodiversity data for marine species.

3.6.2.5 Taxonomists' Grid

A taxonomist's grid is a framework for maintaining a database of taxonomists. The information pertaining to national and international experts in coastal and marine floral and faunal biodiversity is collated and integrated into the CoMBINe portal. The experts would aid in validating the taxonomic data before integration into the database.

Table 3.4 An example of characters and its attributes used for identification of birds

Primary character	Attribute	Definitions	Illustration
Feet shape	Webbed	Webbed feet is characterized by the fusion of two or more digits of the feet by a web or membrane	
	Lobed	Anterior digits (2–4) edged with lobes of the skin. Lobes expand or contract when bird swims	
Beak shape	Flat	Broad	
	Pointed	Strong and pointed beaks	
	Curved	Either curved upward/downward/ slightly curved/strongly curved	
	Hooked	Upper mandible is longer than the lower and hooked at the tip	
	Spoon shape	Spoon shaped with broad end	
	Pouched	Large throat pouch attached with the lower mandible	

3.7 Conclusion

The advancements in the bioinformatics systems, the Internet and the mobile technology have significantly aided in the development of online biodiversity databases. Though species diversity is expectedly high in South Asia, they are either not comprehensively documented or not available in digitized formats for easy access. The national and regional conservation and management programmes are data starved and are essentially implemented based on precautionary principle for biodiversity conservation.

The coastal and marine biodiversity records in the region remain scattered among institutions responsible for documentation of flora and fauna. The species inventories are not periodically updated and suffer from taxonomic inconsistencies like synonyms, emendations, alternate representation, etc. A freely available, high quality, biodiversity data would help in planning conservation strategies and also in tracking the changes in biodiversity. However, the main issue regarding the digital biodiversity data sources available across the world is that the sources vary in quality, scope and accuracy.

The CoMBINe database is being built as a national repository of coastal and marine biodiversity as per international standards. CoMBINe aims at maximizing quality, utility and coverage, in order to make such data useful to a large number of users. The template is scalable, horizontally to cover other countries and vertically to include data with respect to other taxonomic groups.

References

Borgman CL, Wallis JC, Enyedy N (2007) Little science confronts the data deluge: habitat ecology, embedded sensor networks, and digital libraries. Int J Digit Libr 7(1–2):17–30

Business Dictionary (2015) Data architecture. http://www.businessdictionary.com/definition/data-architecture.html Accessed 23 June 2015

CBD (1992) Convention of biological diversity. https://www.cbd.int/doc/legal/cbd-en.pdf Accessed 26 Feb 2016

Chapman AD (2005) Principles of data quality, version 1.0. Report for the Global Biodiversity Information Facility, Copenhagen. p 58

Constable H, Guralnick R, Wieczorek J, Spencer C, Peterson AT, The VertNet Steering Committee (2010) VertNet: a new model for biodiversity data sharing. PLoS Biol 8(2):e1000309. doi:10.1371/journal.pbio.1000309

Edwards JL (2004) Research and societal benefits of the Global Biodiversity Information Facility. Bioscience 54:485–486

Edwards PN, Jackson SJ, Bowker GC, Knobel CP (2007) Understanding infrastructure: dynamics, tensions, and design. Final report of the workshop on history and theory of infrastructure: lessons for new scientific cyber infrastructures. https://deepblue.lib.umich.edu/handle/2027.42/49353 Accessed 21 Mar 2016

Fonselius S (2001) History of hydrographic research, Sweden Proceedings from the Estonian academy of Sciences, Special issue on the history of marine and freshwater research June 2001, p 117

Froese R, Pauly D (eds) (2016) FishBase, www.fishbase.org. Accessed 26 Feb 2016

Hoptman GH (1992) The virtual museum and related epistemological concerns. In: Barrett E (ed) Sociomedia. Multimedia, hypermedia and the social construction of knowledge. MIT-Press, Cambridge, pp 141–159

Kelling S, Hochachka WM, Fink D, Riedewald M, Caruana R, Ballard G, Hooker G (2009) Data-intensive science: a new paradigm for biodiversity studies. Bioscience 59(7):613–620

Lane MA (2007) Copenhagen: global biodiversity information facility; p. 87. GBIF strategic and operational plans 2007–2011: from prototype towards full operation. http://www.gbif.org/GBIF_org/GBIF_Documents/strategic_plans.pdf Accessed 26 Feb 2016

MEA (2005) Online guide to the millennium ecosystem assessment reports. Available via http://www.millenniumassessment.org/en/index.html. Accessed 12 Feb 2016

Michener WK, Brunt J (eds) (2009) Ecological data: design, management and processing. Wiley, London

Morris R, Olson A, O'Tuama E, Riccardi G, Whitbread G, Hagedorn G, Teage I, Heikkinen M, Leary P, Barve V, Chavan VS (2008) Recommendations of the GBIF multimedia resources task group. Global Biodiversity Information Facility, Copenhagen, 18 pp

Nair T, Krishna YC, Sritharan S (2012) The gharial information database. www.gharial-info.com. Accessed 26 Feb 2016

NudiPixel (2015) Nudipixel: nudibranch and sea slug identification with photographs. www.nudipixel.net. Accessed 21 Oct 2015

Ozsoyoglu ZM, Ozsoyoglu G, Nadeau J (2006) Genomic pathways database and biological data management. Anim Genet 37(s1):v41–v47

PMNH (2015) Biodiversity of Pakistan: Pakistan museum of natural history. http://www.pmnh.gov.pk/htm/bgn.html Accessed 21 Oct 2015

Porter JH (2000) Scientific databases. In: Michener WK, Brunt JW (eds) Ecological data: design, management and processing. Blackwell Science, Oxford, pp 48–69

Semple N (2006) Digital repositories. DCC briefing papers: introduction to curation. Digital Curation Centre, Edinburgh Available via http://www.dcc.ac.uk/ resources/briefing-papers/introduction-curation Accessed 26 Feb 2016

Shanmughavel P (2007) An overview on biodiversity information in databases. Bioinformation 1(9):367–369

Shorter C (2016) Barriers to accessing/ sharing data, SND Workgroup, Tulane University. Available via http://www.cdc.gov/nceh/tracking/wkshop04/pdfs/II/discuss1/1_shorter.pdf Accessed 15 Mar 2016

Swartz RC, Wass ML, Boesch DF (1972) A taxonomic code for the biota of the Chesapeake Bay. Special scientific report no. 62 of the Virginia Institute of Marine Science. Gloucester Point, Virginia Institute of Marine Science, p 117

UNEP (2010) State of biodiversity in the Asia and Pacific. Report p 7

UNEP (2012) UNEP year book 2012: emerging issues in our global environment, p 63

Wieczorek J, Bloom D, Guralnick R, Blum S, Doring M et al (2012) Darwin core: an evolving community-developed biodiversity data standard. PLoS ONE 7(1):e29715

Biodiversity in Central Highland Wetlands, a World Heritage Site in Sri Lanka

4

Jeevan Dananjaya Kottawa-Arachchi

Abstract

Wetland ecosystems are among the most productive ecosystems that support many kinds of life. They are valuable in terms of hydrology, plant and animal survival, and biodiversity. National Wetland Directory of Sri Lanka describes 62 important wetlands, with their status. The central highland complex of Sri Lanka is a unique ecosystem and the most important catchment area of major rivers. Therefore, it is identified as a super biodiversity hotspot and a world heritage site. The major wetland types in the central highland ecosystem are freshwater marshes, streams, waterfalls, human-made lakes, reservoirs, and springs. In Sri Lanka, most of the threatened species, which are associated with aquatic habitats, are found in the central highlands with very restricted distribution. Habitat deterioration and degradation, encroachments, clearing of vegetation, water pollution, and spread of invasive alien species are the most significant threats to the highland wetlands. Therefore, demarcation of wetlands, protection of buffer zones, increased public awareness, and implementation of good agricultural practices would certainly bring beneficial changes to the ecosystems.

Keywords

Biodiversity conservation • Ecosystems • Highland wetlands • Threatened species

J.D. Kottawa-Arachchi (✉)
Friends of Horton Plains, Tea Research Institute of Sri Lanka, Talawakelle, Sri Lanka
e-mail: jeevan1188@yahoo.com; jeevank@tri.lk

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_4

4.1 Introduction

Wetlands, both natural and human-made, currently make up about 15% of the land area of Sri Lanka. The natural wetlands comprise rivers, streams, riverine floodplains, small isolated freshwater bodies, freshwater springs, seasonal ponds, and freshwater marshes. The most important wetlands are associated with Sri Lanka's network of 103 major rivers that originate from the central mountains and radiate across the lowland plains until joining the sea. The irrigation tanks and reservoirs are considered as man-made wetlands in Sri Lanka (Dela 2009). Sri Lanka currently has six sites designated as Wetlands of International Importance Ramsar Sites (*viz.*, Vankalai Sanctuary, Anaiwilundawa Sanctuary, Wilpattu National Park, Bundala National Park, Kumana National Park, and Madu Ganga), with a surface area of 198,172 ha (Young 2013). The Wetland Directory of Sri Lanka lists 62 sites with 24 as moderately threatened and 18 as highly threatened sites (IUCN and CEA 2006).

4.1.1 Classification of Wetlands in Sri Lanka

According to the Ramsar definition, the following categories of wetlands can be identified in Sri Lanka: (1) inland natural freshwater wetlands, (2) marine and saltwater wetlands, and (3) man-made wetlands. Man-made and natural wetlands occur throughout the country and together comprise about 15% of the total land area.

4.1.1.1 Inland Natural Freshwater Wetlands

Rivers, streams, tributaries, riverine floodplains, isolated freshwater bodies, freshwater springs, seasonal ponds, and freshwater marshes comprise inland natural freshwater wetlands (Anon 1999). Swamps and marshes are important for maintaining groundwater table and also for mitigating floods. In addition, they play a vital role in purification of water by removing toxic compounds and also serve as a carbon sink.

4.1.1.2 Marine and Saltwater Wetlands

Sri Lanka as an island is rich in coastal wetlands, which include estuaries, mangroves, salt marshes, lagoons, mudflats and sea grass beds along the coastal belt. Lagoons are salt or brackish water coastal wetlands connected to sea with one or more relatively narrow outlets which may be permanent or seasonal (Anon 2004). About 42 lagoons are found around the coastal belt of Sri Lanka.

Coral reefs and sea grass beds are another group of important marine wetlands found in Sri Lanka. Corals, being a unique set of marine invertebrates, are responsible for the formation of calcareous structures with spectacular beauty. Sea grass beds are composed of rooted, seed-bearing marine plants found in shallow, sheltered marine waters, lagoons, and estuaries. Mangroves, marshes, and sea grass beds are extremely important breeding sites for a wide variety of fish.

4.1.1.3 Man-Made Wetlands

These wetlands were created by humans. Although Sri Lanka does not have large natural lakes, an array of ancient irrigation tanks and reservoirs can be seen countrywide. Over 10,000 human-made wetlands of Sri Lanka are a part of the rich cultural heritage of the country. These tanks are interconnected with long canal systems that measure in kilometers.

The wetlands created for aquaculture and agriculture also fall into this category. Rice fields can be considered as agroecosystems, which provide temporary or seasonal aquatic habitats. At present, approximately 12% of the total land under rice cultivation is distributed over all the agroecological regions (Kotagama and Bambaradeniya 2006). Reservoirs created by dams across major rivers in the central highland contribute to a considerable number of human-made wetlands in Sri Lanka. In addition to the giant reservoirs, a large number of smaller reservoirs have also been constructed to generate hydropower as well as drinking water sources at higher elevations (above 1000 m amsl).

4.2 Classification of Central Highland Wetlands in Sri Lanka

Although Sri Lanka is relatively a small island spread over 65,610 km^2, 103 rivers originate from its central highlands. These rivers play a dominant role in shaping the wetland landscape in the country. The major rivers such as Mahaweli, Walawe, and Kelani originating from the wet highlands are perennials. The streams and tributaries of rivers that flow through the high (above 1000 m) and mid (1000–250 m) elevations create several waterfall habitats. Wetlands, especially marshy lands and freshwater lakes in higher elevations are hydrologically important as catchments of major rivers and reservoirs in Sri Lanka. According to Kotagama and Bambaradeniya (2006), highland wetlands can be classified based on hydrological and ecological features or functions.

4.2.1 Freshwater Marshes/Waterlogged Swamps

These are shallow inland depressions either connected to a river or receive water through surface runoff, river floodwater, and groundwater seepage. In general, highland marshes are seen in the valleys and lower slopes of mountains associated with grasslands. In Sri Lanka, these unique wetland ecosystems are found only in higher elevation (Gunatilleke 2007). The highland grasslands and marshes are best represented in Horton Plains National Park at an altitude of about 2000 m (Fig. 4.1). Rainwater accumulates in marshes during the monsoon and gradually released to tributaries of major rivers throughout the year. Partially decomposed organic material in marshes form peat (IUCN and CEA 2006). Few of the larger marshes are also located in dairy farms established at higher elevations, and many relatively small marshes are found in tea plantations. Most of the threatened highland crabs and amphibian species are associated with the aquatic ecosystems such as marshy lands.

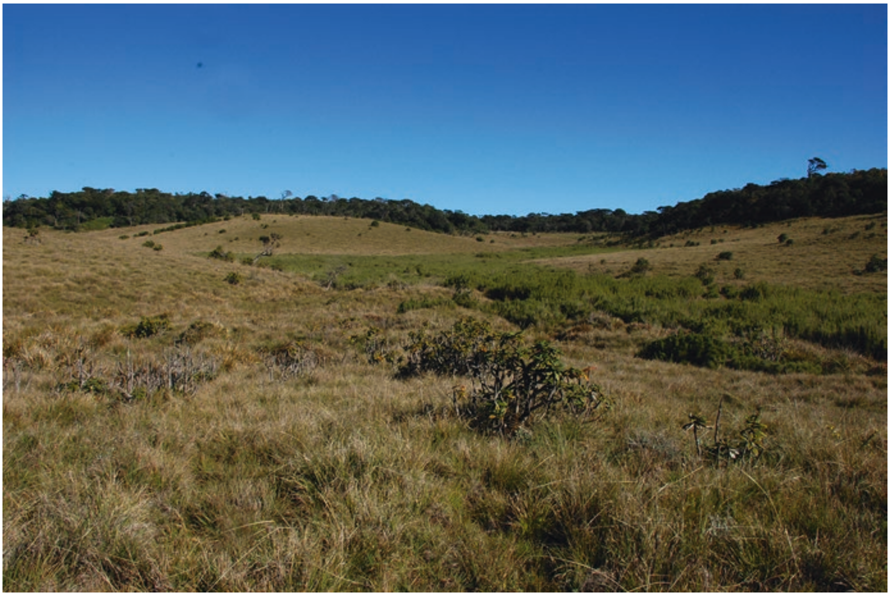


Fig. 4.1 Montane grassland marshes at Horton Plains National Park

4.2.2 Streams

Majority of the rivers originate in the central highlands. Most of the rain falling on the mountain slopes is carried down as surface runoffs leading to fast flowing streams (Amarasiri 2008). These streams contain aquatic plant species that are segregated based on their degrees of tolerance to the rate of water flow (Anon 1999). Grass species such as *Coelachnes impliciuscula* and the sedge *Isolepis fluitans* remain attached to rocks in flowing water. A primitive fern *Osmunda collina* and an endemic dwarf bamboo *Arundinaria densifolia* dominate the banks of streams in Horton Plains National Park. Humid forests in higher altitude exhibit shady condition with thick canopy. In the understory near the streams, various species of *Strobilanthes* dominate. The vegetation structure of streams in tea plantation differs from streams in mountain forests. The invasive Neotropical shrubs *Austroeupatorium inulifolium* and *Tithonia diversifolia* and different species of bamboo dominate in this ecosystem.

Slow flowing streams are very important to aquatic life, especially for invertebrates and amphibians (Fig. 4.2). Crustaceans such as freshwater crabs and shrimps too depend on these streams. Dragonflies dwell in the vicinity of different freshwater habitats. In addition to invertebrates, amphibians except for the direct-developing anurans depend on these water bodies for completion of their life cycle. *Hylarana temporalis*, an endemic but near threatened amphibian species, is regularly observed in the stream and pond habitats within tea plantation ecosystem.

Fig. 4.2 Slow flowing stream in Peak Wilderness Protected Area

4.2.3 Natural and Man-Made Lakes

Although Sri Lanka does not have large natural lakes, the total area covered by human-made water bodies exceeds 170,000 ha (Anon 1999). Majority of larger tanks are located in the dry zone of the country and are used for agriculture purposes. In higher altitude of Sri Lanka (above 1500 m), several tiny natural lakes are scattered in montane ecosystem. Natural lakes in Horton Plains and surrounding forests are important breeding and foraging habitats for threatened fauna especially amphibians and small mammals (Fig. 4.3). In addition to natural lakes, small lakes are constructed in most of the tea plantations for drinking water purpose.

4.2.4 Reservoirs

Reservoirs are large-scale water bodies made for storing surface water. There are several reservoirs built almost exclusively for the purpose of generating hydroelectricity in Sri Lanka and often located in the upper catchments of the major rivers at altitudes above 1000 m (Jayasinghe 2000). Typical example is the Lakshapana complex, which consists of a series of reservoirs. A series of multipurpose reservoirs are available along the Mahaweli, the longest river in the island.

Fig. 4.3 Natural Lake in Horton Plains National Park

4.2.5 Freshwater Springs

A spring is a natural flow of groundwater that intersects the surface of the earth. Many springs are found in the central highland ecosystem and they are active throughout the year. Springs release water stored in the ground that finds way to streams and rivers facilitating continuous flow of water in them throughout the year (Amarasiri 2008). They are valuable sources of water for drinking, bathing, irrigation, etc.

Profuse freshwater springs are found in tea plantations and vegetable cultivation lands in Sri Lanka (Fig. 4.4). With the implementation of Rainforest Alliance Certification in some tea estates, most of the springs and surrounding vegetations have been demarcated for conservation (Kottawa-Arachchi et al. 2015). Many invertebrates and vertebrates depend on these unique habitats to complete their life cycle. Aquatic stage or larval stage of different species of insects and tadpoles live in these springs.

4.2.6 Waterfalls

The country has a large number of waterfalls along the tributaries of major rivers that flow through steep landscape in the central highland. Near the waterfalls and

Fig. 4.4 Freshwater spring in a tea plantation ecosystem

upstream habitats, unique riverine vegetation is seen. Some of the waterfalls are located in montane forests while others are found away from natural forests. The spray zone of waterfalls in the upstream areas harbors herbaceous species such as *Hymenophyllum denticulatum*, *Impatiens* sp., *Sonerila* sp., *Angiopteris fraxinea*, *Asplenium indicum*, *Chirita walkeri*, and *Lindsaea trapeziformis* that grow mostly on rocky substratum.

4.3 Central Highland Complex: A Biodiversity Hotspot

The central highland complex of Sri Lanka is situated in the south central part of the island and comprises of the Peak Wilderness Protected Area (PWPA), the Horton Plains National Park (HPNP), and the Knuckles Conservation Forest (KCF). These montane forests, where the land rises to 2500 m ASL, are home to an extraordinary range of flora and fauna. The region is considered as a super biodiversity hotspot (UNESCO 2010). At present, the central highlands complex consisting of 16 forests is the most important watershed area in Sri Lanka, contributing to less than 5% of the remaining "moist tropical cloud forest" in the world. The Western Ghats in India and Sri Lanka is treated as a Global Biodiversity Hotspot (Myers et al. 2000). More than 50% of Sri Lanka's endemic vertebrates, 50% of the country's endemic flowering plants and more than 34% of its endemic trees, shrubs, and herbs are reported from these diverse montane rain forests and associated grassland areas. Given the number of endemics and threatened species, with their restricted distribution, the Central Highlands Complex including PWPA, HPNP and KCF were declared as

World Heritage Site by UNESCO in 2010. Despite their importance, much of the montane rain forests were cleared in the latter part of the nineteenth century primarily for expansion of plantation or agriculture and allied requirements.

4.3.1 Status of Biodiversity in Central Highland Wetlands

Sustenance of rich biological diversity is the most valuable characteristic of wetlands. A significant number of new species, especially freshwater crabs, have been discovered in and around highland wetlands. The island has 51 species of freshwater crabs, all of which are endemic and approximately 80% are restricted to the island's wet zone, which includes the central highland (Bahir et al. 2005). Recent advances in amphibian taxonomy have revealed that detection of new species of amphibians is higher than previous estimations (Meegaskumbura et al. 2010; Biju et al. 2014). Of the 408 species of vertebrates, 83% of freshwater fishes and 81% of the amphibians in PWPA are endemic. Similarly, 91% of the amphibians and 89% of the reptiles in Horton Plains are endemic (UNESCO 2010). In addition, 64% of the amphibians and 51% of the reptiles in the KCF are endemic (UNESCO 2010). The recent surge in the sphere of Sri Lanka's biodiversity reveals that both species richness and endemism for most groups of animals are much higher than previous estimations (Pethiyagoda 2005). During the last decade, biodiversity research has substantially increased and several new species have been described.

4.3.2 Species Associated with Highland Wetlands

The species composition and the appearance of an aquatic ecosystem vary both temporally and spatially. Sri Lanka harbors over 370 aquatic macrophytes, of which 12% are endemic to the country (Yakandawala 2012). Forty-one percent of the island's aquatic flora is in the threatened category in the National Red List, 2012.

4.3.2.1 Bryophytes and Pteridophytes

There are several species of bryophytes and pteridophytes growing near water bodies. A survey conducted in the central province including highland wetlands reported 44 species of bryophytes, of which 12 were new to science (Ruklani and Rubasinghe 2013). Moss species *Bryum argenteum*, *Pyrrhobryum spiniforme*, and *Hypopterygium* sp. and liverwort species *Plagiochasma nepalense* are common on moist tree branches and embankments near water bodies in Horton Plains. *Cyathea walkerae* and *Cyathea crinite* ferns grow in stream habitats in the central highland.

4.3.2.2 Carnivorous Plants

Where the soil layer is very thin, permanently wet and infertile, carnivorous plants like *Drosera peltata* and *Drosera burmannii* grow among grasslands and wetlands, especially in Nuwara Eliya and Badulla districts (Gunatilleke 2007). In waterlogged depressions and swampy areas in Horton Plains, aquatic plants such as *Juncus* *prismatocarpus*, *Garnotia exaristata*, and *Exacum trinervium* are common. Another group of insectivorous plants is the bladderworts, which are associated with wetlands. All the 15 species of bladderworts are found in Sri Lanka. Three species of bladderworts, i.e., *Utricularia caerulea*, *Utricularia graminifolia*, and *Utricularia moniliformis*, have been recorded from Horton Plains (Gunatilleke and Pethiyagoda 2012). Of these, the last one is endemic.

4.3.2.3 Grasses, Sedges, and Herbaceous Plants

The marshes are characterized by tall grasses, sedges, and herbaceous plants, while lake vegetation is characterized by emergent plants toward the periphery and floating aquatics dominating the water surface (Gunatilleke and Pethiyagoda 2012). Grass species, *viz.*, *Garnotia exaristata* and *Juncus effusus*, are common near marshy areas and stream banks. The dwarf bamboos of the genus *Arundinaria* are represented by five endemic species, all of them occurring in the montane zone above 1500 m. *Arundinaria densifolia* and *Arundinaria debilis* grow in bogs and wet valleys among the grasslands in Horton Plains. *A. densifolia* is widespread in Uva Hills, whereas *A. debilis* occurs in forest understory across central highlands including the Knuckles forests. *Arundinaria floribunda* is known from a single population in Namunukula Forest Reserve, while *Arundinaria scandens* is restricted to upper region of Pidurutalagala Hill above 2100 m (Gunatilleke and Pethiyagoda 2012).

Orchid species such as *Ipsea speciosa* (endemic and endangered) and *Satyrium nepalense* (near threatened) occur in wet grasslands in central highlands. Endemic shrubs, *viz.*, *Impatiens leptopoda*, *Impatiens cuspidate* subsp. *bipartita,* and *Impatiens macrophylla*, usually grow in profusion in damp ground closer to stream and swampy areas. Plant communities dominated by *Eriocaulon* sp. are seen at the edge of water and shallow marshes. Critically endangered species, *viz.*, *Aponogeton jacobsenii* and *Isolepis fluitans*, are restricted to the highlands shallow marshes, especially at the Horton Plains.

4.3.2.4 Invertebrate Fauna

In montane habitats in the wet tropics, large-scale tea cultivation is common. The invertebrate taxa known to be sensitive to anthropogenic disturbances and a general assemblage-level analysis showed significant differences in the composition of macroinvertebrate assemblages between forested and tea plantations streams (Biervliet et al. 2009).

Among invertebrate fauna, odonates are indicator of water quality and environmental quality for conservation and biodiversity studies because of their intimate connection to water. Among odonates, critically endangered species *Elattoneura leucostigma* is restricted to well-vegetated streams in the dense montane forests (Poorten and Conniff 2012). Wijeyeratne (2012) recorded 20 species of dragonflies and damselflies including four endemic species (*Indolestes divisus, Indolestes gracilis, Elattoneura leucostigma*, and *Elattoneura tenax*). Another endemic and critically endangered species *Sinhalestes orientalis* was rediscovered from the Peak Wilderness Sanctuary after 154 years (Sumanapala and Bedjanic 2013). Endemic and vulnerable odonate *Indothemis gracilis* is found in tea plantations at higher elevations (Kottawa-Arachchi et al. 2014a).

Considering crustaceans, two freshwater shrimp species are restricted to the Horton Plains National Park. These include *Lancaris singhalensis* which is confined to streams in and around Horton Plains National Park (alt. 1900–2000 m) and *Lancaris kumariae* which is only found in fast flowing streams (1150 m ASL) away from protected area (Cai and Bahir 2005) of the park. All the 51 species of freshwater crabs recorded from Sri Lanka are endemic. Nearly 90% of the freshwater crabs are globally threatened, and among them, 24 species of freshwater crabs are restricted to montane and submontane habitats (Bahir and Gabadage 2012). Three species of freshwater crabs *Perbrinckia punctata, Perbrinckia glabra*, and *Ceylonthelphusa soror* occur in Horton Plains National Park. Water depth, water-level fluctuations, salinity, and turbidity determine the functions of natural wetlands. These physical parameters influence macrophytes and invertebrates diversity. Macrophytes and invertebrates are the major food source for water birds, which ultimately determines the distribution of water birds communities (Bellio et al. 2009).

4.3.2.5 Vertebrate Fauna

Among the total inland vertebrate species in Sri Lanka, about 30% are ecologically dependent on wetlands (Kotagama and Bambaradeniya 2006). Freshwater fishes, generally considered as important indicator species, are found in all wetland habitats. Several species have become threatened during the past few decades due to habitat loss owing to human intervention and developmental projects. Thus, critically endangered species such as *Dawkinsia srilankensis, Laubuca insularis, Systomus martenstyni, Labeo fisheri*, and *Labeo lankae* are restricted to a single river basin in the Knuckles Forest Reserve (Goonatilake 2012).

Habitat loss, water pollution, and loss of vegetation are the most significant factors for restricted distribution of highland amphibians. Two of the very rare amphibian species were recently rediscovered from the Peak Wilderness, in Central Hills of Sri Lanka (Wickramasinghe et al. 2012, 2013). *Nannophrys marmorata*, an endemic and critically endangered amphibian species, is restricted to the rock strewn streams of the Knuckles Forest Reserve (200–1200 m amsl). Another critically endangered amphibian species, *Adenomus kandianus,* occupies undisturbed primary mountain forests and riparian habitats bordering unpolluted streams (Meegaskumbura et al. 2015). Furthermore, wetland-associated endangered amphibian species, *Taruga eques* and *Pseudophilautus sarasinorum,* are found in freshwater springs and streams in tea plantation ecosystems away from the protected areas in higher elevation (Kottawa-Arachchi et al. 2014b, 2015).

Small mammals, such as *Prionailurus viverrinus* and *Lutra lutra*, living in small lakes and marshes are at risk of their habitat loss, i.e., being converted to human use, endangering these small urban populations. Therefore, different types of wetlands in the central highland can be considered as a place for in-situ conservation of threatened species.

4.3.3 Microclimate of Highland Wetlands

In Sri Lanka, freshwater marshes that are associated with grasslands in higher elevations are subject to wide diurnal temperature fluctuations especially during January to March when rainfall is low and solar radiation is very high. During this period, the night temperature near the ground surface drops below 0 °C and midday temperature goes up to 28 °C (Gunatilleke 2007). Consequently, the plant communities in this ecosystem demonstrate broad adaptability to wide diurnal temperature differences. Within the stream habitats, the ground is sheltered by thick understory and ground vegetation. As a result, the air temperature near the understory goes down to only 10 °C at higher elevations.

Marshlands in tea plantation ecosystems at 1000–1500 m altitude, in close proximity to natural forests, exhibit climatic fluctuations. However, night temperature at ground level may drop to about 5–10 °C during January to March. Besides, the night air temperature in other wetland types such as streams and freshwater springs with good understory may go down only to about 16–19 °C whereas aquatic temperature in man-made lakes is about 17–22 °C (Kottawa-Arachchi et al. 2014b). The wetland habitats especially those of streams associated with thick understory display cool and humid microclimate. The range of relative humidity of wetland habitats in tea plantation ecosystem is about 80–86% (Kottawa-Arachchi et al. 2014b).

4.3.4 Ecosystem Services of Highland Wetlands

Inland wetlands provide an array of services such as provisioning, regulating, and supporting services vital for human well-being. Wetlands are particularly important providers of all water-related ecosystem services (Millennium Ecosystem Assessment 2005). Freshwater marshes and lakes in central highlands play major role as rivers catchments and for regulation and purification of groundwater. Provision of services such as supporting and regulating nutrient cycles and carbon storage are vital ecosystem functions of marshes that deliver many benefits to human and animals. Marshlands are also considered as important breeding habitat for aquatic fauna. Streams and waterfalls in central highlands have high ecotourism values. They are also often inviting places for recreational activities such as hiking, bird watching, and photography.

Groundwater, often discharged through freshwater springs and streams, plays an important role in water supply, providing drinking water to community. Another important water supply for agricultural purpose is represented by the construction of reservoirs that regulate river flow. Besides, hydropower generation is an important role of large reservoirs in higher altitudes. Inland fisheries are of special importance as a primary source of animal protein for rural communities. Therefore, many wetland types including lakes and reservoirs are vital for inland fisheries.

Fig. 4.5 Encroachment of marshland for vegetable cultivation in tea plantation

4.4 Threat to Highland Wetlands

Habitat deterioration and degradation, clearing of vegetation, siltation, water pollution, and spread of invasive alien species are significant threats to highland wetlands (Kotagama and Bambaradeniya 2006). Recent studies revealed that most of the marshy lands and seasonal streams of tea plantations, which support odonates (Kottawa-Arachchi et al. 2014a), amphibians (Kottawa-Arachchi et al. 2014b, 2015), and birds (Kottawa-Arachchi et al. 2015), have been transformed for domestic agriculture by the estate community.

4.4.1 Habitat Deterioration and Degradation

Most of the agricultural lands in the hill country are privately owned, whereas tea plantations are managed by Regional Plantation Companies. Dairy farms are established around Piduruthalagala and Hakgala Mountain forest reserves and Horton Plains National Park. With the increasing demand for agricultural products, wetlands especially marshlands are most vulnerable to encroachment (Fig. 4.5). Encroachment of marshlands and stream habitats happen when the water flow reduces during the dry season. Unfortunately, these encroachments are established permanently leading to significant loss of natural vegetation and biodiversity.

Negligence of soil conservation methods in tea and other agricultural lands lead to soil erosion and land degradation in the hill country (above 1000 m). Consequently, accumulation of sediments in reservoirs leads to reduction in their capacities. Majority of the endemic and threatened species are confined to the wet zone and especially the montane zone where habitat loss and degradation are taking place at a rapid pace. Furthermore, fragmentation of habitats also has a detrimental effect on small populations, especially those with less mobility.

Construction of dams across major rivers, especially the Mahaweli, has affected the downstream vegetation. Due to further diversion and impoundments in the upstream areas of the river, the water flow has been reduced causing drying up of downstream habitats (Yakandawala 2012). Construction of mini-hydropower plants at a rapid rate during the past few years has added to the deterioration of many habitats of aquatic plants that grow only on stones in rapidly flowing streams and rivers. The best example is the construction of the Upper Kotmale hydropower project and restriction of downstream water flow that have affected downstream plants, *viz.*, *Zeylanidium subulatum* and *Zeylanidium olivaceum* (Yakandawala 2012).

4.4.2 Water Pollution

The main causes of pollution in highland wetlands are poor sanitation and hygiene, soil erosion, and excess usage of agrochemicals including inorganic fertilizers. Pollution of natural ecosystems harms living organisms, disturbs ecological systems, and damages structures and/or services (Amarasiri 2008).

A detail study to monitor water quality of selected aquatic habitats in tributaries of Mahaweli River (Wijayawardhana 2006) (Tables 4.1 and 4.2) showed gradual increase of physical parameters along downstream. These data also indicate that the pH values in select aquatic habitats of Mahaweli River are within the maximum permissible level (MPL) of pH for drinking water. On the contrary, Kottawa-Arachchi et al. (2014b) reported the pH values of different types of wetlands in tea plantations is in the range of 5.47–5.98.

The chemical properties of water depend on total dissolved solid, which mainly consists of cations and anions. High concentration of minerals and salt impurities in the water result in increased total dissolved solid. Consequently, other physical parameters (total alkalinity, electrical conductivity, total hardness, and chemical

Table 4.1 Physical parameters in select aquatic habitats in the tributaries of Mahaweli River

		TA	EC	TH	TDS	COD
Habitat	pH	mg dm^{-3}	µS cm^{-1}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}
T1	7.08	7.59	14.50	3.39	9.71	15.60
T2	6.78	10.35	34.30	8.89	22.90	14.40
T3	6.94	10.04	44.30	12.50	29.70	17.20
T4	6.90	13.66	53.20	15.49	35.20	15.00

Source: Wijayawardhana (2006)

T1 natural forest, *T2* tea field, *T3* tea with less anthropogenic activity, *T4* tea with high anthropogenic activity, *TA* total alkalinity, *EC* electrical conductivity, *TH* total hardness, *TDS* total dissolved solids, *COD* chemical oxygen demand

Table 4.2 Ionic concentration of select aquatic habitats in the tributaries of Mahaweli river

	K^+	Na^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	PO_4^{3-}	NO_3^-	Cl^-
Habitat	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}
T1	0.32	1.26	0.68	0.41	1.44	0.03	0.12	11.10
T2	0.80	2.19	1.86	1.02	1.70	0.04	0.93	12.90
T3	1.17	2.47	2.93	1.25	1.78	0.03	1.59	12.90
T4	2.06	3.17	3.70	1.50	2.47	0.04	1.56	10.00

Source: Wijayawardhana (2006)

T1 natural forest, *T2* tea field, *T3* tea with less anthropogenic activity, *T4* tea with high anthropogenic activity

oxygen demand) also showed an increasing trend with increased anthropogenic activities, which indicate accumulation of inorganic ions from usage of fertilizer in surrounding agricultural lands. Extensive agricultural activities in the hill country, especially vegetable cultivation, require many agrochemicals to control pests and diseases. Therefore, agrochemicals are major pollutants that contaminate upland water bodies. It is reported that water quality depletion of reservoirs near farmlands are due to excessive usage of agrochemicals and fertilizers, mixing of animal dung, and dumping of bio- and nonbiodegradable substances (Weerasekara et al. 2010).

4.4.3 Invasive Alien Species

Several exotic aquatic animal and plant species that have eventually entered wild habitats are posing serious threat to native aquatic biodiversity. Observations made during the past couple of years have documented 10 invasive alien faunal and 12 invasive alien floral species spreading in different wetland ecosystems throughout Sri Lanka (Bambaradeniya 2002).

A very thorny species *Ulex europaeus* that is native of Britain has now become invasive along the streams and marshes in Horton Plains National Park. Invasive Neotropical shrub *Austroeupatorium inulifolium* (Fig. 4.6) has rapidly invaded marshlands and steams in addition to being abundant in tea plantations (Pethiyagoda and Nanayakkara 2011). Other exotic plant species such as *Panicum maximum, Clidemia hirta*, and *Mimosa pigra* are becoming serious threat to marshlands. The spread of alien plants such as *Eichhornia crassipes, Xanthium indicum*, and *Salvinia molesta* is another threat to reservoirs and lakes that compete for resources with native species.

Among the invasive fauna are fish species originally introduced for fishing purposes such as the Rainbow Trout (*Oncorhynchus mykiss*), which was introduced to the streams of Horton Plains National park. Another species *Oreochromis mossambicus* was also introduced to reservoirs and both the species are causing destruction of native species. Therefore, these have been included in the list of the world's 100 worst invasive alien species.

Fig. 4.6 Invasion of *Austroeupatorium inulifolium* along a stream in tea plantation

4.5 Conservation of Wetlands

The Fauna and Flora Protection Ordinance of 1937 can be considered as a major step in wetland conservation. Sri Lanka has signed the Ramsar Convention in 1971 and ratified it in 1990. The Central Environmental Authority (CEA) has identified 84 wetland sites of importance for conservation and management through the Wetland Conservation Project of 1991–1998. All Ramsar wetlands are located in low elevations of Sri Lanka. At present, there are several government and nongovernment organizations involved in wetland conservation and management related activities in Sri Lanka.

4.5.1 Protection of Buffer Zones

Terrestrial habitats surrounding wetlands are critical to the management of natural resources. Although the protection of water resources is assured, it is also apparent that terrestrial areas surrounding wetlands are home for many semiaquatic species that depend on mesic ecotones to complete their life cycle (Semlitsch and Bodie 2003). The amphibians, in particular, frequently use both wetland and surrounding habitats. In the modern agricultural landscape, the natural connections between wetlands and natural vegetations have been greatly altered. Increasing plant diversity with native species in buffer zones, maintaining good canopy and understory, and implementing good agricultural practices would bring necessary beneficial changes to these ecosystems.

A recent study indicates that species richness increases with increased hydrologic connectivity of wetlands (Ishiyama et al. 2014). Therefore, it is understood that hydrologic connectivity of wetlands is important for maintaining biodiversity. Furthermore, buffer zone vegetation may facilitate to restore habitat connectivity that helps to increase the free movement of aquatic fauna. Therefore, both aquatic and terrestrial habitats are essential for maintaining biodiversity, and they must be managed as an integral system to protect wetland biodiversity.

4.5.2 Public Awareness

There is an overall lack of awareness among the public on the importance of wetlands, and these habitats are often considered as wastelands or areas used for waste dumps. To change the mind set of people it is important to conduct awareness among public as well as school children through the print and electronic media. Participatory management of wetlands is another practical approach to minimize environmental impact and resource use conflicts. Active involvement of select community groups to restore the degraded wetlands could bring sustainable management of wetlands.

Lack of awareness programs and unavailability of information in the local languages hinder in implementation of wetland conservation measures. Although, a few organizations have attempted to conduct awareness programs for the estate community, they did not succeed much. Recently, Friends of Horton Plains, an environmental organization located in the central hills, carried out awareness programs regarding importance of wetlands and biodiversity conservation of central hills, targeting students and teachers at various locations. Presentations and printed materials in local languages have been distributed through a project taken in collaboration with Department of Wildlife Conservation to carry out field activities.

4.5.3 Legal Provisions for Protecting Wetlands

Nowadays, the value of wetlands is greatly acknowledged and the scenario for conservation of wetlands is encouraging. Site reports and management plans have been prepared for many wetlands under the Wetland Conservation Project of the Central Environmental Authority (CEA). Furthermore, National Wetland Directory of Sri Lanka has been jointly prepared by the CEA, the IUCN Sri Lanka, and the International Water Management Institute (IWMI) in 2006 that presents an overview of 62 important wetland sites in the country (Kotagama and Bambaradeniya 2006).

Wetland delineation is essential for their management. GIS mapping has high potential to categorize the wetland types according to their present status. It also helps to take administrative decision for future protection. Main institutes such as the Ministry of Environment (ME), Department Wildlife Conservation (DWLC), Forest Department (FD), Central Environmental Authority (CEA), and National

Aquatic Resources Research and Development Agency (NARA) should examine government policies, identify gaps, strengthen existing laws, and review the legal framework relating to the conservation of wetlands.

4.6 Prospective for the Conservation of Highland Wetlands

Highland wetlands being hydrologically very important, their status needs to be improved. These valuable ecosystems face severe anthropogenic activities. Considering various issues and threats discussed above, the future management strategies of central highland wetlands need to be focused to conserve this unique ecosystem in a sustainable manner.

From time to time, various national policies such as the National Conservation Strategy (NCS) 1988, the National Wildlife Policy (NWP) 1990, the National Forest Policy (NFP) 1995, and the National Policy on Wetlands (NPW) 2004 have been formulated. Among these is the establishment of a special Wetland Unit in the Natural Resources Division of the CEA to oversee the interests of wetlands and to implement the National Wetlands Policy of 2006.

4.7 Conclusion

The government of Sri Lanka has implemented national policies for the conservation of wetlands in the past 10 years, but highland wetlands continue to be lost and degraded, and their resources are overexploited. Activities such as clearing vegetation, encroachments and spread of invasive alien species are the most significant threats to highland wetlands. These activities have been identified as major issues that cause loss of highland wetland biodiversity. Various government authorities and nongovernment organizations should come forward for working together to identify gaps, conduct awareness programs, strengthen existing laws, and review the legal framework that relates to the conservation of wetlands. Considering various issues and threats discussed above, the future management strategies of central highland wetlands need to be focused to conserve this unique ecosystem in a sustainable manner.

Acknowledgment Information provided by Mr. Asoka Wijayawardhana and Mr. M.C.M. Zakeel for writing this chapter is greatly acknowledged.

References

Amarasiri S (2008) Caring for water. Sri Lanka Nature Forum, Nugegoda

Anon (1999) Biodiversity conservation in Sri Lanka: a framework for action. Ministry of Forestry and Environment, Sri Lanka

Anon (2004) Revised coastal zone management plan, Sri Lanka. Coast Conservation Department and the Ministry of Fisheries and Aquatic Resources Development, Sri Lanka

Bahir MM, Gabadage DE (2012) Taxonomy and conservation status of freshwater crabs (Crustacea: Decapoda) in Sri Lanka. In: Weerakoon DK, Wijesundara S (eds) The national red list 2012 of Sri Lanka; conservation status of the fauna and flora. Ministry of Environment, Colombo, pp 58–64

Bahir MM, Ng PKL, Crandall K, Pethiyagoda R (2005) A conservation assessment of the freshwater crabs of Sri Lanka. Raffles Bull Zool Suppl 12:121–126

Bambaradeniya CNB (2002) The status and implications of invasive alien species in Sri Lanka. Zoo's Print J 17:930–935

Bellio MG, Kingsford RT, Kotagama SW (2009) Natural versus artificial- wetlands and their waterbirds in Sri Lanka. Biol Conserv 142:3076–3085

Biju SD, Garg S, Mahony S, Wijayathilaka N, Senevirathne G, Meegaskumbura M (2014) DNA barcoding, phylogeny and systematics of golden-backed frogs (Hylarana, Ranidae) of the Western Ghats-Sri Lanka biodiversity hotspot, with the description of seven new species. Contrib Zool 83:269–335

Cai Y, Bahir MM (2005) Lancaris, a new genus of freshwater shrimp from Sri Lanka (Crustacea: Decapoda: Atyidae). Raffles Bull Zool Suppl 12:39–46

Dela JDS (2009) Fourth country report from Sri Lanka to the United Nations convention on biological diversity.

Goonatilake SA (2012) The taxonomy and conservation status of the freshwater fishes in Sri Lanka. In: Weerakoon DK, Wijesundara S (eds) The national red list 2012 of Sri Lanka; conservation status of the fauna and flora. Ministry of Environment, Colombo, pp 77–87

Gunatilleke CVS (2007) A nature guide to the world's end trail, Horton plains. Faculty of Science, University of Peradeniya, Sri Lanka

Gunatilleke N, Pethiyagoda R (2012) Grasslands. In: Pethiyagoda R (ed) Horton plains: Sri Lanka's cloud-forest national park. Wildlife Heritage Trust, Sri Lanka, pp 141–168

Ishiyama N, Akasaka T, Nakamura F (2014) Mobility-dependent response of aquatic animal species richness to a wetland network in an agricultural landscape. Aquat Sci 76:437–449

IUCN and CEA (2006) National wetland directory of Sri Lanka. The Central Environmental Authority (CEA), The World Conservation Union (IUCN) and the International Water Management Institute (IWMI), Colombo

Jayasinghe JMPK (2000) Inland aquatic resources. In: Natural resources of Sri Lanka. National Science Foundation, Sri Lanka, pp 195–211

Kotagama SW, Bambaradeniya CNB (2006) An overview of the wetlands of Sri Lanka and their conservation significance. In: National wetland directory of Sri Lanka. IUCN Sri Lanka and Central Environmental Authority, Sri Lanka

Kottawa-Arachchi JD, Gamage RN, Jayathilake GG (2014a) The role of different ecosystems to maintain odonate and butterfly diversity in Mattakelle tea estate, Sri Lanka. In: Proceedings of the International Forestry and Environment Symposium 2014. Department of Forestry and Environmental Science, University of Sri Jayawardenepura, Sri Lanka, p 133

Kottawa-Arachchi JD, Gamage RN, Jayathilake GG, Hiripitiya HSV (2014b) Importance of different habitats for herpetofauna in tea plantation ecosystem in Mattakelle tea estate, Sri Lanka. In: Proceedings of the International Symposium on Agriculture and Environment 2014. University of Ruhuna, Sri Lanka, pp 197–201

Kottawa-Arachchi JD, Gamage RN, Jayathilake GG (2015) Vertebrate diversity and conservation aspects in manmade habitats in Mattakelle Tea Estate, Sri Lanka. WildLanka 3:148–162

Meegaskumbura M, Meegaskumbura S, Bowatte G, Manamendra-Arachchi K, Pethiyagoda R, Hanken J, Schneider CJ (2010) *Taruga* (Anura: Rhacophoridae), a new genus of foam-nesting tree-frogs endemic to Sri Lanka. Ceylon J Sci Biol Sci 39:75–94

Meegaskumbura M, Wijayathilaka N, Abayalath N, Senevirathne G (2015) Realities of rarity: climatically and ecologically restricted, critically endangered Kandian Torrent Toads (*Adenomus kandianus*) breed en masse. Peer J. doi:10.7287/peerj.preprints.1575v2

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: wetlands and water synthesis. World Resources Institute, Washington, DC

Myers N, Mittermeier RA, Mittermeier CG, Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–858

Pethiyagoda R (2005) Exploring Sri Lanka's biodiversity. Raffles Bull Zool Suppl 12:1–4

Pethiyagoda RS, Nanayakkara S (2011) Invasion by *Austroeupatorium inulifolium* (Asteraceae) arrests succession following tea cultivation in the highlands of Sri Lanka. Ceylon J Sci Biol Sci 40:175–181

Ruklani NCS, Rubasinghe SCK (2013) A preliminary survey of bryophytes in the central province of Sri Lanka. Ceylon J Sci (Biol Sci) 42:67–72

Semlitsch RD, Bodie JR (2003) Biological criteria for buffer zones around wetlands and riparian habitats for amphibians and reptiles. Conserv Biol 17:1219–1228

Sumanapala AP, Bedjanic M (2013) Rediscovery of a long lost endemic damselfly *Sinhalestes orientalis* (Hagen in Selys, 1862) from peak wilderness sanctuary, Sri Lanka (Zygoptera: Lestidae). Asian J Conserv Biol 2:44–47

UNESCO (2010) Central highlands of Sri Lanka. Report of the decisions adopted by the World Heritage Committee at its 34th session. WHC-10/34.COM/20.

van Biervliet O, Wisniewski K, Daniels J, Vonesh JR (2009) Effects of tea plantations on stream invertebrates in a global biodiversity hotspot in Africa. Biotropica 41:469–475

van der Poorten N, Conniff K (2012) The taxonomy and conservation of the dragonfly fauna (Insecta: Odonata) of Sri Lanka. In: Weerakoon DK, Wijesundara S (eds) The national red list 2012 of Sri Lanka: conservation status of the fauna and flora. Ministry of Environment, Colombo, pp 1–10

Weerasekara KAWS, Amarathunga AAD, Shirantha RRAR, Sureshkumar N, Azmy SAM (2010) Current status of Ambewela reservoir of Sri Lanka with special reference to water pollution. In: Proceedings of the 15th International Forestry and Environment Symposium 2010. University of Sri Jayewardenepura, Sri Lanka, pp 85–92

Wickramasinghe LJM, Vidanapathirana DR, Wickramasinghe N (2012) Back from the dead: the world's rarest toad *Adenomus kandianus* rediscovered in Sri Lanka. Zootaxa 3347:63–68

Wickramasinghe LJM, Vidanapathirana DR, Airyarathne S, Rajeev G, Chanaka A, Pastorini J, Chathuranga G, Wickramasinghe N (2013) Lost and found: one of the world's most elusive amphibians, *Pseudophilautus stellatus* (Kelaart 1853) rediscovered. Zootaxa 3620:112–128

Wijayawardhana RGA (2006) Effect of fertilizer application in up-country tea lands on downstream pollution. M.Phil. Thesis, University of Peradeniya

Wijeyeratne GS (2012) Dragonfly watching in Horton plains. In: Pethiyagoda R (ed) Horton plains: Sri Lanka's cloud-forest national park. Wildlife Heritage Trust, Sri Lanka, pp 186–188

Yakandawala D (2012) Present status of fresh water aquatic flora in Sri Lanka. In: Weerakoon DK, Wijesundara S (eds) The national red list 2012 of Sri Lanka; conservation status of the fauna and flora. Ministry of Environment, Colombo, pp 186–196

Young L (2013) Wetland conservation in Sri Lanka. The Ramsar Secretariat, Switzerland

Seagrass and Salt Marsh Ecosystems in South Asia: An Overview of Diversity, Distribution, Threats and Conservation Status

5

Shesdev Patro, P. Krishnan, V. Deepak Samuel, R. Purvaja, and R. Ramesh

Abstract

India, Pakistan, Bangladesh, Sri Lanka and the Maldives have extensive coastal and marine ecosystems. Seagrass beds and salt marshes are coastal ecosystems restricted to the subtidal and intertidal zone ranging from shallow water in the case of seagrass to the high upland of intertidal zone in case of salt marsh. The chapter provides an overview of the salt marsh and seagrass ecosystems in India and other South Asian countries. Despite their significant ecological importance, seagrass and salt marsh ecosystems are relatively under-explored or unexplored, particularly in the South Asian countries. Fifteen species of seagrass are reported from South Asian region, all of which are found in India. They are distributed along the coastal states/union territories except Maharashtra, Daman and Diu, Puducherry and West Bengal. The salt marsh species diversity in India and the Maldives is not reported. The chapter provides checklist of salt marshes of India, represented by 14 species, which are distributed along Gujarat, Daman and Diu, Maharashtra, Tamil Nadu, Puducherry, Andhra Pradesh and Andaman and Nicobar Islands.

Keywords

Ecosystem • India • Seagrass • Salt marsh • South Asia

S. Patro • P. Krishnan • V. Deepak Samuel • R. Purvaja • R. Ramesh (✉)
National Centre for Sustainable Coastal Management (NCSCM), Ministry of Environment Forest & Climate Change, Anna University Campus, Chennai 600 025, Tamil Nadu, India
e-mail: shesdevpatro@yahoo.com; krishnanars@yahoo.com; deepakocean@gmail.com; purvaja.ramachandran@gmail.com; rramesh_au@yahoo.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_5

5.1 Introduction

The South Asia's coastal countries (India, Pakistan, Bangladesh, Sri Lanka and the Maldives) have extensive coastal and marine ecosystems. The coastal regions of South Asia are among the most populous regions in the world and home to around 400 million people who are dependent on coastal and marine ecosystems for their livelihoods (UNISDR-UNDP 2012). All the South Asian countries recognize the importance of the coastal sensitive ecosystems and have appropriate regulatory regimes for their conservation. In India, mangroves, coral reefs, seagrass meadows, salt marshes and coastal sand dunes are declared as ecologically sensitive areas, under the Coastal Regulation Zone (CRZ) notification (2011). The seagrass and salt marsh are coastal ecosystems restricted to the subtidal and intertidal zone ranging from shallow water, in the case of seagrass, to the high upland of intertidal zone for salt marshes.

Extensive studies have been made on some of the coastal ecosystems like mangroves and coral reefs. However, seagrass and salt marsh ecosystems are relatively under-explored or unexplored, particularly in the South Asian countries. Seagrass and salt marsh ecosystems have significant importance as they are sheltering and nursing grounds for several species (Jagtap and Rodrigues 2004). Seagrass meadows are well known for their high productivity and their significant role as carbon sink. They are the important feeding grounds for some of the endangered species such as green sea turtles (*Chelonia mydas*) and dugong (*Dugong dugon*) (Jagtap and Rodrigues 2004; Anand et al. 2012). Salt marshes protect the coast from erosion and sea level rise (SLR). Salt marsh species such as *Suaeda monoica* can bioaccumulate salt and heavy metals (such as Cr, Cu, Cd and Zn) and thus can be used for restoration (Ayyappan et al. 2013; Ayyappan and Ravindran 2014). Similarly, *Salicornia* sp. has high market demand in certain countries, where it is used as food and in medical and pharmaceutical industries (Stanley 2008).

Among the South Asian countries, seagrass is reported from India, Sri Lanka, Bangladesh and the Maldives (Jayasuriya 1991; Abu Hena and Khan 2009; Kaladharan et al. 2011; Payri et al. 2012). Salt marsh has been reported from India, Bangladesh, Pakistan and Sri Lanka (Abeywickrama and Arulgnanam 1993; Gul and Khan 1995; Khan et al. 2000, 2005; Khan and Gul 2002; Nayak and Bahugune 2001; Gulzar et al. 2003; Kathiresan and Ramanathan 2004; Agha et al. 2009; Abu Hena and Khan 2009). The present chapter provides a comprehensive overview on the species diversity, distribution, threats, needs and challenges in conservation with respect to seagrass and salt marsh ecosystems in South Asia.

5.2 Seagrasses: The Underwater Meadows

Seagrasses are extremely widespread underwater flowering plants occurring in coastal and estuarine waters worldwide, except the polar region (Short et al. 2007; Nobi et al. 2011). Globally, species diversity of seagrass is very low (60 species) and comprises 0.02% of the angiosperms (Nobi et al. 2011). Though the name stands, seagrasses are not true grasses; they belong to two related families Hydrocharitaceae and Potamogetonaceae (Kannan et al. 1999). Unlike other submerged plants (e.g. seaweeds), seagrasses have flowers and fruits and they produce seeds (Sulochanan 2012). They are dependent on sunlight for photosynthesis, and due to turbid estuarine and coastal environment of India, seagrasses are distributed only up to 10 m depth in estuarine environments and in shallow coastal waters up to 10–15 m depth (Nobi et al. 2010; Sulochanan 2012). But in less turbid waters, as in Caribbean Sea and Australian coast, seagrasses can be found at depths of 50 m or more (Sulochanan 2012). They commonly grow in sandy and muddy substrata and are adapted to withstand wave energy, grow while completely submerged, have air-filled tissues and show salt tolerance (Miththapala 2008).

5.2.1 Significance of Seagrass Beds

Seagrass beds offer a wide range of ecosystem goods and services and the most significant ones as reported by researchers are summarized below:

(a) Seagrass ecosystems are considered to be very productive and act as nursing and breeding grounds for marine organisms (Jagtap 1991).
(b) They help in reducing the speed and changing the pattern of currents and sediment transportation, thus playing a vital role of basic land builder and stabilizer, similar to sand dune and mangrove vegetation (Jagtap and Rodrigues 2004).
(c) Seagrasses reduce water movement and trap heavy metals and nutrients from the surrounding, thus aid in improving the water quality for corals and fish communities (Manikandan et al. 2011a).
(d) They provide substratum for epiphytes, are a good source of food for marine herbivores (e.g. green sea turtles and dugongs) and act as nursing and breeding grounds for numerous marine invertebrates (Jagtap 1991) as well as some vertebrates.
(e) They prevent coastal erosion (Kamboj 2014), serve as primary producer of shallow coastal regions and act as carbon sink by sequestering carbon dioxide from the atmosphere (Miththapala 2008).
(f) Seagrass beds harbour rich biodiversity with commercial value. In Sri Lanka, bristle worms (polychaetes) are harvested from seagrass beds as brood stock feed for aquaculture. Aquarium fishes, such as sea horses, are also collected from seagrass meadows in Puttalam Lagoon, Sri Lanka (Kallesøe et al. 2008). In the Gulf of Mannar, India, green tiger prawn *Penaeus semisulcatus* is extensively harvested for the export market (Anon 2000). They enhance commercial fishery resources by providing shelter to the juveniles as well as adults.

Fig. 5.1 Map showing global locations with high seagrass diversity

5.2.2 Seagrass Diversity in South Asia

Globally, there are five locations of high diversity of seagrasses (Fig. 5.1). Of these, all occurs in the eastern hemisphere and four (insular Southeast Asia, Southeastern India, Eastern Africa and Southern Japan) in the tropical Indo-Pacific bioregion (Short et al. 2007). The fifth, southwestern Australia, occurs in the adjacent Temperate Southern Oceans bioregion. The first and largest of these, by far with the greatest number of seagrass species (19), lies in insular Southeast Asia.

A comprehensive review of the literature on the seagrass diversity in the South Asian countries revealed that 16 species of seagrass are reported from the region (Table 5.1), all of which are found in India (Kannan et al. 1999). Bangladesh has five seagrass species (Abu Hena and Khan 2009), of which two are also found in Sri Lanka. There have been diverse claims on the seagrass diversity from Sri Lanka with Jayasuriya (1991) reporting 12 species and De Silva and Amarasinghe (2007) reporting 15 species. However, neither of the studies provided a checklist of the seagrass species from Sri Lanka. Jayasuriya (1991) listed eight seagrass species from the Puttalam Lagoon, Sri Lanka. Studies on the seagrass diversity in the Maldives are very scanty. Only two seagrass species, *viz. Thalassia hemprichii* and *Syringodium isoetifolium*, have been reported from the Maldives, specifically from the Baa Atoll (Payri et al. 2012). Both these species are also found in Sri Lanka and India. There is no report on the occurrence of any seagrass species from Pakistan.

Table 5.1 Diversity of seagrasses from South Asian maritime states

Species	India	Bangladesh	Sri Lanka	Maldives	Pakistan
Cymodocea rotundata	✓		✓		No reports available
Cymodocea serrulata	✓		✓		
Enhalus acoroides	✓		✓		
Halodule pinifolia	✓	✓			
Halodule uninervis	✓	✓	✓		
Halophila beccarii	✓	✓			
Halophila decipiens	✓	✓	✓		
Halophila ovalis ovalis	✓		✓		
Halophila ovalis ramamurthiana	✓				
Halophila ovata	✓				
Halophila stipulacea	✓				
Halophila wrightii	✓				
Ruppia maritima	✓	✓			
Syringodium isoetifolium	✓		✓	✓	
Thalassia hemprichii	✓		✓	✓	
Zostera marina	✓				

India, Kannan et al. (1999), Kaladharan et al. (2011), Anand et al. (2012) and Kamboj (2014); *Bangladesh*, Abu Hena and Khan (2009); *Sri Lanka*, Jayasuriya (1991); *Maldives*, Payri et al. (2012)

5.2.3 Distribution of Seagrass Beds in India

Distribution of seagrass species along different coastal states of India is presented in Table 5.2. Along the east coast, the maximum species diversity was reported in Tamil Nadu (14 species), followed by six species from Andhra Pradesh and five species from Odisha. Totally six seagrass species have been reported from the west coast, all of which are found in Gujarat. In the island ecosystems, nine species of seagrass were reported, and the maximum diversity of seagrass in India is observed in Andaman and Nicobar Islands. *Halophila beccarii* is the most commonly distributed species in India as was reported from all coastal states except the islands, followed by *H. ovalis*, *H. ovata* and *Halodule uninervis*. *Halophila stipulacea* and *H. ovalis* sub sp. *ramamurthiana* are reported only from Tamil Nadu, while *Ruppia maritima* and *Zostera marina* are reported to be restricted to Karnataka (only in estuaries) and Gujarat, respectively.

Distribution of seagrass is recorded from all the coastal states and union territories (UT islands) of India except Maharashtra, Daman and Diu, West Bengal and Puducherry (Table 5.3). In Gujarat, seagrass meadows are reported mainly from the Gulf of Kachchh (Anand et al. 2012; Kamboj 2014). The total seagrass area in the Gulf of Kachchh is estimated as 2432.31 ha (Kamboj 2014). In Goa, a tiny patch of 0.01 km^2 is recorded from Mandovi estuary with two species of seagrass. In Karnataka, seagrass meadows are reported from Karwar, Swarna-Sita, Chakra,

Table 5.2 Distribution of seagrass along different coastal states of India

No	Species	East coast			West coast			Islands		
		TN	AP	OD	KL	KA	GA	GJ	ANI	Lak
1	*Cymodocea rotundata*	✓							✓	✓
2	*Cymodocea serrulata*	✓							✓	✓
3	*Enhalus acoroides*	✓							✓	
4	*Halodule pinifolia*	✓	✓	✓					✓	
5	*Halodule uninervis*	✓	✓	✓				✓	✓	✓
6	*Halodule wrightii*	✓	✓							
7	*Halophila stipulacea*	✓								
8	*Halophila beccarii*	✓	✓	✓	✓	✓	✓	✓		
9	*Halophila decipiens*	✓								
10	*Halophila ovalis*	✓	✓	✓			✓	✓	✓	✓
11	*Halophila ovalis sub sp. ramamurthiana*	✓								
12	*Halophila ovata*	✓	✓	✓				✓	✓	✓
13	*Syringodium isoetifolium*	✓							✓	✓
14	*Thalassia hemprichii*	✓						✓	✓	✓
15	*Ruppia maritima*					✓				
16	*Zostera marina*							✓		

TN Tamil Nadu, *AP* Andhra Pradesh, *OD* Odisha, *KL* Kerala, *GA* Goa, *GJ* Gujarat, *ANI* Andaman and Nicobar Islands, *Lak* Lakshadweep

Haladi and Kollur estuary. The seagrass of Karwar is represented by *Halophila ovalis*, and the seagrass of Swarna-Sita, Chakra, Haladi and Kollur estuary was represented by *Ruppia maritima* and *Halophila beccarii* (Bopaiah and Neelkantan 1982; Kaladharan et al. 2011). From Kerala, seagrass beds are reported from two estuaries, Kumbala and Kadalundi. Of these, at the latter location, seagrass beds spread in about 2 ha (Kaladharan 2006; Kaladharan and Asokan 2012).

The seagrass diversity is highest (14 species) in Tamil Nadu with the highest area coverage in Palk Bay and Gulf of Mannar region (Kalimuthu et al. 1995; Kannan et al. 1999; Mathews et al. 2008; Selva Ranjitham et al. 2008; Sulochanan et al. 2010). The estimated extent in Palk Bay and Gulf of Mannar is 175.2 km^2 and 55.15 km^2, respectively (Manikandan et al. 2011b; Raja et al. 2012). Three seagrass species have been recorded from Theetapuram in Andhra Pradesh district, but the extent of coverage is not reported. In Odisha, seagrass distribution is limited only to Chilika lake and is spread across an area of 80 km^2 (Kannan et al. 1999; Pati et al. 2014a, b). The seagrass area in Lakshadweep is estimated to be 12 km^2 and is distributed in Kavaratti, Kalpeni, Agatti, Bangaram, Thinnakara, Parali, Amini, Kadmat, Kiltan, Chetlat and Bitra islands (Jagtap 1998; Nobi et al. 2011). It has been observed that the extent of seagrass in ANI stands at 2943.3 ha, and about 1619.4 ha of seagrass area have been denuded during 1996–2007 (Nobi et al. 2013).

Table 5.3 Seagrass meadows in India

State/UT	Reported locations	Recorded species	References
Gujarat	Paga Reef, Chandri Reef, Noru Reef, Bhural Chank Reef, Kalubhar Reef, Narara Reef, Boria Reef, Mangunda Reef, Goose Reef, Pirotan Island, Meetha Chusna Island, Bhaidar Island, Chank Island, Ajad Island, Jindra Island, Chhad Island, Poshitra Reef, Sika Reef, Dedika-Mundika Reef	*Halophila beccarii*, *Halophila ovalis*, *Halodule uninervis*, *Halophila ovata*, *Zostera marina*, *Thalassia hemprichii*	Anand et al. (2012) and Kamboj (2014)
Goa	Mandovi estuary	*Halophila beccarii, Halophila ovalis*	Jagtap and Untawale (1981) and Jagtap and Rodrigues (2004)
Karnataka	Karwar, Swarna-Sita, Chakra, Haladi, Kollur estuary	*Halophila beccarii Ruppia maritima*	Bopaiah and Neelkantan (1982) and Kaladharan et al. (2011)
Kerala	Kumbala estuary, Kadalundi estuary	*Halophila* sp., *Halophila beccarii*	Kaladharan (2006) and Kaladharan and Asokan (2012)
Tamil Nadu	Pulicat Lake, Muttukadu, Idaiyar, Paramakeni, Kadapakkam, Thenpakkam, Uppanar, Vellar estuary, Pichavaram, Thirumullaivasal, Palk Bay, Gulf of Mannar	*Halodule uninervis*, *Halodule pinifolia*, *Halodule wrightii*, *Syringodium isoetifolium*, *Halophila beccarii*, *Halophila ovalis*, *Halophila stipulacea*, *Halophila decipiens*, *Halophila ovata*, *Thalassia hemprichii*, *Cymodocea rotundata*, *Cymodocea serrulata*, *Enhalus acoroides*	Kalimuthu et al. (1995), Kannan et al. (1999), Mathews et al. (2008), Selva Ranjitham et al. (2008), Sulochanan et al. (2010) and Lynda Keren and Inbaraj (2013)
Andhra Pradesh	Theetapuram	*Halophila ovalis*, *Halodule pinifolia,* *Halodule uninervis*, *Halodule wrightii*, *Halophila beccarii*, *Halophila ovata*	Kannan et al. (1999) and Jagtap et al. (2003)
Odisha	Chilika	*Halophila beccarii*, *Halophila ovata*, *Halophila ovalis*, *Halodule uninervis*, *Halodule pinifolia*	Kannan et al. (1999) and (Pati et al. 2014b)

(continued)

Table 5.3 (continued)

State/UT	Reported locations	Recorded species	References
Andaman and Nicobar Islands	Little Andaman, Red Skin, Chidiya Tapu, Kodiyaghat, Neil, Havelock, Henry Lawrence, Kalipur, Great Nicobar, Nancowry, Car Nicobar	*Enhalus acoroides*, *Halophila ovalis*, *Halophila ovata*, *Thalassia hemprichii*, *Cymodocea rotundata*, *Cymodocea serrulata*, *Halodule uninervis*, *Halodule pinifolia*, *Syringodium isoetifolium*	Jayabarathi et al. (2012), Nobi et al. (2013) and Ragavan et al. (2013)
Lakshadweep	Kavaratti, Kalpeni, Agatti, Bangaram, Thinnakara, Parali, Amini, Kadmat, Kiltan, Chetlat, Bitra	*Halophila ovalis*, *Halophila ovata*, *Thalassia hemprichii*, *Cymodocea rotundata*, *Cymodocea serrulata*, *Halodule uninervis*, *Syringodium isoetifolium*	Jagtap (1998), Prabhakaran (2008) and Nobi et al. (2011)

5.2.4 Trends in Seagrass Research

5.2.4.1 Seagrass Research in South Asian Countries

The occurrence, distribution and diversity of seagrasses have been reported from Bangladesh (Abu Hena et al. 2007; Abu Hena and Khan 2009; Abu Hena and Short 2009), Sri Lanka (Jayasuriya 1991; De Silva and Amarasinghe 2007; Kallesøe et al. 2008; Miththapala 2008) and the Maldives (Miller and Sluka 1999; Erftemeijer and Lewis 2006; Anon 2011; Payri et al. 2012). No research reports are available for Pakistan with respect to the seagrass distribution in the country. Our review reveals that the research activity on seagrass ecosystem in South Asian maritime countries is meager, only very few reports or research articles being available discussing their status. Therefore, it can be concluded that though the research on seagrasses is on its rise in India, it is still neglected in other South Asian countries.

5.2.4.2 Seagrass Research in India

There have been extensive studies on the seagrass ecosystems in India. The first report of seagrass study in India was by Balsubramanian and Wafar (1975) from the Gulf of Mannar, Tamil Nadu. Though, ever since, there has been a steady increase in the publications on seagrass ecosystems (Fig. 5.2), seagrass remained a forgotten marine ecosystem in India till 1990 (Jagtap and Rodrigues 2004). Since 2000, there has been a significant increase in the studies on seagrass ecosystems, and the recent trend is that the ecosystem is gaining attention from biologists and ecologists. During 2011–2015, over 30 research papers, cutting across different fields on these ecosystems, have been published (Fig. 5.3).

A comprehensive review was undertaken to trace the specific areas of interests of the researchers among the studies conducted on seagrass ecosystems in India from

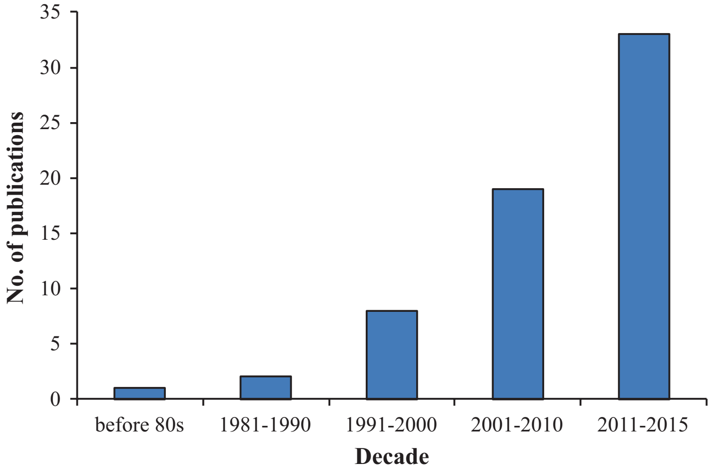


Fig. 5.2 Decadal variation in the number of studies on seagrass ecosystems in India

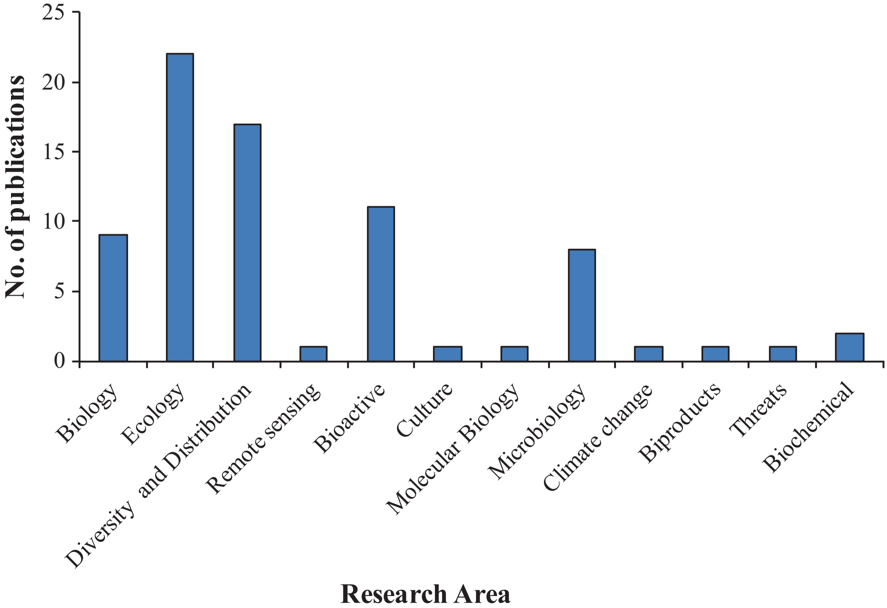


Fig. 5.3 Subject area-wise variation in the publications on seagrass ecosystems in India

1975 to date. It showed that most of the studies are related to ecology (29%, 22 No.), followed by studies focused on diversity and distribution (23%, 17 No.), biology (12%, 9 No.), bioactive properties of seagrasses (15%, 11 No.) and microbiology (11%, 8 No.). It showed that the studies on the culture, climate change impacts, threats and spatial mapping of seagrasses are scanty.

5.3 Salt Marshes

Salt marshes comprise intertidal rooted vegetation, which are periodically inundated by tidal waters (Abu Hena et al. 2007; Nobi et al. 2011). It is defined as the ecosystem consisting of halophytic grass, shrub and herb-like species that live in an area, which is periodically inundated in sea water (Beeftink 1977; Dijekema 1984). Salt marsh ecosystem is confined to temperate region, but in tropics, a different type of salt marsh (herbaceous species) is present in muddy shores where mangroves have failed to colonize (Nayak and Bahuguna 2001). There are confusions in defining halophytes regarding which species should be considered as a true salt marsh species among the coastal vegetation (Grigore et al. 2010). Abeywickrama and Arulgnanam (1993) stated that the salt marsh plants grow well only when they are supplied with salt water. Other coastal vegetation found along with salt marsh plants in higher grounds capable of growing without salt water are termed as their associates. Research studies on the coastal salt marshes in South Asian countries are very scanty. There is no inventory on salt marsh species diversity in India. The current review updates information hitherto published on the salt marsh ecosystems of South Asian countries.

5.3.1 Significance of Salt Marshes

Salt marshes offer a wide range of ecosystem goods and services. The significant ones reported by researchers are summarized below:

(a) Salt marshes in the intertidal area serve as a nursery ground, nutrient source and primary food source for fishes, invertebrates and coastal birds (Abu Hena et al. 2013).
(b) They protect the coastal region from natural processes like erosion and SLR.
(c) Certain species like *Suaeda monoica* can bioaccumulate heavy metals (Ayyappan and Ravindran 2014).
(d) *Suaeda monoica* can be used for restoration of saline agricultural soil (Ayyappan et al. 2013).
(e) *Salicornia* sp. is used as food and in medical and pharmaceutical industries in different countries (Stanley 2008). Field observations revealed that *Suaeda* sp. and *Sesuvium portulacastrum* are used as food in certain parts of Maharashtra, India.

5.3.2 Salt Marsh Diversity in South Asia

In South Asia, salt marsh vegetation is represented by 18 species. Bangladesh, Sri Lanka and Pakistan accounted for five species each. There is no report on the occurrence of salt marshes from the Maldives. In Sri Lanka, salt marshes are found in Gampaha, Puttalam, Mannar, Kilinochchi, Jaffna, Mullaitivu, Trincomalee,

Table 5.4 Species diversity of salt marshes from South Asian maritime nations

Species	India	Bangladesh	Sri Lanka	Maldives	Pakistan
Arthrocnemum indicum	✓		✓	No reports available	✓
Atriplex stocksii					✓
Cressa cretica	✓				✓
Eriochloa procera		✓			
Fimbristylis ferruginea	✓				
Heliotropium curassavicum	✓				
Imperata cylindrica		✓			
Myriostachya wightiana	✓	✓			
Porteresia coarctata	✓	✓			
Phragmites karka		✓			
Salicornia brachiata	✓		✓		
Scirpus littoralis	✓				
Sesuvium portulacastrum	✓				
Suaeda maritima	✓		✓		
Suaeda nudiflora	✓		✓		
Suaeda monoica	✓		✓		
Suaeda fruticosa	✓				✓
Urochondra setulosa	✓				✓

India, Nayak and Bahugune (2001) and Kathiresan and Ramanathan (2004); *Bangladesh*, Abu Hena and Khan (2009); *Sri Lanka*, Abeywickrama and Arulgnanam (1993); *Pakistan*, Gul and Khan (1995), Khan et al. (2000), Khan and Gul (2002), Gulzar et al. (2003), Khan et al. (2005) and Agha et al. 2009

Batticaloa, Ampara, Hambantota and Galle districts, spread across 23,819 ha (Anon 1997). In Pakistan, salt marshes are distributed along Gizri creek, Monora channel, Gadoni, Sonmiani, Sindh, Balochistan and southern coast (Gul and Khan 1995; Khan and Gul 2002; Gulzar et al. 2003; Khan et al. 2005; Agha et al. 2009). Salt marshes have been observed in Bakkhali estuary and Muradur area, in Bangladesh (Abu Hena et al. 2007; Aysha et al. 2015). Out of the 18 recorded species in this region, 14 species have been reported from India (Table 5.4).

5.3.3 Distribution of Salt Marsh in India

Salt marshes are distributed in seven coastal districts/UT in India, *viz.* Gujarat, Daman and Diu, Maharashtra, Tamil Nadu, Puducherry, Andhra Pradesh and ANI, covering an approximate area of 1,61,144 ha (SAC 2011). The highest area (1,44,268 ha) of salt marsh is found in Gujarat followed by Tamil Nadu (6108 ha), ANI (6029 ha), Andhra Pradesh (4002 ha), Maharashtra (614 ha), Puducherry (66 ha) and Daman and Diu (57 ha). In Gujarat, salt marshes are found near Lakhpat, Varsana, Luni and Jakhau port, Balachhadi, Navlakhi-Kandala, between Sabarmati and Tapi estuary, along Mahi and Dhadhar estuary, Mindhola, Purna, Ambica, Auranga and Damanganga estuary (Nayak and Bahuguna 2001). Along the east coast of India, salt marshes are reported from Pichavaram, Muthupet, east of Nizampatnam, near Pedda Valsala and Valsapakala.

5.3.4 Trends in Salt Marsh Research

5.3.4.1 Salt Marsh Research in South Asian Countries

Salt marsh is a well-known ecosystem in the temperate region; however, studies on this ecosystem are scanty. The checklist of salt marsh species found in Sri Lanka (Abeywickrama and Arulgnanam 1993) includes *Arthrocnemum indicum*, *Salicornia brachiata*, *Suaeda maritima*, *Suaeda monoica* and *Suaeda nudiflora*. Mathuranthini (2014) reported the succession pattern between *Halosarcia indica* (*Arthrocnemum indicum*) and *Salicornia brachiata* where the area was colonized by *Halosarcia indica* as the first species and *Salicornia brachiata* as the second. The salt marsh species of Bangladesh include *Porteresia coarctata*, *Imperata cylindrica*, *Eriochloa procera*, *Myriostachya wightiana* and *Phragmites karka* (Abu Hena and Khan 2009). There are only few reports on the ecology of salt marsh of Bangladesh (Abu Hena et al. 2007, 2013; Siddique and Aktar 2012; Aysha et al. 2015). The common salt marsh species reported from Pakistan are *Arthrocnemum indicum*, *Suaeda fruticosa*, *Cressa cretica*, *Urochondra setulosa* and *Atriplex stocksii* (Gul and Khan 1995; Khan et al. 2000, 2005; Khan and Gul 2002; Gulzar et al. 2003; Agha et al. 2009).

5.3.4.2 Salt Marsh Research in India

There are 45 species of salt marshes and other coastal vegetation in India (Kathiresan and Ramanathan 2004). It is difficult to distinguish the true salt marsh species from coastal vegetation. After considering the definition of salt marsh (Beeftink 1977; Dijekema 1984) and qualifying characteristics of salt marsh species (Abeywickrama and Arulgnanam 1993), those trees and vegetation that can grow in freshwaters were dropped from the species checklist; thus, the checklist of true salt marsh species of India comprise 14 species. *Cressa cretica* is also added to the list of salt marshes since it is considered so in other South Asian countries, thus raising the total true salt marsh diversity in India to 14 species which are *Arthrocnemum indicum*, *Cressa cretica*, *Fimbristylis ferruginea*, *Heliotropium curassavicum*, *Myriostachya wightiana*, *Porteresia coarctata*, *Salicornia brachiata*, *Scirpus littoralis*, *Sesuvium portulacastrum*, *Suaeda fruticosa*, *Suaeda maritima*, *Suaeda monoica*, *Suaeda nudiflora* and *Urochondra setulosa*.

Some studies on the distribution of salt marsh along Indian coast (Nayak and Bahuguna 2001; Stanley 2008; SAC 2011; Ayyappan et al. 2013; Ayyappan and Ravindran 2014) have documented the importance of certain salt marsh species, such as *Suaeda monoica* and *Salicornia brachiata* with respect to economical aspects. There are no studies reporting about the ecological status of salt marshes in India.

5.4 Issues, Threats and Conservation of Coastal Wetlands

5.4.1 Issues and Threats for Seagrass Ecosystem

Seagrass meadows, like all coastal ecosystems, are subjected to multiple impacts at local, national and global levels (Kamboj 2014). Natural causes for seagrass meadow are tsunami, cyclone, high waves, continuous exposure to sunlight, intensive grazing, infestation of fungi and epiphytes as well as "dieback" disease (Jagtap and Rodrigues 2004; Nobi et al. 2013). The anthropogenic causes leading to degradation of seagrasses include pollution, dredging and siltation and illegal fishing techniques.

Nobi et al. (2013) reported that in Andaman and Nicobar Islands, nearly 1619.4 ha of seagrass meadows were denuded during the 2004 Indian Ocean tsunami. It is also reported that, in a few islands like the North Reef and Interview Island, seagrass beds were degraded due to exposure to direct sunlight following the uplift of the land because of the earthquake. A few cases of damage were also reported from the Gulf of Mannar and Palk Bay during tsunami (Kumaraguru et al. 2005). The Indian coastline is under threat of tropical cyclones every year. The cyclone "Lehar" which passed over the coast of ANI on 25 November 2013 was reported to have damaged a seagrass meadow of approximately 1.96 ha in Ross and Smith Islands, Andaman (Sachithanandam et al. 2014).

One of the major threats to the seagrass meadows in the Gulf of Kachchh Marine National Park and Sanctuary is the pollution due to various industries and sedimentation affecting the water quality (Kamboj 2014). As the seagrass meadows require proper sunlight for photosynthesis, the turbid water reduces the light availability. Siltation of seagrass beds is most commonly observed in the Gulf of Kachchh, Gujarat, in ANI and in most of the estuaries (Jagtap and Rodrigues 2004). Illegal fishing technique, such as trawling, is another problem observed in the Palk Bay region, which leads to degradation of seagrass beds (Sivaleela et al. 2013). In Sri Lanka, seagrass beds have been reported to be damaged due to the use of destructive fishing gears, such as bottom trawling and drag net fisheries, digging for polychaetes and smothering of seagrass by siltation, sedimentation and eutrophication. Traditional fishing is a major threat to the seagrass meadows of Puttalam Lagoon, Sri Lanka (Jayasuriya 1991). Dredging of seagrasses has been reported from the resorts in the Maldives (Erftemeijer and Lewis 2006). These reports highlight the lack of awareness of benefits from the seagrass ecosystems in South Asian countries.

5.4.2 Issues and Threats for Salt Marsh Ecosystem

Salt marsh ecosystems distributed in the temperate regions face threats from changes in natural hydrology, pollution, coastal development, fill/improper marsh elevations and non-native/invasive species (EFC 2004). In case of subtropics, the identified threats include climate change; overgrazing; embankment; excessive agricultural use; urbanization; new developments; building of levees, drainage, seawalls and retaining walls; recreation and coastal erosion; pollution and industrial waste water; rubbish dumping; and invasion by weeds (MESA 2006). Reports on the threats to salt marshes from tropical waters are scanty. Lowry and Wickremeratne (1987) reported that overgrazing by cattle, conversion to saltpans and conversion to aquaculture ponds are major threats to the salt marsh of Sri Lanka. However, some of the other threats like pollution and eutrophication also affect the salt marshes, though specific studies have not been undertaken in South Asian countries.

5.4.3 Conservation of Salt Marshes and Seagrasses

Seagrass and salt marsh ecosystems have been left out of education, research and public awareness considerations for a long time. Recent worldwide decline in seagrass abundance has alarmed ecologists and coastal managers (Mathews et al. 2008). In India, though there has been a significant increase in the research studies undertaken on seagrass ecosystems during the last 15 years, studies on salt marsh ecosystems are scanty.

In Bangladesh, though seagrass ecosystem is protected under the Coastal Zone Policy (2005), it is reported that the approaches and management rules are not very effective, thus demanding stronger protection and conservation policies (Abu Hena and Khan 2009). In case of Pakistan, there are no specific regulations to protect or conserve seagrass ecosystems. Incidentally, seagrass beds are considered as a nuisance in the Maldives, and numerous resorts have invested to remove them from the lagoon areas under regular beach cleaning programme (Anon 2011).

The first step towards conservation is mapping and delineation of these ecosystems. Seagrass and salt marsh ecosystems have been declared as ecologically sensitive areas in India under the CRZ notification (2011), which have been delineated with stringent regulations. The total extent of salt marsh and seagrass ecosystems in India is 471 km^2 and 415 km^2, respectively (unpublished data of authors). India, Bangladesh and the Maldives are involved in "Seagrass-Watch" (www.seagrasswatch.org), which is a global scientific, non-destructive, seagrass assessment and monitoring programme. People involved in the programme develop a deep sense of custodianship and understanding of their local marine environments that reach out to a wider community, for their conservation. It has recognized the importance of involving the coastal community in sensitizing the condition of the ecosystems and loss of seagrasses in their regions. The coastal communities have been keen to play the role of gathering primary information and work in partnership with government agencies.

5.5 Conclusion

The research on salt marsh and seagrass ecosystem in South Asian countries is scanty and needs serious attention from ecologists and policymakers. Though few studies have been carried out on seagrass ecosystems of India, the status in other

South Asian countries is poor. The present document inventorizes the salt marsh species in India comprising of 14 true salt marsh species.

India has taken a significant step by recognizing seagrass and salt marsh ecosystems as ecologically sensitive and bringing them under regulatory regime. In the light of the significance of these coastal ecosystems, the maritime South Asian countries shall establish regional networks for sharing research expertise and management experiences with respect to seagrasses and salt marshes.

References

Abeywickrama BA, Arulgnanam P (1993) The coastal plants of Sri Lanka, part I (Salt Marsh Plants). UNESCO: Man and the Biosphere National Committee for Sri Lanka. Publication No. 20. Natural Resources, Energy and Science Authority of Sri Lanka, Colombo, p 19

Abu Hena MK, Khan MAA (2009) Coastal and estuarine resources of Bangladesh: management and conservation issues. Maejo Int J Sci Tech 3(02):313–342

Abu Hena MK, Short F (2009) A new record of seagrass *Halophila beccarii* Ascherson in Bangladesh. CMU J Nat Sci 8(2):201–206

Abu Hena MK, Short FT, Sharifuzzaman SM, Hasan M, Rezowan M, Ali M (2007) Salt marsh and seagrass communities of Bakkhali Estuary, Cox's Bazar, Bangladesh. Estuar Coast Shelf Sci 75:72–78

Abu Hena MK, Japar SB, Aysha A, Ahasan H, Short FT (2013) Estuarine macrophytes at Bakkhali, Cox's Bazar, Bangladesh with reference to mangrove diversity. Chiang Mai J Sci 40(4):556–563

Agha F, Gul B, Khan MA (2009) Seasonal variation in productivity of *Atriplex stocksii* from a coastal marsh along the Arabian Sea coast. Pak J Bot 41(3):1053–1068

Anand Y, Tatu K, Pandey CN (2012) First record of feeding trails of dugong in Gulf of Kachchh (GoK), Gujarat. Indian For 138(10):968–969

Anon (1997) Revised coastal zone management plan. Coast Conservation Department of the Ministry of Fisheries and Aquatic Resources Development, Sri Lanka, p 137

Anon (2000) Studies on socioeconomics of coral reef resource users in the Gulf of Mannar coast, south India: final report. Centre for marine and coastal studies, School Of Energy, Environment and Natural Resources, Madurai Kamaraj University, Madurai, p 163

Anon (2011) Survey of climate change adaptation measures in Maldives. Ministry of Housing and Environment, Maldives, p 128

Aysha A, Abu Hena MK, Mishra M, Nesarul MH, Padhi BK, Mishra SK, Islam MS, Idris MH, Masum MB (2015) Sediment and carbon accumulation in sub-tropical salt marsh and mangrove habitats of north-eastern coast of Bay of Bengal, Indian Ocean. Int J Fish Aquat Stud 2(4):184–189

Ayyappan D, Ravindran KC (2014) Potentiality of *Suaeda monoica* forsk; a salt marsh halophyte on bioaccumulation of heavy metals from tannery effluent. Int J Mod Res Rev 2(9):267–274

Ayyappan D, Balakrishnan V, Ravindran KC (2013) Potentiality of *Suaeda monoica* forsk; a salt marsh halophyte on restoration of saline agricultural soil. World Appl Sci J 28(12):2026–2032

Balsubramanian T, Wafar MVM (1975) Primary productivity of some sea grass beds in the Gulf of Mannar. Mahasagar 8(1 & 2):87–92

Beeftink WG (1977) Salt marshes. In: Barnes RSK (ed) The coastline. Wiley, London, pp 93–121

Bopaiah BA, Neelkantan B (1982) Ecology of a tidal pond in an estuarine environment, Karwar. Mahasagar 15(1):29–36

Coastal Regulation Zone (CRZ) Notification (2011) Ministry of Environment & Forests (Department of Environment, Forests & Wildlife). http://www.moef.nic.in/downloads/public-information/CRZ-Notification-2011.pdf. Accessed 7 June 2016

Coastal Zone Policy (2005) Ministry of Water Resources, Government of the People's Republic of Bangladesh. http://lib.pmo.gov.bd/legalms/pdf/Costal-Zone-Policy-2005.pdf. Accessed 7 June 2016

De Silva KHWL, Amarasinghe MD (2007) Substrate characteristics and species diversity of marine angiosperms in a micro-tidal basin estuary on the west coast of Sri Lanka. Sri Lanka J Aquat Sci 12:103–114

Dijekema KS (1984) Salt marshes in Europe. Nature and Environment Series No. 30. 178 p

EFC (2004) Environmental fact sheet. New Hampshire Dept. of Environmental Sciences. http://des.nh.gov/organization/commissioner/pip/factsheets/cp/documents/cp-08.pdf. Accessed 7 Jun 2016

Erftemeijer PLA, Lewis RRR (2006) Environmental impacts of dredging on seagrasses: a review. Mar Pollut Bull 52:1553–1572

Grigore MN, Toma C, Boşcaiu M (2010) Dealing with halophytes: an old problem, the same continuous exciting challenge, An. Şt. Univ. Al. I. Cuza's. II.a. Biol Veg 56(1):21–32

Gul B, Khan MA (1995) Productivity of an *Arthrocnemum indicum* dominated coastal salt marsh at Karachi, Pakistan. In: Khan MA, Ungar IA (eds) Biology of salt tolerant plants. University of Karachi, Karachi, pp 99–105

Gulzar S, Khan MA, Ungar IA (2003) Salt tolerance of a coastal salt marsh grass. Commun Soil Sci Plant Anal 34(17 & 18):2595–2605

Jagtap TG (1991) Distribution of seagrass along the Indian coast. Aquat Bot 40:379–386

Jagtap TG (1998) Structure of major seagrass beds from three coral reef atolls of Lakshadweep, Arabian Sea, India. Aquat Bot 60:397–408

Jagtap TG, Rodrigues RS (2004) Seagrasses: the forgotten marine habitat. In: Untawale AG (ed) Know our shore. World Wide Fund for Nature, Goa, pp 57–67

Jagtap TG, Untawale AG (1981) Ecology of seagrass bed of *Halophila beccarii* (Aschers) in Mandovi estuary, Goa. Indian J Mar Sci 10:402–404

Jagtap TG, Deepali SK, Rodrigues RS (2003) Status of a seagrass ecosystem: an ecologically sensitive wetland habitat from India. Wetlands 23(1):161–170

Jayabarathi R, Padmavati G, Anandavelu I (2012) Abundance and species composition of harpacticoid copepods from a sea grass patch of south Andaman, India. Curr Res J Biol Sci 4(6):717–724

Jayasuriya PMA (1991) The species composition, abundance and the distribution of seagrass communities in Puttalam lagoon. Vidyo J Sci 3(2):93–102

Kaladharan P (2006) Occurrence of *Halophila beccarii* Asch. from Kumbala estuary, Kerala. J Bombay Nat Hist Soc 103(1):137–138

Kaladharan P, Asokan PK (2012) Dense bed of the seagrass *Halophila beccarii* in Kadalundi Estuary, Kerala. Mar Fish Infom Ser 212:18

Kaladharan P, Zacharia PU, Vijayakumaran K (2011) Coastal and marine floral biodiversity along the Karnataka coast. J Mar Biol Assoc India 53(1):121–129

Kalimuthu S, Kaliaperumal N, Ramalingam JR (1995) Distribution of algae and seagrasses in the estuaries and backwaters of Tamil Nadu and Pondicherry. Seaweed Res Util 17:79–86

Kallesøe MF, Bambaradeniya CNB, Iftikhar UA, Ranasinghe T, Miththapala S (2008) Linking coastal ecosystems and human well-being: Learning from conceptual frameworks and empirical results. Ecosystems and Livelihoods Group, Asia, IUCN, Colombo, 49p

Kamboj RD (2014) Biology and status of seagrasses in Gulf of Kachchh Marine National Park and Sanctuary, India. Indian Ocean Turt News 19:8–11

Kannan L, Thangaradjou T, Anantharaman P (1999) Status of seagrass of India. Seaweed Res Util 21(1&2):25–33

Kathiresan K, Ramanathan T (2 004) Salt marsh and other coastal flora. In: Kathiresan K, Ajmal Khan S, editors. Biodiversity in mangrove ecosystems: UNU-INWEH-UNESCO International Training Course. Annamalai University, Sabanayagam Printers, pp 179–190

Khan MA, Gul B (2002) Salt tolerant plants of coastal Sabkhat of Pakistan. In: Barth, Boer (eds) Sabkha ecosystems. Kluwer Academic Publishers, Amsterdam, pp 123–139

Khan MA, Ungar IA, Showalter AM (2000) The effect of salinity on the growth, water status, and ion content of a leaf succulent perennial halophyte *Suaeda fruticosa* (L.) Forssk. J Arid Environ 45:73–84

Khan MA, Ungar IA, Showalter (2005) Salt stimulation and tolerance in an intertidal stem-succulent halophyte. J Plant Nutr 28:1365–1374

Kumaraguru AK, Jayakumar K, Wilson JJ, Ramakritinan CM (2005) Impact of the tsunami of 26 December 2004 on the coral reef environment of Gulf of Mannar and Palk Bay in the southeast coast of India. Curr Sci 89(10):1729–1741

Lowry K, Wickremeratne HJM (1987) Coastal area management in Sri Lanka. The University of Chicago, Chicago, pp 263–293

Lynda Keren T, Inbaraj M (2013) Spatial and temporal variation in the environmental parameters and its impact on the seagrass and associated macrofauna of Pulicat. Ecoscan 7(3&4):115–121

Manikandan S, Ganesapandian S, Singh M, Kumaraguru AK (2011a) Seagrass diversity and associated flora and fauna in the coral reef ecosystem of the Gulf of Mannar, southeast coast of India. Res J Environ Earth Sci 3(4):321–326

Manikandan S, Ganesapandian S, Parthiban K (2011b) Distribution and zonation of seagrasses in the Palk Bay, southeastern India. J Fish Aquat Sci 6(2):178–185

Mathews G, Diraviya Raj K, Patterson Edward JK (2008) Seagrass abundance in Manoli Island of the Gulf of Mannar, southeast of India. Seaweed Res Utiln 30:59–65

Mathuranthini S (2014) Cyclic succession in salt marsh vegetation involving *Halosarcia indica* and *Salicornia brachiata* in Sri Lanka. Sciscitator 1:7–9

MESA (2006) Marine Education Society Australasia. http://www.mesa.edu.au/saltmarsh/saltmarsh07.asp. Accessed 7 June 2016

Miller MW, Sluka RD (1999) Patterns of seagrass and sediment nutrient distribution suggest anthropogenic enrichment in Laamu atoll, Republic of Maldives. Mar Pollut Bull 38(12):1152–1156

Miththapala S (2008) Seagrasses and Sand Dunes. Colombo: Ecosyst Livelihoods Group Asia, IUCN 3:36

Nayak S, Bahuguna A (2001) Application of remote sensing data to monitor mangroves and other coastal vegetation of India. Indian J Mar Sci 30(4):195–213

Nobi EP, Dilipan E, Sivakumar K, Thangaradjou T (2010) Distribution and biology of seagrass resources of Lakshadweep group of Islands, India. Ind J Geol Sci 40(5):624–634

Nobi EP, Dilipan E, Sivakumar K, Thangaradjou T (2011) Distribution and biology of seagrass resources of Lakshadweep group of Islands, India. Indian J Mar Sci 40(5):624–634

Nobi EP, Dilipan E, Thangaradjou T (2013) Integrating Indian remote sensing multi-spectral satellite and field data to estimate seagrass cover change in the Andaman and Nicobar islands, India. Ocean Sci J 48(2):173–181

Pati MP, Nayak L, Sharma SD (2014a) Studies on biomass of Seagrass, Seaweed and its associated fauna from Chilika lagoon. Int J Environ Sci 5(2):423–431

Pati MP, Nayak L, Sharma SD, Sahoo J, Behera DP (2014b) Studies on Seagrasses in relation to some environmental variables from Chilika Lagoon, Odisha, India. Int Res J Environ Sci 3(11):92–101

Payri C, N'Yeurt ADR, Mattio L (2012) Benthic algal and seagrass communities in Baa atoll, Maldives. In: Andréfouët Serge, editor. Biodiversity, resources, and conservation of Baa atoll (Republic of Maldives): a UNESCO Man and Biosphere Reserve. Atoll Research Bulletin, pp 31–66

Prabhakaran MP (2008) Ecological studies on the seagrass ecosystem of Minicoy Lagoon, Lakshadweep. Ph.D. thesis submitted to Cochin University of Science and Technology, Cochin

Ragavan P, Saxena A, Mohan PM, Coomar T, Ragavan A (2013) Leaf reddening in seagrasses of Andaman and Nicobar Islands. Trop Ecol 54(2):269–273

Raja S, Thangaradjou T, Sivakumar K, Kanna L (2012) Rhizobacterial population density and nitrogen fixation in seagrass community of Gulf of Mannar, India. J Environ Biol 33:1033–1037

SAC (2011) National wetland atlas. Ministry of Environment and Forest, India, Space Application Centre, Ahmedabad, p 334

Sachithanandam V, Mageswaran T, Sridhar R, Purvaja R, Ramesh R (2014) Assessment of Cyclone Lehar's impact on seagrass meadows in Ross and Smith Islands, north Andaman. Nat Hazards 72:1253–1258

Seagrass watch. http://www.seagrasswatch.org/about.html. Accessed 09 June 2015

Selva Ranjitham N, Thirumaran G, Anantharaman P, Nightingale VDR, Balasubramanian R (2008) Associated Fauna of seaweeds and seagrasses in Vellar Estuary. Am-Eurasian J Bot 1(1):9–16

Short F, Carruthers T, Dennison, Waycott M (2007) Global seagrass distribution and diversity: a bioregional model. J Exp Mar Biol Ecol 350:3–20

Siddique MAM, Aktar M (2012) Heavy metals in salt marsh sediments of Porteresia bed along the Karnafully river coast, Chittagong. Soil Water Res 7(3):117–123

Sivaleela G, Samuel DV, Anbalagan T, Shrinivaasu S (2013) Seagrass associated marine sponges in Palk Bay. Rec Zool Surv India 113(3):1–7

Stanley OD (2008) Bio prospecting marine halophyte *Salicornia brachiata* for medical importance and salt encrusted land development. J Coast Dev 11(2):62–69

Sulochanan B (2012) Seagrass distribution and its vulnerability in India. CMFRI Bull 19:18–23

Sulochanan B, Kumaraguru AK, Mathew G (2010) Seagrass diversity and influence of beach erosion in Palk Bay and Gulf of Mannar seagrass beds. In: Meenakumari B, Boopendranath MR, Edwin L, Sankar TV, Gopal N, Ninan G (eds) Coastal fishery resources of India – conservation and sustainable utilisation. Society of Fisheries Technologists, New York, pp 209–219

UNISDR-UNDP (2012) A tool kit for integrating disaster risk reduction and climate change adaptation into ecosystem management of coastal and marine areas in south Asia. Outcome of the South Asian Consultative Workshop on "Integration of Disaster Risk Reduction and Climate Change Adaptation into Biodiversity and Ecosystem Management of Coastal and Marine Areas in South Asia", New Delhi, p 173

Conserving Wetlands for Migratory Waterbirds in South Asia

6

Judit K. Szabo and Taej Mundkur

Abstract

Wetlands are highly productive ecosystems and provide many crucial services. Most waterbird species depend on wetlands throughout their life cycle. The Central Asian Flyway covers a large continental area of Eurasia bounded by the Arctic and Indian Oceans, connecting breeding grounds in Siberia and temperate Eurasia with nonbreeding grounds in West and South Asia. Species that breed in wetlands in the Arctic and northern latitudes of Central Asia migrate along different routes, stopping to rest and refuel in wetlands, grasslands and sometimes in deserts on the way to their nonbreeding grounds, where they spend the northern winter. Over 180 species of waterbirds use the Central Asian Flyway, among which are pelicans, ducks, geese, swans, cranes, waders (also called shorebirds), herons, storks and cormorants. Due to past and ongoing destruction, and degradation of coastal and inland wetlands, many of these species are now threatened with extinction. Strict habitat protection, adaptive management of both protected and unprotected areas (including managing water for wildlife) and, when necessary, restorations of wetlands are essential to maintaining functional wetland ecosystems and combating declines of wetland-dependent bird species. Most importantly, monitoring is crucial to guide effective management and conservation.

J.K. Szabo (✉)
East Asian – Australasian Flyway Partnership Secretariat,
3F G-Tower, 175 Art center-daero (24-4 Songdo-dong), Yeonsu-gu, Incheon 406-840,
Republic of Korea

Charles Darwin University, Darwin, Northern Territory 0810, Australia
e-mail: judit.szabo@cdu.edu.au

T. Mundkur
Wetlands International, Horapark 9, 6717 LZ Ede, The Netherlands
e-mail: taej.mundkur@wetlands.org

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_6

Keywords
Central Asian Flyway • Conservation • Migration routes • Migratory species • Waterbirds

6.1 Introduction

Wetlands come in many shapes and sizes. They can be located inland or on the coast and with salinity ranging from freshwater though brackish water (e.g. coastal marshes) to saline (e.g. salt marshes). They can be open bodies of water consisting of seasonally or permanently waterlogged soil, mangrove forests and intertidal mudflats (such as those of the Sundarbans shared by Bangladesh and India) or coralline islands and atolls (such as in the Maldives and Lakshadweep in India). Some wetlands, such as ponds, scattered through the extensive open, mixed forests of the Russian taiga, measuring only a few km^2 each, while the major flood plains of the Indus, Ganga and Brahmaputra rivers extend over hundreds of thousands km^2.

Wetlands provide provisioning, regulating, cultural and supporting ecosystem services to billions of people worldwide (Millennium Ecosystem Assessment 2005; McInnes 2013). Although many uses and values of wetlands are evident, wetlands have historically been regarded as wastelands and whenever possible turned into something more "useful" (Daryadel and Talaei 2014). As a result, wetlands have been drained and converted into agricultural land or commercial and residential developments all around the world. Due to these past and ongoing human demands on water and land, wetlands are one of the most threatened habitats in the world. In the last three centuries, global wetland loss is estimated to be 54–57%, but it might be as high as 87% (Davidson 2014). Intertidal wetlands have seen some of the greatest losses worldwide. For instance, the area of the Yellow Sea tidal flat ecosystem lost to reclamation in the last 50 years is 50–80%, which qualifies it as endangered according to the International Union for Conservation of Nature (IUCN) Red List of Ecosystems criteria (Murray et al. 2015).

One of the crucial ecosystem services of wetlands is supporting biodiversity. Given that wetlands are among the most threatened habitats, the species that depend on them are among the most threatened taxa. According to BirdLife International (2016), modification of inland wetlands and habitat conversion for agriculture are threatening over 100 species of birds in Asia and around 60 species in India. One of them, the pink-headed duck *Rhodonessa caryophyllacea* is possibly extinct, with the last definite observation in the wild in 1935 (Rahmani and Islam 2008).

Monitoring wetland condition and biodiversity is vital for conservation, restoration and management and often relies on the use of surrogate taxa. Waterbirds are commonly used as flagships of biodiversity and are the subject of major wetland conservation initiatives. As wetlands are usually highly productive, relatively small areas can support large concentrations of waterbirds. This dependence may be so strong that the population dynamics of waterbirds is often used as an indicator of wetland conservation status (Péron et al. 2013). For instance, in Australia, waterbirds provide a useful indicator of river and wetland condition that can be monitored across large spatial scales (Kingsford and Auld 2003). Besides their role as bioindicators, waterbirds play a range of key functional roles in wetland ecosystems, among others serving as predators, insectivores, herbivores and vectors of seeds (Figuerola and Green 2002). As birds move among habitats, they also reallocate a considerable amount of nutrients, for instance, within agricultural fields and between agricultural areas and wetlands (Navedo et al. 2015). In some cases, humans have capitalized on these natural dynamics. For instance, in southern India, the guano of spot-billed pelican *Pelecanus philippensis* has traditionally been used to fertilize fields to increase crop yields (Kannan and Pandiyan 2013). Feeding on economically harmful species, waterbirds can provide an effective and free service to farmers by controlling pests or weeds. As over 350 bird species use rice fields for feeding in the Indian subcontinent (Sundar and Subramanya 2010), this service can be substantial. In China and Southeast Asia, ducks have been used since ancient times to reduce the number of crabs, locusts and weeds in rice paddies (Peng 1984; Suh 2014). Additionally, waterbirds provide a range of important provisioning (such as meat, feathers and eggs) and cultural services to both indigenous and westernized societies (Galbraith et al. 2014; Green and Elmberg 2014). Migratory and resident birds provide substantial recreational services, supporting bird watching, hunting and ecotourism (Bibby 2002). Waterbirds have also been used as sentinels of potential disease outbreaks (Green and Elmberg 2014).

6.2 The Central Asian Flyway and Its Waterbirds

Migratory animals connect distant countries as they cover immense distances through their annual movements. This mobility makes their conservation particularly challenging, especially when the same individuals have to cope with various pressures at breeding, stopover (or staging) and nonbreeding sites. Members of the orders Anseriformes (ducks, geese and swans), Pelecaniformes (pelicans, herons, egrets, ibises and spoonbills), Gruiformes (cranes and rails), Charadriiformes (waders, gulls and terns), Ciconiiformes (storks) and Suliformes (cormorants and darters) migrate between wetlands in the northern breeding areas and southern nonbreeding areas and in doing so regularly cross the borders of two or more countries. The routes that these birds take are known as flyways, which are defined as "the entire range of a migratory bird species (or groups of related species or distinct populations of a single species), through which it moves on an annual basis from the breeding grounds to non-breeding areas, including intermediate resting and feeding places, as well as the area within which the birds migrate" (Boere and Stroud 2006). In the subtropical and tropical regions, where the cold season may not be very pronounced, herons, storks, ibises and other waterbirds may move locally, within or across national boundaries, largely in response to the availability of water. Complex migratory systems lead to a complex conservation problem, and as species have different ecological needs and varying patterns, a species-specific network of protected and properly managed sites is necessary to support all stages (breeding, stopover

Fig. 6.1 The Central Asian Flyway is one of the nine global waterbird flyways, covering a large continental area of Eurasia between the Arctic and Indian Oceans and the associated inland chains connecting breeding grounds in Russia to the southernmost nonbreeding grounds in West and South Asia, encompassing 30 countries of North, Central and South Asia and Transcaucasia

and nonbreeding) of their migration cycle. Thus, all long-distance, short-distance and nomadic species depend on a large network of wetlands throughout their range to complete their annual cycle.

The Central Asian Flyway (CAF) is one of the nine global waterbird flyways. It covers a large continental area of Eurasia bound by the Arctic and Indian Oceans and the associated inland mountain chains (Fig. 6.1). This flyway comprises of several important migration routes of waterbirds, most of which extend from the northernmost breeding grounds in Siberia to the southernmost nonbreeding grounds in West and South Asia, the Maldives and the British Indian Ocean Territory. The CAF Action Plan for the Conservation of Migratory Waterbirds and their Habitats (CMS 2006) encompasses about 30 countries of North Asia (the part of the Russian Federation from the Ural Mountains east to around the Kolyma River), Central Asia (Afghanistan, western parts of China, Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan and Uzbekistan), Southwest Asia (Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, the United Arab Emirates and Yemen), Transcaucasia (Armenia, Azerbaijan and Georgia) and South Asia (Bangladesh, Bhutan, India, Maldives, Myanmar, Nepal, Pakistan, Sri Lanka and the British Indian Ocean Territory). This is the shortest of the major flyways, lying largely north of the equator. At least 279 waterbird populations of 182 species inhabit this flyway, including long- and medium-distance migrant wader, duck and goose populations that breed in the central Siberian Arctic, boreal Russia and the Central Asian steppe, as well as short-distance migrants and residents that breed south of the Hindu Kush – Himalayan mountain chain.

Under current population delimitations, there is considerable overlap between migratory populations of the CAF and both the West Asian-East African Flyway and the East Asian-Australasian Flyway (Iverson et al. 2011). Staging areas where long- and medium-distance migrants stop during migration to rest and refuel are poorly known, but are believed to be inland freshwater and saline wetlands in Central Asian countries.

The breeding ranges of the critically endangered Slender-billed Curlew *Numenius tenuirostris* and the near threatened Asian Dowitcher *Limnodromus semipalmatus* are largely restricted to the region although their nonbreeding ranges overlap with adjoining flyways (Mundkur 2005). Some examples among threatened waders that occur in the CAF and other flyways include the critically endangered Spoon-billed Sandpiper *Calidris pygmaea*, Spotted Greenshank *Tringa guttifer* and Great Knot *Calidris tenuirostris* (both endangered), Eurasian Curlew *Numenius arquata* (near threatened) and Black-tailed Godwit *Limosa limosa* (near threatened). All of these waders depend on intertidal mudflats and are threatened by habitat loss and degradation (Chowdhury et al. 2011).

Cranes are among the most threatened group globally, and Central Asian cranes are no exception (Harris and Mirande 2013). Of the two populations of the critically endangered Siberian Crane *Leucogeranus leucogeranus*, the central population that used to spend the nonbreeding period in Bharatpur in India has not been recorded for the last decade (Rahmani and Islam 2008), while the western population that used to migrate to Iran is now down to one individual (Tavakoli 2014). It appears that these populations have been pushed to the brink of extinction by the loss and degradation of wetlands that were indispensable for the birds either as stopover sites during migration or as nonbreeding areas (Meine and Archibald 1996). These wetlands have been lost by diversion of water for human use, agricultural development, the development of oil fields and other human utilization. Illegal shooting of birds during migration might also have contributed to their demise (Meine and Archibald 1996), and for the western population, hunting on passage and during the nonbreeding period is still hindering recovery of the population (BirdLife International 2016). Similarly, Central Asian ducks and geese are negatively affected by loss of wetland habitats and hunting. One example is the Lesser White-fronted Goose *Anser erythropus* that used to be a common species only a century ago, but became globally threatened with extinction and is currently listed as vulnerable (Jones et al. 2008). Among storks, the Greater Adjutant *Leptoptilos dubius* used to be widespread and common across south and mainland Southeast Asia, but its number has drastically declined, and the species now qualifies as endangered. Breeding success has been extremely poor in Assam and many breeding sites have been abandoned (BirdLife International 2016).

6.3 Waterbird Habitat in South Asia

South Asia has a high diversity of natural freshwater and brackish wetland habitats ranging from high-altitude bogs and lakes, marshes and riverine wetlands to brackish salt flats, as well as coastal mudflats, mangroves, coral reefs and atolls. These, along with rice fields and other artificial wetlands, provide suitable breeding habitat for many resident species and local migrants. They also serve as feeding or resting areas for birds that breed further north in temperate and arctic Asia and only spend the nonbreeding period in the region. Some migratory waterbirds, such as Bar-headed Goose *Anser indicus*, Ruddy Shelduck *Tadorna ferruginea*, Brown-headed Gull *Larus brunnicephalus* and Common Tern *Sterna hirundo*, use high-altitude wetlands as breeding grounds and migrate into plains and coastal areas during the nonbreeding period.

Across the region, several major river systems, like the Indus, Ganga, Brahmaputra, Narmada, Cauvery, Irrawaddy, etc., have extensive floodplains and associated temporary lakes, beels and marshes that provide a range of habitats for millions of migratory and resident ducks, geese and other waterbirds. Most of these river systems have been transformed over the years through the construction of barrages and dams along with the creation of extensive canal systems that are used for irrigating rice, wheat and other crop fields and to provide water supply to urban and rural communities. Several of these areas are also important for waterbirds, although intensive pesticide use may be detrimental to the survival and productivity of the birds. In addition, the extensive network of small ponds and tanks across southern India and Sri Lanka provides valuable habitat for a large number of waterbirds. The seasonal and highly productive shallow saline wetlands of the Great Rann of Kachchh that is shared by India and Pakistan and the Little Rann of Kachchh and brackish Sambhar Lake in India support large numbers of waterbirds (BirdLife International 2016).

A variety of intertidal wetlands on the extensive coastline between Pakistan and Myanmar provide important habitat to migratory waders, gulls and terns and other coastal waterbird species. Some areas of international importance include the Indus Delta in Pakistan; the gulfs of Kachchh, Khambhat and Mannar; Chilika and Pulicat lagoons; Mahanadi and other major estuaries and associated mangrove forests of India; coastal lagoons and estuaries in Sri Lanka; the mudflats of the Sundarbans shared by India and Bangladesh; and deltas, mangroves and intertidal mudflats found on islands and along the coast of Bangladesh and Myanmar. The islands and atolls in Lakshadweep, the Maldives and the British Indian Ocean Territory provide habitat for a number of migratory wader, gull and tern species.

6.4 Migration Routes

The main migration routes of waterbirds to South Asia are dictated by the chain of mountains from the Hindu Kush in the west to the Himalayas across the north and east that serve as a physical barrier for many species. These mountains force many birds to choose a route over the lowlands in the west and east or between mountain passes. For instance, ruddy shelducks avoid flying at very high altitudes and cross over the Sikkim region between Nepal and Bhutan that provides a narrow corridor of slightly lower mountains (Newman et al. 2012; Palm et al. 2015). However, satellite telemetry studies have demonstrated that some geese (e.g. bar-headed goose (Kalra et al. 2011; Bishop et al. 2015)) and crane species (e.g. common crane *Grus grus* (Meine and Archibald 1996) and demoiselle crane *Anthropoides virgo* (Kanai et al. 2000)) are well adapted to fly across the Himalayas, capable of travelling at and above 5000 m.

6.5 State of Knowledge on Waterbirds

Sparked by the rich avian diversity, there has been an interest to study the distribution, breeding and ecology of waterbirds since the time of the British rule in the region. Nowadays, in most countries research activities are conducted by universities, research institutions, non-governmental organizations and individuals. In India, the Bombay Natural History Society, established in 1883, has the largest collection of bird specimens in the region and a long history of bird research. The study of migratory waterbirds routes in the South Asian region was pioneered in India in the late 1950s as part of a regional initiative in collaboration with the World Health Organization to investigate the possible role of birds in the dissemination of diseases linked with arthropod-borne viruses (Balachandran 1998). These studies have continued in India, particularly during 1980–1990, when research on the ecology of important wetlands [Keoladeo National Park (KNP) in Bharatpur, Rajasthan state in North West India and Point Calimere Sanctuary (PCS) on the coast of Tamil Nadu and a few other field stations] provided valuable information on the migratory habitat use of waterbirds, as well as more detailed ecological studies on the Siberian crane and several wader species. Large-scale bird-marking activities across the country allowed for identification of the breeding grounds and migration routes of the common teal *Anas crecca* (Ambedkar and Daniel 1990) and a range of other species (Rahmani and Islam 2008).

The use of satellite telemetry in migration studies started in the early 1990s, when two bar-headed geese were tracked north to China from Bharatpur (Javed et al. 2000) and common cranes were tracked from Bharatpur to Kazakhstan (Higuchi et al. 1994). The spread of highly pathogenic avian influenza H5N1 strain to bar-headed geese and other waterbirds in 2005 in China led to extensive research into the migratory routes and strategies of a number of waterbird species in Asia. Bar-headed goose, ruddy shelduck, northern pintail *Anas acuta*, northern shoveler *Spatula clypeata*, Pallas's gull *Larus ichthyaetus* and other species have been tracked from India, Bangladesh and Nepal, as well as from their breeding grounds, particularly in Mongolia and China (Muzaffar et al. 2008; Pawar et al. 2009; Iverson et al. 2011; Newman et al. 2012). This, complemented by large-scale colour marking of birds at breeding and nonbreeding grounds, has further improved our knowledge of movements and connectivity (Kasambe et al. 2008). Improved standardizations of techniques for capture and marking have been crucial in obtaining reliable data (Balachandran 2002; FAO 2007).

Breeding, moulting, staging and nonbreeding locations, as well as distances travelled by migratory birds and variation in migration behaviour, have been identified through analyses of stable isotope ratio in feathers (Bridge et al. 2014) and attaching small geolocators to birds (Bridge et al. 2013), although these techniques are still to be widely used in South Asia.

A recent publication *Waterbirds of India* (Gopi and Hussain 2014) provides a valuable synthesis of state of knowledge and ecology of a variety of waterbirds and their conservation needs. The *Handbook on Indian Wetland Birds and their*

Conservation (Kumar et al. 2005) provides a useful overview of the status of migratory and resident waterbirds in India.

6.6 Status and Monitoring of Waterbirds

Monitoring of waterbirds across the region has been undertaken through a number of programmes, most notably the Asian Waterbird Census (AWC). This census was initiated in 1987 in India, Pakistan and Sri Lanka under the name of Asian Waterfowl Census (van der Van 1987) and was later extended to other parts of South Asia, Southeast and East Asia and Australasia, coordinated by Wetlands International (Li et al. 2009). This volunteer-based programme made it possible to collect data on the distribution and abundance of waterbird species across the region, identify important wetlands and promote waterbird and wetland conservation. In the states of Andhra Pradesh and Kerala in south India, the programme has been undertaken diligently over the last decades, enabling more detailed data analyses that provided new knowledge about the distribution and changes in abundance of waterbirds (Pittie and Taher 2004; Nameer et al. 2014). The major aim of MigrantWatch, another citizen science programme initiated in 2007, is to gather information on the migration of birds, including waterbirds across the Indian subcontinent. It has generated useful data on the timing of migration of species (MigrantWatch Team 2013). Nevertheless, detailed information on the bulk of migratory waterbird distribution, abundance, and resource use is rudimentary at best (Urfi et al. 2005; Namgail et al. 2011) and provides opportunities for future research (Gopi 2014). There are severe knowledge gaps in other countries of the region too.

The annual Asian Waterbird Census and other national and local waterbird monitoring programmes provide data to feed into periodical updates of the estimates and trends of waterbird populations summarized in the Waterbird Population Estimates (Li et al. 2009). This information is crucial to prioritize conservation actions, including the designation of Ramsar sites. However, compared to other flyways, up-to-date information of the status and trends of waterbirds in the CAF is limited (Mundkur 2005). In the most recent (fifth) edition of the Waterbird Population Estimates (Wetlands International 2012), most population status and trends for this flyway are of high uncertainty, and much of the available information for migratory bird populations found in South Asian countries is at least 10–15 years old. Lack of information is not only a problem for migratory species; the current status and trends of many resident populations are also poorly known. As shown below for a subset of birds (Asian migratory ducks and geese), not only rare, but also common species are declining (such as Baikal Teal *Sibirionetta formosa*), and our uncertainty across the range of population sizes is substantial. Population size estimates range widely both for species with large population sizes but also for the ones on the brink of extinction, such as the Baer's Pochard *Aythya baeri* and Scaly-sided Merganser *Mergus squamatus*, and for species with intermediate population size, such as Lesser White-fronted Goose or Swan Goose *Anser cygnoid* (Fig. 6.2).

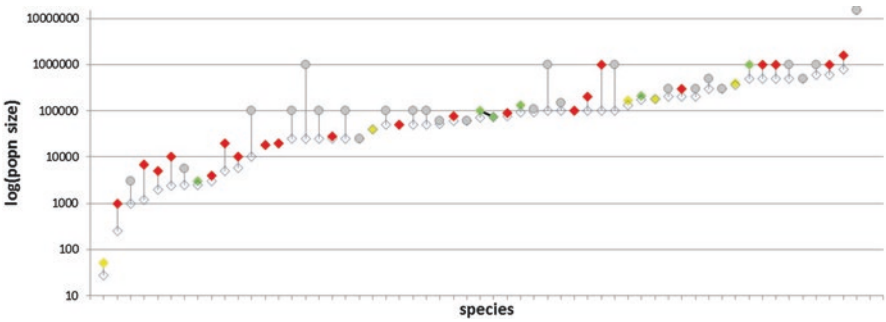


Fig. 6.2 An example to show population trends and numbers for Asian migratory ducks and geese based on the Waterbird Population Estimates 5th Edition (Wetlands International 2012). *Red dots* indicate declining, *yellow* stable and *green* increasing species. The length of the lines connecting minimum and maximum population estimates for a given species represents uncertainty about population size. *Grey dots* indicate no knowledge about population trends

It appears that in this flyway, very few migratory waterbird populations are increasing, while more (possibly around three to four times as many) are declining. This is reflected in the IUCN assessment of these species; currently many of them are globally threatened or near threatened. In fact, the highest numbers of threatened inland-breeding waterbirds in the world are in Eastern Asia, India and Kazakhstan (Williamson et al. 2013). Some of these threatened species exclusively or largely occur in this flyway, such as Sociable Lapwing *Vanellus gregarius*, which is critically endangered, and Black-necked Crane *Grus nigricollis* and Indian Skimmer *Rynchops albicollis*, both of which qualify as vulnerable (BirdLife International 2016). Other largely flyway-endemic waterbirds (Bar-headed Goose, Ibisbill *Ibidorhyncha struthersii* and Brown-headed Gull) still considered as of least concern, are facing many threats (Mundkur 2005; BirdLife International 2016).

6.7 Threats to Wetlands and Waterbirds

Major threats to migratory waterbirds in the CAF are loss and degradation of wetlands, exposure to pollutants and pesticides, invasive species, hunting and disease (CMS 2006; BirdLife International 2016). With the rapid rate of development in the South Asian region over the last decades, wetlands are under increasing threat from a wide range of large- and small-scale changes in landscapes, including changes to traditional agricultural and forestry practices. By converting and degrading wetlands, humans have made previously suitable habitats unsuitable for many organisms, including migratory waterbirds. Loss and degradation of wetlands are primarily caused by human activities, such as wetland reclamation, agriculture, pollution, land development, transportation corridors and energy production (Sutherland et al. 2012). In some countries, there is still an agricultural policy in place that encourages wetland drainage and the expansion of row-crop agriculture into grasslands (Hagy et al. 2014).

Many wetlands have suffered irrevocable changes through trophic cascades, triggered by the addition or removal of top predators and involving reciprocal changes in the relative populations of predator and prey through a food chain, which often results in dramatic changes in ecosystem structure and nutrient cycling (Estes et al. 2011). For example, in addition to the increase of fisheries in the Yangtze (Chen et al. 2011), the river's floodplain shows signs of local collapse of submerged macrophytes (Fox et al. 2011). There is a decrease in submerged vegetation, particularly tuber-producing *Vallisneria*, caused by introduction of intensive aquaculture. Changes in lake hydrology following construction of the Three Gorges Dam may also have adversely affected submerged vegetation productivity along the Yangtze River (Zhang et al. 2011), leading to a decline in the food source of the vulnerable swan goose that spends the nonbreeding season at Shengjin Lake.

Wind farms placed near wetlands have been reported to cause avian mortalities and to disrupt feeding and breeding behaviour of waterbirds and other species (Kumar et al. 2012; Prinsen et al. 2012). In addition, human development also accelerates effects of climate change, including increased occurrence of droughts or other natural disasters, such as earthquakes and tsunamis (Daryadel and Talaei 2014). Increasing pressures, particularly in the coastal areas due to recent, ongoing and planned urbanization, industrialization and port facilities across the region (e.g. along Gulfs of Kachchh and Khambhat in Gujarat, Uran in Maharashtra, Pulicat Lake in Andhra Pradesh in India and Sonadia Island in Cox's Bazaar in Bangladesh), as well as climate change-related effects, are negatively impacting intertidal mudflats and associated mangrove wetlands and coral reefs (Mathew et al. 2010; Prerna et al. 2015), resulting in reduction of the suitable habitats for migratory waterbirds, including the critically endangered Spoon-billed Sandpiper (Chowdhury et al. 2011).

Another major source of habitat degradation is pollution. Urban and industrial wastewater, agricultural activities, combustion of fossil fuels, mining and smelting, processing and manufacturing industries and solid waste disposal are major anthropogenic sources of pollution that affect the flora and fauna of wetlands. Some pollutants, such as mercury, bioaccumulate and biomagnify, meaning that the toxicant is increasingly accumulated in the tissues through the trophic levels and the effects on organisms are greater higher up the food chain, for example, in fish-eating birds (Eagles-Smith and Ackerman 2014). Reclaimed and cultivated wetlands have also been shown to contain considerable amounts of heavy metals (Ghabour et al. 2013). Animals congregate in wetlands to find water, food and shelter; therefore deleterious accumulations of persistent organic pollutants in small areas can potentially have broader effects on wildlife populations (Tran et al. 2014). Birds that feed in agricultural areas are often exposed to pesticides. Even though acutely toxic organophosphates are being phased out in many parts of the world, they are still used in some countries. Legal and illegal uses of organophosphates have resulted in poisonings, especially when birds consume treated seeds (Pain et al. 2004). Pesticide use in open rubbish dumps in India has led to several mortalities of greater adjutant (Lowe et al. 2000).

Increased nutrient input causes eutrophication and encourages nutrient-loving invasive alien plants (Kaushik and Gupta 2014). Compared to other habitat types, wetlands are disproportionally invaded by alien species: even though they only

Fig. 6.3 Pollution is common in many wetlands – here a Wood Sandpiper *Tringa glareola* is resting on a pile of plastic in an urban lake in Coimbatore, India (Photo by Judit Szabo)

cover 6% of the surface of the Earth, they host 24% of the most invasive species on the planet (Zedler and Kercher 2004). One of the most problematic species is water hyacinth *Eichhornia crassipes*, native to the Amazon basin, which now affects innumerable wetlands in over 50 countries, including in South Asia. This fast-growing invader restricts open water, impacts water flow, blocks sunlight from native aquatic plants and starves fish of oxygen (Lowe et al. 2000) and has negatively affected important waterbird habitats (Fig. 6.3).

In some regions, waterbirds are also frequently hunted for subsistence, as well as sport and the primary source of protein for humans (Kanstrup 2006). Although killing migratory waterbirds is officially banned in Bhutan, India and Nepal with legal provisions for hunting selected species in Afghanistan, Iran and Pakistan, illegal take of waterbirds is still a problem in many countries of the CAF, for instance, in Afghanistan (Ostrowski et al. 2008), India (Ahmed 1996; Ahmed and Rahmani 2002; Lahkar et al. 2013; Ramachandran 2014) and Iran (Tayefeh et al. 2011). Hunting decreases the population viability by killing birds directly, but it also causes substantial disturbance to the individuals not injured or killed. During breeding season, human disturbance increases nest trampling, jeopardizing successful breeding (Crossland et al. 2014).

Urban expansion also increases unauthorized access by people and feral animals to sensitive wetland areas, causing disturbance (Antos et al. 2007). Increasing anthropogenic disturbance and predation has been negatively affecting bar-headed geese breeding on the Mongolian Plateau (Batbayar et al. 2014).

Similar to other birds, waterbirds carry a range of viral, bacterial and fungal organisms, some of them manifesting in disease (Gogu-Bogdan et al. 2014; McCoy et al. 2016). Avian influenza has been an issue of increased regional and global concern, especially over the last decade, particularly since a large number of bar-headed geese and other waterbirds were affected by highly pathogenic avian influenza (H5N1) in 2005 in Qinghai Lake, China (Chen et al. 2005). Low-pathogenic forms of the avian influenza virus are often isolated from ducks, geese, swans, waders and gulls (FAO 2007). These low-pathogenic forms can sometimes mutate into highly pathogenic forms in poultry that can cause fatalities not only in domestic poultry but also in wild birds and humans. Even though highly pathogenic avian influenza (H5N1) has not been detected at the major wetland complexes in central or southern parts of Central Asia where many birds congregate and agriculture is most extensive (Iverson et al. 2011), it has been detected, or believed to have caused mortality of migratory waterbirds in India, Bangladesh, Nepal and Pakistan, as well as in Southeast and East Asia (Cappelle et al. 2014). The large scale and intensification of poultry production, including domestic ducks in wetlands in South Asia, facilitate transmission of low-pathogenic forms of the virus between wild and domestic birds and spillover of the highly pathogenic virus from domestic birds back to the wild. Routine and regular surveillance of wild birds can help in monitoring virus movements (Parvin et al. 2014; Hoque et al. 2015). In order to protect wild birds from the virus and minimize spillover and spillback, the poultry industry and relevant authorities need to enforce more stringent biosecurity measures at domestic poultry facilities.

6.8 Conservation and International Cooperation

Highly mobile organisms, such as waterbirds, have a complex migratory system, and therefore they pose a significant and complex conservation challenge. Typically, these species have population dynamics that require the use of multiple wetlands, but this aspect of their life history has often been ignored in planning for their conservation (Haig et al. 1998).

One way of conserving highly mobile species is protecting and managing the habitat they use during their annual cycle (Runge et al. 2014). In response to the increasing loss and degradation of wetlands, to prevent their further destruction, the Ramsar Convention on Wetlands was established in 1971 (Ramsar Convention Secretariat 2013). The Convention recognizes that wetlands need to be sustainably managed due to their important economic, cultural, scientific, biodiversity and recreational values. Key areas are designated and managed by the countries as Wetlands of International Importance ("Ramsar sites"). A wetland can qualify under various criteria of international importance (Ramsar Convention Secretariat 2013). Of these criteria, the ones most frequently used to identify sites important for waterbirds are Criterion 5 (sites that regularly support 20,000 or more waterbirds) or Criterion 6 (sites that regularly support 1% of the individuals in a population of one species or subspecies of waterbird). Additionally, Criterion 4 allows for the recognition of internationally important sites based upon the movement of significant numbers of birds through a site during migration (serving a critical staging function), while Criterion 2 can be used to identify sites regularly used by globally threatened species.

Under the criteria developed by BirdLife International, wetlands can also be recognized as Important Bird and Biodiversity Areas (IBAs) if they support significant numbers of globally threatened species, hold restricted-range species or have a high proportion (more than 1%) of a biogeographic population of a congregatory waterbird species or more than 20,000 waterbirds (BirdLife International 2016). Some of

Table 6.1 Summary of important sites for which waterbird counts have been provided by participants of the Asian Waterbird Census 1987–2007

Country	AWC sites	Ramsar sites	IBAs	Protected areas	Sites with >20,000 waterbirds	Number of sites meeting >1% criterion
Bangladesh	199	2	7	7	13	67
Bhutan	15	0	6	1	0	3
India	3,296	18	126	112	100	458
Maldives	2	0	0	0	0	0
Nepal	30	4	7	5	1	5
Pakistan	534	17	29	18	56	124
Sri Lanka	160	2	21	17	14	53

Source: Li et al. (2009)

the important wetlands in South Asia have already been designated as protected areas under national legislation and as Ramsar sites, while a large number are still not designated or adequately managed, although many have been identified as IBAs (Table 6.1).

It is particularly important to identify and protect "bottleneck" sites, areas where very high proportions of a population stop over or pass through. These include the main staging areas for common and demoiselle cranes, pelicans, ducks and geese in the mountain passes in the Hindu Kush; the lower section of the Himalayas between Nepal and Bhutan, through which a large number of waterbirds including bar-headed geese pass; and the eastern Himalayas (Choudhury 2000). Conservation of such key areas is essential if we wish to maintain the migration and the continued existence of these species. However, identification of important sites is often difficult, because characteristics of the bird species (cryptic, non-flocking or occurs in habitats difficult to count) or the site (found in areas that are difficult and expensive to access) limit collection of information and therefore data availability.

The Convention on the Conservation of Migratory Species of Wild Animals (CMS or Bonn Convention) with its Programme of Work on Migratory Birds and Flyways 2014–2023 (UNEP/CMS Secretariat 2014) and the Central Asian Flyway Action Plan (CMS 2006) provide a powerful basis for international cooperation for the conservation of migratory waterbirds and wetlands in the flyway. This Action Plan, adopted in New Delhi in 2005, aims to better protect waterbirds and their habitats in the CAF, based on sound ecological knowledge and by enhancing regional environmental cooperation among the CAF states. It calls for a wide range of actions at both flyway and national levels, including improved legislation for species, regulations on hunting, habitat management, training, education and awareness and species monitoring. In addition, it calls for establishment of a network of internationally important sites. Besides the CAF Action Plan that provides an overall framework for conservation action, recognizing the special needs of threatened species, a number of flyway-level conservation action plans have been developed. These plans prioritize research and conservation for Siberian crane (UNEP/CMS/ICF 2011), Eurasian Spoonbill

Platalea leucorodia (Triplet et al. 2008), Spoon-billed Sandpiper (Zöckler et al. 2010), Lesser Flamingo *Phoeniconaias minor* (Childress et al. 2008), White-headed Duck *Oxyura leucocephala* (Hughes et al. 2006), Ferruginous Duck *Aythya nyroca* (Robinson and Hughes 2006) and Sociable Lapwing (Sheldon et al. 2012). Proper implementation of these plans should achieve improvement in the status of these threatened species and also improve conditions for other waterbirds.

Along the CAF, the current network of protected areas and managed sites provides inadequate coverage for threatened and nonthreatened waterbirds (Williamson et al. 2013). The Western/Central Asian Site Network established under the CMS in 2007 (UNEP/CMS/ICF 2011) provides a framework for conservation of some of the important sites, although there is an urgent need to enhance the geographic coverage of the network to include many additional important sites in the whole of the South Asian region and the rest of the CAF and to improve their management. In addition to these conventions, the Convention on Biological Diversity (CBD), to which all countries in the region are signatories, provides a global mandate for the conservation of all biodiversity, including waterbirds (Secretariat of the Convention on Biological Diversity 2010) and should be more effectively used as a tool to promote international cooperation and conservation action for waterbirds and their wetland habitats.

6.9 Raising Awareness

It is important to involve local communities in conservation and encourage the wise use of wetlands (Bosselmann et al. 2008), balancing the needs of people and wild species. Raising awareness on the importance of wetland habitats and the threats to them is vital for their protection and continued existence. Involving local communities in coordinated training and large-scale monitoring can enhance people's awareness of wetlands and wetland birds. It is also important to enhance public knowledge of the situation and involvement in solutions, as well as to gain support from local and multinational organizations in order to support enactment and implementation of international protection measures (Szabo et al. 2016).

Many awareness-raising efforts, such as the annually held World Wetlands Day in February (promoted by the Ramsar Convention) and World Migratory Bird Day in May (promoted by the Convention on Migratory Species and the African-Eurasian Waterbird Agreement), are being actively observed by governments, NGOs assisted by local groups and communities in the region. These and other activities, such as the annual Flamingo Watch organized by the Bombay Natural History Society in India, raise awareness and local interest in migratory waterbirds and their conservation (Anonymous 2013). There is a need to increase such activities to educate and engage a wider audience in conservation actions.

Strategically located visitor centres can play a pivotal role in public education and awareness about wetlands and waterbirds (Do et al. 2015), and the region has a large number of centres operating at many national parks and sanctuaries, such as the KNP in Bharatpur, India. However, maintaining buffer zones between tourists and sensitive areas is very important to protect birds from human and other disturbances (Weston et al. 2009) particularly during times when birds are breeding and are the most vulnerable.

With increasing affluence in the region and the availability of high-quality equipment, there is a growing interest in bird photography. While photographing waterbirds can increase awareness and engagement with conservation, there is also the growing pressure from photographers as they can disturb feeding and resting birds, possibly negatively impacting their survival, migration and breeding potential. Similarly, wetland tourism can provide positive opportunities, but also pressures (Fernando et al. 2013), and there is a need to guide the development of these activities to ensure their impacts on waterbirds and wetlands are minimized.

6.10 Management Actions

For management to be effective, we need to understand what species use the habitat and how these interact to form ecosystems, the natural processes that sustain them and the threats to these processes (Chatterjee et al. 2008). Management of wetlands requires coordinated multisectoral planning and implementation to realize the needs of biodiversity conservation and local people (Mundkur 2005).

Habitat management is commonly used to maintain and enhance the value of seminatural habitats where natural processes no longer create suitable conditions for the desired species. Habitat restoration and creation are increasingly being used to expand ecologically important habitats in order to mitigate the impacts of human development. Modification of past management techniques and introduction of new ones can provide additional benefits. In wetlands, such techniques include the manipulation of water levels or the water quality, i.e. nutrient levels that are too high or too low, pH, pesticide residues or salinity (Ausden 2008). Other management actions for waterbirds can include the control of invasive alien plant or animal species or the temporary exclusion of grazing animals.

Creating a diverse and heterogeneous complex of wetlands will support more waterbird species than a single lake of the same total surface area (Sebastian-Gonzales and Green 2014). Tidal freshwater wetlands (Beauchard et al. 2013), as well as floodplains (Bartha et al. 2014) have been successfully restored. However, restoration might take a long time, for instance, in the case of salt marshes, it was estimated that 20 years was necessary to fully restore all ecological functions (Warren et al. 2002).

For some species, artificial wetlands are believed to partly compensate for the loss of natural wetlands (Márquez-Ferrando et al. 2014). For instance, saltpans are very important for migratory waders in India (Pandiyan et al. 2014). According to a study in Spain, larger species used saltpans during the northern winter and southward migration, while smaller species were still dependent on mudflats for feeding (Dias et al. 2014). When found close to natural habitats, even aquaculture ponds were able to provide alternative roosting and supplemental foraging habitat (Choi et al. 2014). Other studies found that alternative habitats were not satisfying the needs of waterbirds (Bellio et al. 2009), reinforcing that artificial wetlands provide only secondary habitat, while most species are dependent on natural wetlands (Li et al. 2013). Therefore maintaining natural wetlands is of great importance for the conservation of many bird species.

The monitoring of wildlife populations is essential if they, and the sites on which they depend, are to be managed and conserved effectively. Monitoring is also required to assess the fulfilment of objectives of the Ramsar Convention and the Convention on Migratory Species. However, as both time and resources available for conservation are finite, we need to prioritize actions and design monitoring schemes accordingly to identify sites or species for which conservation actions are most needed. For large-scale national monitoring schemes, it is necessary to collect and analyse count data at a range of spatial scales, relating population changes to established thresholds for conservation action (Greenwood et al. 1994).

Monitoring waterbird populations is also important in order to evaluate the success of restoration activities. For instance, breeding colonial waterbirds have been used as indicators to evaluate the success of adaptive management of river flows (Kingsford and Auld 2003). In the case of the Kissimmee River Restoration Project, egret, heron, duck and other waterbird species were integral components of the floodplain ecosystem before the river channel got straightened and deepened. However, after channelization these species have declined substantially. Restoration was expected to attract wading birds and waterfowl by reintroducing naturally fluctuating water levels, seasonal hydroperiods and historic vegetation communities (Cheek et al. 2014). The authors found that evaluating wetland restoration success by monitoring wading birds and waterfowl relative to historical conditions was a practical means to measure the return of ecological integrity to a system. However, this process relied on the availability of historical (reference) data. Cheek et al. (2014) advise that choosing species for monitoring that are of great interest to the public can be beneficial for communicating restoration goals and measures of success. However, restoration expectation targets should be formulated with multi-year running averages appropriate to the study site and study species to help buffer against climatic or other stochastic events that can significantly affect monitoring data across years and seasons.

The size and footprint of the human population keeps increasing. Humans compete for resources not only among themselves, but also with other living organisms. This is currently one of the biggest challenges for conservation. As climate change is expected to affect the distribution and availability of suitable wetland habitats, these sites need to be created for the future as well as for the present (Bellisario et al. 2014). However, protection and management do work, for example, waterbird species richness and abundance increased more rapidly in Ramsar wetlands than in non-designated wetlands (Kleijn et al. 2014). In addition, over 70% of threatened migratory ducks and geese are recorded in Ramsar sites; however, only 10% of threatened non-migratory ducks and geese are protected at the same level (Green 1996). The situation has not improved much in the last 20 years; looking at all 1,451 migratory bird species, currently only 9% of them are adequately covered by protected areas across all stages of their annual cycle (Runge et al. 2015).

6.11 Conclusions and Recommendations

The management of coastal and inland wetlands of southern Asia is of crucial importance for conservation of waterbirds of the Central Asian Flyway, especially as many of these species are rapidly declining in number and are already globally threatened. A wide range of actions are needed to enable their conservation and to restore populations. It is crucial to step up actions to identify species and sites at greatest risk and to collect, analyse and regularly share information to support their conservation and management. We need to strengthen the existing protected area network through designation and management of currently unprotected critically important sites. The protection and adequate management of these key breeding, stopover and nonbreeding sites can provide a functional ecological network for the conservation of threatened migratory waterbird species in the long term. These wetland habitats will need to be adaptively managed under the overarching influence of climate change and a rapidly growing human population that uses more and more resources. This will require greater efforts to mainstream and integrate priorities for waterbird and wetland management into national and local human development plans and programmes.

We need to increase monitoring efforts to learn about the status and trends of waterbird populations through strengthening national monitoring programmes. Monitoring data can provide the basis to assess the effectiveness of implementation of wetland management and restoration actions. Law enforcement needs to be strengthened as illegal harvest of waterbirds is a common practice in many countries where hunting is banned outside the legal hunting period and inside protected areas. It is necessary to monitor other direct and indirect threats to waterbirds and wetlands and to build local capacity to undertake the monitoring.

Raising awareness among the general public, government and corporate sectors and decision makers about the amazing beauty and value of waterbirds and wetlands is essential. Gaining wider and stronger interest from these stakeholders is crucial to provide the long-term basis and increase the support needed for species conservation and wetland management.

Conservation of migratory species is a matter of international concern, and its success is completely dependent on the development and implementation of conservation actions and enhanced cooperation between countries. Implementation of existing government commitments to international conservation frameworks (under Ramsar, CMS, CBD and others) is urgently needed to strengthen ongoing programmes and initiatives and to initiate new ones. Such efforts will need to be strongly supported by the public and corporate sectors to ensure the survival of migratory waterbirds and their wetland habitats in the Central Asian Flyway.

References

Ahmed A (1996) Live bird trade in northern India. TRAFFIC-India report, New Delhi

Ahmed A, Rahmani A (2002) Illegal trade of waterbirds. In: Rahmani AR, Ugra G (eds) Birds of wetlands and grasslands: proceedings of the Sálim Ali Centenary Seminar on Conservation of Avifauna of Wetlands and Grasslands. Bombay Natural History Society, Mumbai, pp 65–68

Ambedkar VC, Daniel JC (1990) A study of the migration of common teal *Anas crecca crecca* Linnaeus based on ring recoveries in India and U.S.S.R. J Bombay Nat Hist Soc 87(3):405–420

Anonymous (2013) Flamingo festival 2013. Mistnet 14(2):13

Antos MJ, Ehmke GC, Tzaros CL, Weston MA (2007) Unauthorised human use of an urban coastal wetland sanctuary: current and future patterns. Landscape Urban Plan 80:173–183

Ausden M (2008) Habitat management for conservation: a handbook of techniques, Techniques in Ecology and Conservation, vol USA. Oxford University Press, Oxford

Balachandran S (1998) Studies on the movement and population structure of Indian avifauna. Phase I:1980–1986. Bird migration. Phase II: 1987–1992. Final Report. Bombay Natural History Society, Mumbai

Balachandran S (2002) Indian bird banding manual. Bombay Natural History Society, Mumbai

Bartha J, Vlad LM, Toma D, Toacă D, Cotiușcă-Zaucă D (2014) Rehabilitation and extension of wetlands within floodplains of embanked rivers. Environ Eng Manag J 13(12):3143–3152

Batbayar N, Takekawa JY, Natsagdorj T, Spragens KA, Xiao X (2014) Site selection and nest survival of the Bar-Headed Goose (*Anser indicus*) on the Mongolian Plateau. Waterbirds 37(4):381–393

Beauchard O, Jacobs S, Ysebaert T, Meire P (2013) Avian response to tidal freshwater habitat creation by controlled reduced tide system. Estuar Coast Shelf Sci 131:12–23

Bellio MG, Kingsford RT, Kotagama SW (2009) Natural versus artificial – wetlands and their waterbirds in Sri Lanka. Biol Conserv 142:3076–3085

Bellisario B, Cerfolli F, Nascetti G (2014) Climate effects on the distribution of wetland habitats and connectivity in networks of migratory waterbirds. Acta Oecol 58:5–11

Bibby C (2002) Why conserve bird diversity? In: Norris K, Pain DJ (eds) Conserving bird biodiversity: general principles and their application. Cambridge University Press, Cambridge

BirdLife International (2016) http://www.birdlife.org/datazone/home. Accessed 02 Aug 2016

Bishop CM, Spivey RJ, Hawkes LA, Batbayar N, Chua B, Frappell PB, Milsom WK, Natsagdorj T, Newman SH, Takekawa JY, Wikelski MC, Butler PJ (2015) The roller coaster flight strategy of bar-headed geese conserves energy during Himalayan migrations. Science 347(6219):250–254

Boere GC, Stroud DA (2006) The flyway concept: what it is and what it isn't. In: Boere GC, Galbraith CA, Stroud DA (eds) Waterbirds around the world. Stationery Off, Edinburgh, pp 40–47

Bosselmann K, Engel R, Taylor P (2008) Governance for sustainability – issues, challenges, successes. IUCN Environmental Policy and Law Paper No. 70., Gland

Bridge ES, Kelly JF, Contina A, Gabrielson RM, MacCurdy RB, Winkler DW (2013) Advances in tracking small migratory birds: a technical review of light-level geolocation. J Field Ornithol 84(2):121–137

Bridge ES, Kelly JF, Xiao X, Takekawa JY, Hill NJ, Yamage M, Ul Haque E, Islam MA, Mundkur T, Erciyas Yavuz K, Leader P, Leung CYH, Smith B, Spragens KA, Vandegrift KJ, Hosseini PR, Saif S, Mohsanin S, Mikolon A, Islam A, George A, Sivananinthaperumal B, Daszak P, Newman SH (2014) Bird migration and avian influenza: a comparison of hydrogen stable isotopes and satellite tracking methods. Ecol Indic 45:266–273

Cappelle J, Zhao D, Gilbert M, Nelson MI, Newman SH, Takekawa JY, Gaidet N, Prosser DJ, Liu Y, Li P, Shu Y, Xiao X (2014) Risks of avian influenza transmission in areas of intensive free-ranging duck production with Wild Waterfowl. Ecohealth 11:109–119

Chatterjee A, Phillips B, Stroud DA (2008) Wetland Management Planning. A guide for site managers. WWF, Wetlands International, IUCN & Ramsar Convention

Cheek MD, Williams GE, Bousquin SG, Colee J, Melvin SL (2014) Interim Response of Wading Birds (Pelecaniformes and Ciconiiformes) and Waterfowl (Anseriformes) to the Kissimmee River Restoration Project, Florida, U.S.A. Restor Ecol 22(3):426–434

Chen H, Smith GJD, Zhang SY, Qin K, Wang J, Li KS, Webster RG, Peiris JSM, Guan Y (2005) H5N1 virus outbreak in migratory waterfowl. Nature 436:191–192

Chen J, Zhou L, Zhou B, Xu R, Zhu W, Xu W (2011) Seasonal dynamics of wintering waterbirds in two shallow lakes along Yangtze River in Anhui Province. Zool Res 32(5):540–548

Childress B, Nagy S, Hughes B (2008) International single species action plan for the conservation of the Lesser Flamingo (*Phoeniconaias minor*). CMS Technical Series No. 18, AEWA Technical Series No. 34., Bonn

Choi C, Gan X, Hua N, Wang Y, Ma Z (2014) The habitat use and home range analysis of Dunlin (*Calidris alpina*) in Chongming Dongtan, China and their Conservation Implications. Wetlands 34:255–266

Choudhury A (2000) The birds of Assam. Gibbon Books & WWF, Guwahati

Chowdhury SU, Foysal M, Das DK, Mohsanin S, Abu Diyan MA, Alam ABMS (2011) Seasonal occurrence and site use by shorebirds at Sonadia Island, Cox's Bazar, Bangladesh. Wader Study Group Bull 118(2):77–81

CMS (2006) Central Asian Flyway Action Plan for the Conservation of Migratory Waterbirds and Their Habitats. CMS Secretariat, Bonn. Available online at http://www.cms.int/sites/default/files/document/CAF_action_plan_e_0.pdf

Crossland AC, Sitorus AW, Sitorus AS (2014) Land use change impacts shorebird habitat at an important site for Javan Plover *Charadrius javanicus* and Sanderling *Calidris alba* in Java, Indonesia. Stilt 66:30–36

Daryadel E, Talaei F (2014) Analytical study on threats to wetland ecosystems and their solutions in the Framework of the Ramsar Convention. Int J Soc Manag Econ Bus Eng 8(7):1970–1980

Davidson NC (2014) How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar Freshw Res 65:934–941

Dias MP, Lecoq M, Moniz F, Rabaca J (2014) Can human-made Saltpans represent an alternative habitat for shorebirds? Implications for a Predictable Loss of Estuarine Sediment Flats. Environ Manag 53:163–171

Do Y, Kim JY, Lineman M, Kim D-K, Joo G-J (2015) Using internet search behavior to assess public awareness of protected wetlands. Conserv Biol 29(1):271–279

Eagles-Smith CA, Ackerman JT (2014) Mercury bioaccumulation in estuarine wetland fishes: evaluating habitats and risk to coastal wildlife. Environ Pollut 193:147–155

Estes JA, Terborgh J, Brashares JS, Power ME, Berger J, Bond WJ, Carpenter SR, Essington TE, Holt RD, Jackson JBC, Marquis RJ, Oksanen L, Oksanen T, Paine RT, Pikitch EK, Ripple WJ, Sandin SA, Scheffer M, Schoener TW, Shurin JB, Sinclair ARE, Soulé ME, Virtanen R, Wardle DA (2011) Trophic downgrading of planet earth. Science 333:301–306

FAO (2007) Wild birds and avian influenza: an introduction to applied field research and disease sampling techniques, Animal Production and Health Manual, vol 5. FAO, Rome

Fernando S, Jothirathna L, Shariff NM (2013) Wetland ecotourism in Sri Lanka: Issues and challenges. Geografia Malaysian J Soc Space 9(4):99–105

Figuerola J, Green AJ (2002) Dispersal of aquatic organisms by waterbirds: a review of past research and priorities for future studies. Freshw Biol 47:483–494

Fox AD, Cao L, Zhang Y, Barter MA, Zhao M, Meng F, Wang S (2011) Declines in the tuber-feeding waterbird guild at Shengjin Lake National Nature Reserve, China – a barometer of submerged macrophyte collapse. Aquat Conserv 21:82–91

Galbraith CA, Jones T, Kirby J, Mundkur T (2014) A review of migratory bird flyways and priorities for management. CMS Technical Series No. 27 UNEP/CMS Secretariat. Bonn

Ghabour TK, Rahim IS, Morgan RS (2013) Heavy metals status of some wetlands of Egypt. J Appl Sci Res 9(7):4345–4350

Gogu-Bogdan M, Damoc I, Pall E, Niculae M, Spinu M (2014) Wild birds as potential vectors for pathogen dissemination on migration routes in the Danube Delta Wetlands. Int J Curr Microbiol App Sci 3(5):890–897

Gopi G (2014) Waterbird research and conservation in India: an overview. In: Gopi GV, Hussain SA (eds) Waterbirds of India, ENVIS Bulletin, vol 16. Wildlife Institute of India, Dehra Dun, pp 26–29

Gopi GV, Hussain SA (eds) (2014) Waterbirds of India, ENVIS Bulletin, vol 16. Wildlife Institute of India, Dehra Dun

Green AJ (1996) Analysis of globally threatened Anatidae in relation to threats, distribution, migration patterns, and habitat use. Conserv Biol 10(5):1435–1445

Green AJ, Elmberg J (2014) Ecosystem services provided by waterbirds. Biol Rev 89:105–122

Greenwood JJD, Baillie SR, Gregory RD, Peach WJ, Fuller RJ (1994) Some new approaches to conservation monitoring of British breeding birds. Ibis 137(S1):S16–S28

Hagy HM, Yaich SC, Simpson JW, Carrera E, Haukos DA, Johnson WC, Loesch CR, Reid FA, Stephens SE, Tiner RW, Werner BA, Yarris GS (2014) Wetland issues affecting waterfowl conservation in north America. Wildfowl 4:343–367

Haig SM, Mehlman DW, Oring LW (1998) Avian movements and wetland connectivity in landscape conservation. Conserv Biol 12(4):749–758

Harris DJ, Mirande C (2013) A global overview of cranes: status, threats and conservation priorities. Chinese Birds 4(3):189–209

Higuchi H, Nagendran M, Sorokin AG, Ueta M Satellite tracking of common cranes *Grus grus* migrating north from Keoladeo National Park, India. In: Proceedings of the International Symposium "The Future of Cranes and Wetlands". Tokyo, 1994. pp 26–31

Hoque MA, Burgess GW, Cheam AL, Skerratt LF (2015) Epidemiology of avian influenza in wild aquatic birds in a biosecurity hotspot, North Queensland, Australia. Prev Vet Med 118:169–181

Hughes B, Robinson JA, Green AJ, Li ZWD, Mundkur T (2006) International single species action plan for the conservation of the White-headed Duck *Oxyura leucocephala*. CMS Technical Series No. 13, AEWA Technical Series No. 8., Bonn

Iverson SA, Gavrilov A, Katzner TE, Takekawa JY, Miller TA, Hagemeijer W, Mundkur T, Sivananinthaperumal B, Demattos CC, Ahmed LS, Newman SH (2011) Migratory movements of waterfowl in Central Asia and avian influenza emergence: sporadic transmission of H5N1 from east to west. Ibis 153:279–292

Javed S, Takekawa JY, Douglas DC, Rahmani AR, Kanai Y, Nagendran M, Choudhury BC, Sharma S (2000) Tracking the spring migration of a Bar-headed Goose (*Anser indicus*) across the Himalaya with satellite telemetry. Global Environ Res 4(2):195–206

Jones T, Martin K, Barov B, Nagy S (2008) International single species action plan for the conservation of the western palearctic population of the Lesser White-fronted Goose *Anser erythropus*. AEWA Technical Series No. 36. Bonn

Kalra M, Kumar S, Rahmani AR, Khan JA, Belal SM, Khan AM (2011) Satellite tracking of Bar-Headed Geese *Anser indicus* Wintering in Uttar Pradesh, India. J Bombay Natur Hist Soc 108(2):79–94

Kanai Y, Minton J, Nagendran M, Ueta M, Auyrsana B, Goroshko O, Kovshar AF, Mita N, Suwal RN, Uzawa K, Krever V, Higuchi H (2000) Migration of demoiselle cranes in Asia based on satellite tracking and fieldwork. Global Environ Res 4:143–153

Kannan V, Pandiyan J (2013) A review on the spot-billed pelican *Pelecanus philippensis* literature. Front Biol 8(3):333–352

Kanstrup N (2006) Sustainable harvest of waterbirds: a global review. In: Boere GC, Galbraith CA, Stroud DA (eds) Waterbirds around the world. The Stationery Office, Edinburgh, pp 98–106

Kasambe R, Joshi A, Shivkar A, Niranjan M, Bhusari S (2008) Resighting of Mongolian tagged bar-headed Geese *Anser indicus* in India. Newsl Birdwatchers 48(2):24–25

Kaushik TK, Gupta RC (2014) Deteriorating rural ponds: a threat to overseas migratory wetland birds in Kurukshetra suburbs, Haryana, India. J Appl Natur Sci 6(2):570–577

Kingsford RT, Auld K (2003) Waterbird breeding in the Macquarie Marshes – a guide to river health. National Parks and Wildlife Service (NSW)

Kleijn D, Cherkaoui I, Goedhart PW, van der Hout J, Lammertsma D (2014) Waterbirds increase more rapidly in Ramsar-designated wetlands than in unprotected wetlands. J Appl Ecol 51(2):289–298

Kumar A, Sati JP, Tak PC, Alfred JRB (2005) Handbook on Indian wetland birds and their conservation. Zoological Survey of India, Ministry of Environment and Forests, Government of India

Kumar SR, Ali AMS, Arun PR (2012) Impact of wind turbines on birds: a case study from Gujarat, India. Sci J Environ Sci 1(1):9–20

Lahkar D, Sahu HK, Rahman S (2013) Status of the waterbirds of Sunabeda Wildlife Sanctuary, Odisha, India. Indian Forester 139(10):906–911

Li D, CHen S, Lloyd H, Zhu S, Shan K, Zhang Z-W (2013) The importance of artificial habitats to migratory waterbirds within a natural/artificial wetland mosaic, Yellow River Delta, China. Bird Conserv Int 23(02):184–198

Li D, Wei Z, Bloem A, Delany S, Martakis G, Quintero JO (2009) Status of waterbirds in Asia – results of the Asian Waterbird Census: 1987–2007. Wetlands International, Kuala Lumpur

Lowe S, Browne M, Boudjelas S, De Poorter M (2000) 100 of the world's worst invasive alien species: a selection from the global invasive species database. Invasive Species Specialist Group, Auckland

Márquez-Ferrando R, Figuerola J, Hooijmeijer JCEW, Piersma T (2014) Recently created man-made habitats in Doñana provide alternative wintering space for the threatened Continental European black-tailed godwit population. Biol Conserv 171:127–135

Mathew G, Jeyabaskaran R, Prema D (2010) Mangrove ecosystems in India and their conservation. In: Meenakumari B, Boopendranath MR, Edwin L, Sankar TV, Gopal N, Ninan G (eds) Coastal fishery resources of India – conservation and sustainable utilisation. Society of Fisheries Technologists, New Delhi, pp 186–196

McCoy KD, Dietrich M, Jaeger A, Wilkinson DA, Bastien M, Lagadec E, Boulinier T, Pascalis H, Tortosa P, Le Corre M, Dellagi K, Lebarbenchon C (2016) The role of seabirds of the Iles Eparses as reservoirs and disseminators of parasites and pathogens. Acta Oecol 72:98–109

McInnes RJ (2013) Recognizing ecosystem services from wetlands of International Importance: an example from Sussex, UK. Wetlands 33:1001–1017

Meine CD, Archibald GW (1996) The cranes – status survey and conservation action plan. IUCN, Gland

MigrantWatch Team (2013) MigrantWatch 2007–2012. Unpublished report. Citizen Science Programme, National Centre for Biological Sciences

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: current state and trends. Island Press, Washington

Mundkur T (2005) Building bridges for migratory waterbird conservation in the Central Asian Flyway. Indian Birds 1(2):46–47

Murray NJ, Ma Z, Fuller RA (2015) Tidal flats of the Yellow Sea: a review of ecosystem status and anthropogenic threats. Austral Ecol 40:472–481

Muzaffar SB, Takekawa JY, Prosser DJ, Douglas DC, Yan B, Xing Z, Hou Y, Palm EC, Newman SH (2008) Seasonal movements and migration of Pallas's Gulls *Larus ichthyaetus* from Qinghai Lake, China. Forktail 24:100–107

Nameer PO, Praveen J, Tom G, Sreekumar B, Sashikumar C (2014) Long term population trends of waterbirds in Kerala (1987–2014). In: Gopi GV, Hussain SA (eds) Waterbirds of India, ENVIS Bulletin, vol 16. Wildlife Institute of India, Dehra Dun, pp 44–69

Namgail T, Takekawa JY, Sivananinthaperumal B, Areendran G, Sathiyaselvam P, Mundkur T, McCracken T, Newman SH (2011) Ruddy Shelduck *Tadorna ferruginea* home range and habitat use during the non-breeding season in Assam, India. Wildfowl 61:182–193

Navedo JG, Hahn S, Parejo M, Abad-Gómez JM, Gutiérrez JS, Villegas A, Sánchez-Guzmán JM, Masero JA (2015) Unravelling trophic subsidies of agroecosystems for biodiversity conservation: food consumption and nutrient recycling by waterbirds in Mediterranean rice fields. Sci Total Environ 511:288–297

Newman SH, Hill NJ, Spragens KA, Janies D, Voronkin IO, Prosser DJ, Yan B, Lei F, Batbayar N, Natsagdorj T, Bishop CM, Butler PJ, Wikelski M, Balachandran S, Mundkur T, Douglas DC, Takekawa JY (2012) Eco-virological approach for assessing the role of wild birds in the spread of Avian influenza H5N1 along the Central Asian flyway. PLoS One 7(2):e30636

Ostrowski S, Rajabi AM, Noori H (2008) Birds and mammals in Dasht-e Nawar, Afghanistan: occurrence and hunting pressure, 2007 surveys. Unpublished report. Wildlife Conservation Society, New York

Pain DJ, Gargi R, Cunningham AA, Jones A, Prakash V (2004) Mortality of globally threatened Sarus cranes *Grus antigon* from monocrotophos poisoning in India. Sci Total Environ 326:55–61

Palm EC, Newman SH, Prosser DJ, Xiao X, Ze L, Batbayar N, Balachandran S, Takekawa JY (2015) Mapping migratory flyways in Asia using dynamic Brownian bridge movement models. Mov Ecol 3(3):1–10

Pandiyan J, Naresh B, Nagarajan R (2014) Temporal variations of shorebirds and benthic community, traditional saltpans of east coast of southern India. Int J Pure Appl Zool 2(1):14–25

Parvin R, Kamal AHM, Haque ME, Chowdhury EH, Giasuddin M, Islam MR, Vahlenkamp TW (2014) Genetic characterization of highly pathogenic H5N1 avian influenza virus from live migratory birds in Bangladesh. Virus Genes 49:438–448

Pawar S, Pande SA, Jamgaonkar A, Koratkar S, Pal B, Raut S, Nanaware M, Ray K, Chakrabarti A, Kode S, Thite V, Khude M, Randive S, Basu A, Pawashe A, Ponkshe A, Pandit PS, Deshpande P (2009) Avian influenza surveillance in wild migratory, resident, domestic birds and in poultry in Maharashtra and Manipur, India, during avian migratory season 2006–2007. Curr Sci 97(4):550–554

Peng S (1984) Pest control methods in ancient Chinese agriculture. Agr Archaeology 2:266–268

Péron G, Ferrand Y, Leray G, Gimenez O (2013) Waterbird demography as indicator of wetland health: the French-wintering common snipe population. Biol Conserv 164:123–128

Pittie A, Taher S (2004) Mid-winter waterfowl census in Andhra Pradesh: 1987–1996. BSAP, Hyderabad

Prerna R, Naidu VS, Sukumaran S, Gajbhiye SN (2015) Observed changes in extent of mangroves and coral reefs in southern Gulf of Kachchh over ten years using principal component analysis and geo-spatial techniques: a case study. J Coast Conserv 19(3):257–267

Prinsen HAM, Smallie JJ, Boere GC, Pires N (2012) Guidelines on how to avoid or mitigate impact of electricity power grids on migratory birds in the African-Eurasian Region. AEWA Conservation Guidelines No. 14, CMS Technical Series No. 29, AEWA Technical Series No. 50, CMS Raptors MOU Technical Series No. 3, Bonn

Rahmani AR, Islam MZ (2008) Ducks, geese and swans of India: their status and distribution. Indian Bird Conservation Network; Bombay Natural History Society; Royal Society for the Protection of Birds and BirdLife International. Oxford University Press, Oxford

Ramachandran R (2014) Impacts of hunting on the community structure of wetland avifauna in a human dominated landscape in Tamil Nadu, India., Unpublished Thesis submitted to the Tata Institute of Fundamental Research. Mumbai; National Centre for Biological Research, Bengaluru

Ramsar Convention Secretariat (2013) The Ramsar convention manual: a guide to the convention on wetlands (Ramsar, Iran, 1971), 6th edn. Ramsar Convention Secretariat, Gland

Robinson JA, Hughes B (2006) International single species action plan for the conservation of the Ferruginous Duck *Aythya nyroca*. CMS Technical Series No. 12, AEWA Technical Series No. 7., Bonn

Runge CA, Martin TG, Possingham HP, Willis SG, Fuller RA (2014) Conserving mobile species. Front Ecol Environ 12(7):395–402

Runge CA, Watson JEM, Butchart SHM, Hanson JO, Possingham HP, Fuller RA (2015) Protected areas and global conservation of migratory birds. Science 350(6265):1255–1258

Sebastian-Gonzales E, Green AJ (2014) Habitat use by waterbirds in relation to pond size, water depth, and isolation: lessons from a restoration in southern Spain. Restor Ecol 22(3):311–318

Secretariat of the Convention on Biological Diversity (2010) Global Biodiversity Outlook 3. Montreal, Canada

Sheldon RD, Koshkin MA, Kamp J, Dereliev S, Donald PF, Jbour S (2012) International single species action plan for the conservation of the Sociable Lapwing (*Vanellus gregarius*). CMS Technical Series No. 28, AEWA Technical Series No. 47., Bonn

Suh J (2014) Theory and reality of integrated rice–duck farming in Asian developing countries: a systematic review and SWOT analysis. Agr Syst 125:74–81

Sundar KSG, Subramanya S (2010) Bird use of rice fields in the Indian Subcontinent. Waterbirds 33 (Special Publication 1):44–70
Sutherland WJ, Alves JA, Amano T, Chang CH, Davidson NC, Finlayson CM, Gill JA, Gill RE Jr, Gonzalez PM, Gunnarsson TG, Kleijn D, Spray CJ, Székely T, Thompson DBA (2012) A horizon scanning assessment of current and potential future threats to migratory shorebirds. Ibis 154:663–679
Szabo JK, Choi C-Y, Clemens RS, Hansen BD (2016) Conservation without borders – solutions to address migratory shorebird declines in the east Asian-Australasian flyway. Emu 116:215–221
Tavakoli EV (2014) A Siberian Crane wintering in Iran in 2013/2014. Newsletter of Crane Working Group of Eurasia 13:180 pp
Tayefeh FH, Zakaria M, Amini H, Ghasemi S, Ghasemi M (2011) Breeding waterbird populations of the islands of the northern Persian Gulf, Iran. Podoces 6(1):49–58
Tran T, Barzen JA, Choowaew S, Engels JM, Duong VN, Nguyen AM, Inkhavilay K, Kim S, Rath S, Gomotean B, Le XT, Aung K, Nguyen HD, Nordheim R, Lam HST, Moore DM, Wilson S (2014) Persistent organic pollutants in wetlands of the Mekong Basin: U.S. Geological Survey Scientific Investigations Report 2013–5196
Triplet P, Overdijk O, Smart M, Nagy S, Schneider-Jacoby M, Karauz ES, Pigniczki C, Baha El Din S, Kralj J, Sandor A, Navedo JG (2008) International single species action plan for the conservation of the Eurasian Spoonbill *Platalea leucorodia*. AEWA Technical Series No. 35., Bonn
UNEP/CMS Secretariat (2014) Resolution 11.4: programme of work on migratory birds and flyways. Adopted by the Conference of the Parties at its 11th Meeting (Quito, 4–9 November 2014). United Nations Environment Programme (UNEP)/Convention on Migratory Species (CMS), Bonn
UNEP/CMS/ICF (2011) Conservation measures for the Siberian Crane, Technical Report Series, vol 23, Fifth edn. UNEP/CMS Secretariat, Bonn
Urfi AJ, Sen M, Kalam A, Meganathan T (2005) Counting birds in India: methodologies and trends. Curr Sci 89(12):1997–2003
van der Van J (1987) Asian waterfowl 1987. Midwinter bird observations in some Asian countries. IWRB, Slimbridge
Warren RS, Fell PE, Rozsa R, Brawley AH, Orsted AC, Olson ET, Swamy V, Niering WA (2002) Salt marsh restoration in connecticut: 20 years of science and management. Restor Ecol 10(3):497–513
Weston MA, Antos MJ, Glover HK (2009) Birds, buffers and bicycles: a review and case study of wetland buffers. Vic Nat 126(3):79–86
Wetlands International (2012) Waterbird population estimates, Fifth edn. Wetlands International, Wageningen
Williamson L, Hudson M, O'Connell M, Davidson NC, Young R, Amano T, Székely T (2013) Areas of high diversity for the world's inland-breeding waterbirds. Biodivers Conserv 22:1501–1512
Zedler JB, Kercher S (2004) Causes and consequences of invasive plants in wetlands: opportunities, opportunists, and outcomes. Crit Rev Plant Sci 23:431–452
Zhang Y, Cao L, Barter MA, Fox AD, Zhao M, Meng F, Shi H, Jiang Y, Zhu W (2011) Changing distribution and abundance of Swan Goose *Anser cygnoides* in the Yangtze River floodplain: the likely loss of a very important wintering site. Bird Conserv Int 21(01):36–48
Zöckler C, Syroechkovskiy EE, Bunting G (2010) International single species action plan for the conservation of the Spoon-billed Sandpiper (*Eurynorhynchus pygmeus*), Technical Report Series, vol 23. BirdLife International Asia Division, Tokyo CMS Secretariat, Bonn, Germany

Foraging Ecology of Aquatic Birds: Implications for Conservation Intervention and Suggestions for Future Research

7

Abdul Jamil Urfi

Abstract

India's rich diversity of water-dependent birds includes more than 200 species of which 37 are listed as threatened. Modern bird conservation science depends upon accurate information on the diet, ecology, and foraging behavior of threatened species, and therefore, it is important to take stock of the research on foraging ecology of these birds. The same is reviewed here along with an outline of developments in foraging ecology worldwide. This paper flags out a number of areas for future research such as ingesting contaminants (particularly pesticides and other toxins) along with food, impacts of invasive ichthyofauna, etc., and discusses the conservation aspects of aquatic birds in the context of monsoon-dependent, multiple use wetland landscapes. An effort is made to attempt a pan-Asian perspective and ideas for future research are enumerated.

Keywords

Aquatic birds • Ecology • Foraging • Monsoon

7.1 Introduction

Birds are a conspicuous element of aquatic bodies and the subject of considerable popular interest. The involvement of hundreds of amateur birdwatchers in bird counting events such as the "Asian Waterfowl Census" (Scott and Rose 1989; Li et al. 2009) and, on a global level, the focus on aquatic birds providing ecosystem services (Green and Elmberg 2013) – a concept which gained popularity after the initiation of the "Millennium Ecosystem Assessment (MEA)" project – are a case in

A.J. Urfi (✉)
Department of Environmental Studies, University of Delhi, New Delhi 110007, India
e-mail: ajurfi@rediffmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_7

Table 7.1 A summary of wetland/aquatic taxa among Indian birds

Family	Group names	Total number of taxa	Number of threatened taxa	Broad diet
Dendrocygnidae	Whistling ducks	2	0	M
Anatidae	Ducks, swans, geese	36	8	M, P
Alcedinidae	Kingfisher	4	1	F, M
Halcyonidae	Kingfisher	6	1	F, M
Cerylidae	Kingfisher	2	0	F
Gruidae	Cranes	4	3	C, M, H
Heliornithidae	Masked finfoot	1	1	C
Rallidae	Crake, rail, coot	15	1	C, M, H
Scolopacidae	Woodcock, snipe, godwit, whimbrel, curlew, redshank, sandpiper, greenshank, dowitcher, tattler, turnstone, knot, sanderling, stint, ruff, phalarope, dunlin, curlew sandpiper	34 (approx)	6	C, M
Rostratulidae	Painted-snipe	1	0	M
Jacanidae	Jacanas	2	0	M
Charadriidae	Oystercatcher, ibisbill, stilt, avocet, plover, dotterel, lapwing	22 (approx)	2	C, M
Glareolidae	Crab plover, pratincole	7	1	C, M
Laridae	Skimmer, gull, tern	33	3	F, M
Podicipedidae	Grebe	5	0	F, M
Anhingidae	Darter	1	1	F
Phalacrocoracidae	Cormorant	3	0	F
Ardeidae	Egret, heron, bittern	19	1	F, C
Phoenicopteridae	Flamingo	2	1	P, M
Threskiornithidae	Ibis	4	1	C, M
Pelecanidae	Pelican	3	2	F
Ciconiidae	Stork	8	4	F, C

The column under total number of taxa includes both migratory and resident species but excludes rare/accidental ones. The column under broad diet includes fish eating (F), carnivorous birds which eat invertebrates, mollusk, etc., but excludes fish-eating species (C), planktivorous (P), herbivore birds which consume aquatic or other vegetation (H), and species which consume a mixed diet (M)
Source: Ali and Ripley (1987) and BirdLife International (2001)

point. Meanwhile, recent studies on birds in limnological context (Kerekes and Pollard 1994; Hansen and Kerekes 2006) reemphasize on their strong role in aquatic food webs and ecosystem dynamics.

India has a rich diversity of water-dependent birds (Ali and Ripley 1987). Of approximately 214 species of interest (excluding the pelagic birds, passerines, and raptors), about 37 are threatened (Table 7.1) due to a variety of factors (BirdLife International 2001). In order to formulate conservation strategies for different species, knowledge about their diet, foraging ecology, ecosystem dynamics, and the environmental factors influencing food availability are important. In a global context, foraging ecology is a strong area of research, particularly in Western Europe, America, and Australasia, where extensive research programs have unraveled interesting ecological relationships between wetland birds and various biotic and abiotic features of their habitats, especially during migration (Ens et al. 1990; Blomert et al. 1996). These studies have paved the way for improved conservation intervention along scientific lines (e.g., Colwell 2010; Boere and Piersma 2012). Elaborate modeling exercises have also been undertaken to predict the impact of anticipated sea-level rise on wader populations following reduction of their foraging habitats (e.g., Goss-Custard et al. 1994). Research has to be conducted on India's extensive coastline; several large and significant inland wetlands, many of which have been declared as Ramsar sites; and its rich diversity of aquatic birds, particularly by research departments of colleges, universities, and other academic institutions (Urfi 2015).

7.1.1 Definitions

Aquatic/wetland birds: Strictly speaking, no birds are aquatic in the manner of fishes or other water-dwelling animals. While all birds are essentially terrestrial, those forms that are known to inhabit wetlands (shallow) and other (aquatic/deeper) waterbodies, at major stages of their life cycle, are included in the present discussion though the terms are sometimes used interchangeably in the text.

Aquatic/wetland taxa: A taxa (say family) which has at least one sub-taxa (species) known to be significantly dependent upon wetlands or waterbodies.

7.1.2 Broad Theoretical Considerations

In the context of birds, the centrality of food and foraging, *viz.*, nutrient content, calorific intake, procurement, availability, and harvesting of prey, can hardly be overemphasized. Largely, inspired by ideas initially proposed by David Lack (1968), ecologists have developed the "food availability-breeding time" hypothesis, which occupies a central position in ornithology and behavioral ecology. In the context of birds, food availability per se is a much more interesting factor in their timing of reproduction, as compared to the other category of warm-blooded vertebrates, i.e., mammals, where milk production requires only a certain minimum quantity of food on which the adults feed (Dawson 2002). In the case of birds however, which feed their young ones on food more or less as it is, i.e., without any processing or predigestion (with some exceptions), the food supply has to be both abundant and constant. Since peaks of food abundance tend to be very short in nature and confined only to certain seasons, the breeding seasons of birds are consequently also highly localized temporally. Thus, while birds have the capacity to disperse over fairly large geographical areas, when it comes to breeding they tend to remain restricted only to certain localities that mostly lie in the vicinity of constant and abundant food supplies. Secondly, since most birds lack the necessary structures to cut down food objects to smaller sizes, adaptations of the bill (and correspondingly feet and other structures) often dictate where they forage, i.e., the “patch.” Finally, a living bird does not exist in isolation since it influences and is influenced by its immediate environment. It responds to energy flows therein and to ecosystem functioning (Lampert and Sommer 2007) and so these factors also have to be taken into consideration.

7.2 Foraging Ecology

While the items of food/prey consumed by aquatic birds are of central concern, forming the basis of much of our understanding of aquatic food webs, it is important from our point of view to also highlight certain other relevant concepts. Thus, in order to fully appreciate the importance of foraging ecology in the overall context of bird habitats, we need to embed our discussion in the broad theoretical framework of behavioral ecology (Kushlan 1978; Krebs and Davies 1984), which is attempted in an elementary fashion in this section.

The most relevant concept is that of optimal foraging theory (OFT), first proposed in the mid-1960s by American ecologists MacArthur, Eric Pianka, and J M Emlen (Stephens et al. 2007). Among the issues which OFT addresses is the question of diet, i.e., what decisions does a solitary forager make when presented by a range of prey sizes, with different nutritional values. As far as wetland birds are concerned, one of the landmark field studies was by Goss-Custard (1977) on the Common Redshank (*Tringa totanus*). In several studies, the data from field observations on an “optimal forager” appears to be at variance from the model predictions, providing us with an opportunity to identify the constraints, which had previously not been suspected, in the animal’s behavioral repertoire. Second-type questions which OFT often addresses, especially in the context of central place foragers, are related to decisions about how long to stay in a (foraging) patch and how large should be the load size. This is done by taking into consideration the distance, generally a surrogate for energy expenditure for foraging flights, between the central place (usually the nest) and foraging patch.

Taking ideas from OFT into account, a number of interesting questions can be asked in the context of foraging ecology of aquatic birds. At the patch level, the question of how long to forage and what prey to select can be dictated by several factors because certainly, not everything available in a patch can be harvested by the bird, principally due to the limitations imposed by the specialized morphology of its trophic apparatus and ancillary structures. Since a host of factors are involved at the patch level, the situation is essentially complex. Availability of food/prey, its density (functional response relationship), the behavior of prey, and its movements within the patch in relation to biotic and abiotic factors (particularly temperature) can play a role in influencing food intake. Besides a host of social factors such as the density of conspecifics that affects the degree of kleptoparasitism and interference (Goss-Custard 1980) and dominance hierarchies on the basis of age, sex at the patch can also play a crucial role (Goss-Custard et al. 1994) by mostly depressing the intake rate of a solitary forager. From a broader, ecosystem perspective (Gere and Andrikovics 1992; Scheffer et al. 2006; Mooij et al. 2007), the quantities (biomass) of food removed and nutrients (by way of droppings) recycled, the possible role of aquatic birds in dispersal of spores or seeds of animals and plants (Kristiansen 1996), and influencing the structure of aquatic communities (Hurlbert and Chang 1983; Blomert et al. 1996) are also relevant.

7.3 Foraging Adaptations

At a general level, wetland birds possess interesting adaptations of feet and bill, depending upon their mode of foraging and location of food resources. Since most of them are detailed in standard ornithology texts (e.g., Brooke and Birkhead 1991), we shall take up only a few cases here for the purpose of illustration. Adaptations of legs include those for swimming, wading at different depths of water in the littoral zone, etc. Cormorants are said to be "self-propelled pursuit divers," and their feet and wet-able plumage play an important role in their foraging activity. Studies have shown that length of legs dictates the depth up to which shorebirds can wade into the water (Weller 1999). The feet of raptors in aquatic habitats are adapted for grasping prey available in water. The bills are adapted to the mode of foraging, *viz.*, visual or tactile. The bill of herons is specially adapted for spearing fish. One of the most interesting adaptations is that of the skimmers which scoop out the prey while skimming over the surface of water. Adaptations in the eye have evolved for a variety of different reasons and none is more interesting than the presence of red oil droplets, with colored carotenoid pigments, in the cone of retinas, especially in the case of birds like gulls, terns, and herons, which have to locate their prey through an air-water interface (Ziegler and Bischof 1993). Overall, the shape of the bill has been the subject of considerable interest, and ornithologists are puzzled over questions such as why does the curlew (*Numenius*) have a decurved bill (Davidson et al. 1986), why does the openbill (*Anastomus*) have a gap between the mandibles (Ali and Ripley 1987), why is the avocet (*Recurvirostra*) bill upturned, etc.

At a behavioral level, several interesting patterns have been recorded among waterbirds. While many species tend to be solitary foragers, some others (notably pelican) use social foraging methods. In view of the tremendous variations in foraging behaviors, a number of terms such as "sit and wait predator" (herons, kingfisher), "pursuit predators" (raptors, cormorants), "search predators", "perch predators," etc., are in use. Most of these terms are self-explanatory and require no further elaboration. At the foraging ground, different species remain largely segregated, each specialized in procuring specific types of food/prey (Fig. 7.1), though there can be overlaps. In broad terms, the littoral, pelagic, and deeper zones are utilized in separate ways by different birds (Weller 1999). For sympatric forms,

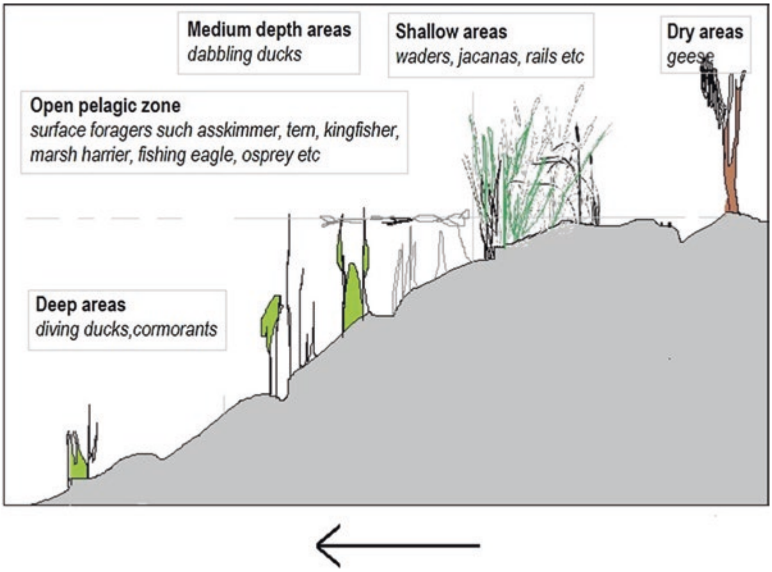


Fig. 7.1 Schematic diagram to depict the utilization of different strata of a wetland by different types of aquatic birds. The *arrow* depicts increasing depth (Adapted from Weller 1999)

which may utilize the same patch, even small variations in the dimensions of the trophic apparatus (and body size) lead to a separation in terms of their foraging activity, spatially. Thus, they can all coexist at the foraging patch without actually competing with one another (Sodhi 1992; Mahendiran and Urfi 2010; Borah et al. 2012).

7.4 Birds in the Ecosystem Context

An important aspect which we need to concern ourselves is birds in the context of their ecosystems, i.e., an investigation into how individual birds or populations impact energy flows in their environment, besides eutrophication, nutrient cycling, and, indirectly, the structure of aquatic communities (Gere and Andrikovics 1992; Kristiansen 1996; Scheffer et al. 2006). In this regard, resident species of colonial waterbirds or the heronry birds have received most attention, which is not surprising considering that their droppings are highly concentrated in the surrounding waters and can be sampled easily for chemical analysis (see Urfi 2011a for discussion).

7.4.1 Hydrological Cycles and Birds

Across much of Asia, the chief driver of the life cycles of aquatic organisms, particularly plankton that form the foundation of aquatic food chains, is the monsoon.

Much natural history data are collected on the relationships between food cycles of wetlands and the response, chiefly in terms of nesting of birds (Ali and Vijayan 1983; Ali and Ripley 1987; Naik and Parasharya 1987; Sankhala 1990; Urfi 2011a, b). Thus, the monsoon triggers the reproduction cycles of plankton, which have been lying in a dormant stage as spores or resting eggs throughout the summer (Tonapi 1980). Following the rains as the plankton populations grow, the fishes in rivers and lakes spawn and produce fry in large numbers (Urfi 2011c), providing the prey base for fish-eating birds. Of course, the effects of the monsoon on the food cycles of birds vary from species to species. For example, in the case of the Asian openbill (*Anastomus oscitans*) which breeds in June in various parts of north India, after the first monsoon showers, its principal prey, the apple snail (*Pila globosa*), emerges from aestivation and a situation of food abundance is created (Ali and Ripley 1987). However, the painted stork (*Mycteria leucocephala*) which in the same region breeds toward the end of August does so because by that time the fishes have spawned and reached fingerling stage. But now, since the monsoon patterns are themselves believed to be under threat due to global climate change (Goswami et al. 2006; Wills and Bhagwat 2009), there is an urgent need for further systematic studies in this regard, particularly how such changes will affect the food cycles of wetland birds. With respect to wetland birds from Asia, long-term studies on their response to climate change are an area full of opportunities and challenges.

7.4.2 Threats and Conservation

In the Asian region, almost 20% of threatened bird species are inhabitants of wetlands (BirdLife International 2001). In many cases, habitat loss or its transformation is a major factor posing a threat for several birds in Asia (Rahmani (2012). At several inland and coastal sites, the conversion of natural wetlands into fish and shrimp farms has led to a significant reduction of food supplies for birds (Nagarajan and Thiyagesan 2006). Rapid urbanization, besides negatively impacting upon local hydrology and drainage, is causing loss of wetlands at an alarming pace, all across the region. However, interestingly, in some cases the effects of habitat transformation have resulted in an increase in waterbird populations, seemingly by increasing foraging opportunities for them. A classic example in this regard is that of the "Indira Gandhi Nahar Pariyojana" (IGNP), an irrigation canal that traverses through western Rajasthan, Western India, quite close to the international border. Due to seepage from the canal, ponds and other wetlands have sprung up on the sides of the canal, which have started attracting aquatic birds in large numbers (Rahmani 1997; Idris et al. 2009).

7.4.2.1 Pesticides and Toxins Ingested with Food

Linked to the question of foraging are issues of what else do the aquatic birds ingest along with food. This is of high relevance in today's context because most waterbodies are severely contaminated by toxins, pesticides, and heavy metals, which get bioaccumulated and biomagnified as they travel up the food chain. They culminate in lethal levels in the bodies of top-level carnivorous predators, particularly raptors and fish-eating birds. Pesticides directly affect the birds, causing in behavioral abnormalities and at times mortalities. In areas in and around the Keoladeo National Park (KNP) in Rajasthan state of Western India, water samples were shown to contain extremely high levels of pesticides (Muralidharan and Jayakumar 2012). Several bird mortalities were also recorded from the adjacent agricultural fields. Since most pesticides are neurotoxic, one of the visible effects of pesticide poisoning is changes in the motor behavior of organisms after consuming contaminated food.

7.5 Recent Research Trends Across Asia

7.5.1 Southeast Asia

In Southeast Asia, ornithologists have been quite active in terms of documenting food habits of coastal and other wetland birds. The fact that the Asian Wetland Bureau (AWB) and other agencies have been headquartered in Malaysia could have contributed toward facilitating greater interest in aquatic birds and studies on their food and foraging. Just an examination of all issues of *Forktail*, the journal of the Oriental Bird Club (starting from volume 1, 1986, uptill volume 30, 2014) reveals interesting studies on waders (Bijlsma and De Roder 1986; McWhirter 1987; Mundkur 1991), stork, heron, etc. (Swennen and Marteijn 1987; Indrawan et al. 1993; Allen 1996; Tyler 2005), merganser and crakes (Moller 1992; Zhengjie and Zhengjie 1998). Of course, focusing on only one source has its own limitations, because field workers would be publishing in other periodicals too, but for the present purpose, it serves to provide an idea of the pace of research activity with respect to the study of the food and foraging behavior of aquatic birds (Urfi 2015).

7.5.1.1 India

Much of the earliest information on the food of Indian waterbirds emanates from an interest in sport, especially during the British period. Summaries on the diet of various species, often based on gut-content analysis, are provided in the popular treatise, such as Ali and Ripley (1987). One particular study on the food habits of birds of the Sundarbans, 24-Parganas District of West Bengal (Mukherjee 1969, 1971a, b, 1974, 1975), conducted in India after its independence is exemplary. To find out if there had been any significant additions to the earlier body of knowledge, after the publication of the abovementioned treatise, a recent literature survey was conducted, the details of which are described in Urfi (2015). Limiting the secondary literature search to articles in peer-reviewed journals (and excluding PhD thesis, project reports, and notes published in non-refereed periodicals), only 15 studies could be located. As shown in Fig. 7.2, the majority of the studies (>50%) were on stork, cormorant, herons, and their allies. Studies on the food of waterfowl, waders, and kingfisher were just spread over 02–03 papers only.

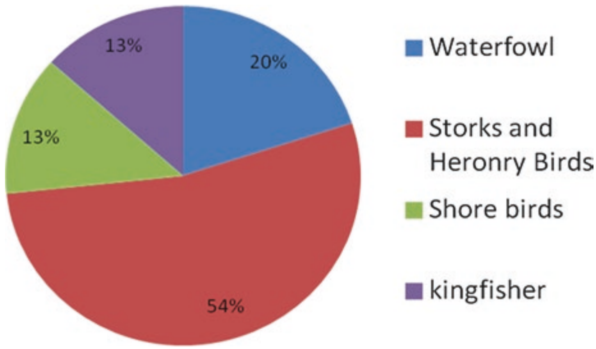


Fig. 7.2 An analysis of 15 studies on different species of aquatic birds published in peer-reviewed journals post 1987 from India. For an explanation of the cutoff date, see text. The studies included are Shah and Qadri (1988), Middleton (1993), Middleton and Van der Valk (1987) (waterfowl), Kalam and Urfi (2008), Urfi (2011a, b), Maheswaran and Rahmani (2002), Naik and Parasharya (1987), Sodhi (1992), Mukherjee and Borad (2001), Mahendiran and Urfi (2010) (storks, cormorant, heron and their allies), Urfi (2002), Sampath (1990) (shorebirds), Jior and Dhindsa (1988) and Borah et al. (2012) (Kingfisher)

7.6 Conclusions and Recommendations

The worldwide trend in foraging ecology has been dominated by studies firmly embedded in ecological theory. But in the Indian context, we find virtually no detailed study that had employed modern model building approaches to test simple patch or diet models. Also, there seems to be an overall paucity of studies on the diet of aquatic birds, through either direct methods or onsite sampling for potential prey. The general lack of interest among Indian investigators to combine theory and empirical work in so far as foraging ecology is concerned is perhaps not difficult to understand given that the trend during the 1970s and 1980s was largely that of gathering basic natural history data and channeling all energies for site-specific or species-specific conservation. While in the west, the formation of a special research groups such as the Wader Study Group added fillip to ecological studies, in India, academic institutions lagged in playing a strong role in developing ecological studies. However, while important advances were made in India, more studies with implications for conservation intervention are required. Some suggestions are enumerated below:

- Quantitative estimates of prey harvesting by wetland birds along with foraging ecology studies and documentation of diets of different species are required. Such studies can form the base for ecosystem modeling studies.
- No detailed scientific studies have been undertaken to assess the impact of invasive species of plants and animals (especially fishes) either on the aquatic communities or on the foraging ecology of birds. Detailed and scientific studies on this aspect can yield important insights about management.

- The role of birds in enrichment of waters by their droppings (especially in the case of heronry birds) and dispersal of seeds of aquatic plants and spores of organisms needs to be explored further.
- Studies on pesticide load in food and its impact on behavior and fitness of birds are required.

Acknowledgment *This chapter is in memory of Dr. Bhupathy Subramanian, principal scientist, a talented naturalist, and above all a very fine colleague, who tragically passed away in May 2014 while doing fieldwork in Agasthyamalai hills.* The ideas presented in this chapter were developed from a lead talk delivered by the author at the “2nd International Conference on Indian Ornithology” (ICIO-2013), organized by Sálim Ali Centre for Ornithology and Natural History (SACON) in November 2013. I thank the conference participants and particularly Dr. P. A. Azeez, Dr. Rajah Jaypal, (Late) Dr. S. Bhupathy, Dr. R. Nagarajan, and Dr. B. Anjan Kumar Prusty for their valuable comments and suggestions. I thank the University of Delhi, India, for funding my research under the schemes, “providing funds to university faculty” and DST Purse grant.

References

Ali S, Ripley SD (1987) Handbook of the birds of India and Pakistan together with those of Bangladesh, Nepal, Bhutan and Sri Lanka. Oxford University Press, Delhi

Ali S, Vijayan VS (1983) Hydrobiological (ecological) research at Keoladeo National Park, Bharatpur (first interim report). Bombay Natural History Society, Mumbai

Allen D (1996) Unusual feeding behaviour of black-faced spoonbills *Platalea minor*. Forktail 12:161–162

Bijlsma RG, De Roder FE (1986) Notes on Nordmann’s Greenshank *Tringa guttifer* in Thailand. Forktail 2:92–94

BirdLife International (2001) Threatened birds of Asia: the birdlife international red data book. BirdLife International, Cambridge

Blomert A-M, Ens B, Goss-Custard JD, Hulscher JB, Zwarts L (eds) (1996) Oystercatchers and their estuarine food supplies. Ardea 84A (special issue)

Boere GC, Piersma T (2012) Flyway protection and the predicament of our migrant birds: a critical look at international conservation policies and the Dutch Wadden Sea. Ocean Coast Manag. http://dx.doi.org/10.1016/j.ocecoaman.2012.05.019

Borah J, Ghosh M, Harihari A, Pandav B, Gopi GV (2012) Food-niche partitioning among sympatric kingfishers in Bhitarkanika mangroves, Odisha. J Bombay Nat Hist Soc 109:72–77

Brooke M, Birkhead T (1991) Cambridge encyclopedia of ornithology. Cambridge University Press, Cambridge, UK

Colwell MA (2010) Shorebird ecology, conservation, and management. University of California Press, California

Davidson NC, Townshend DJ, Pienkowski MW, Speakman JR (1986) Why do curlews *Numenius* have decurved bills? Bird Stud 33:61–69

Dawson A (2002) Photoperiodic control of the annual cycle in birds and comparisons with mammals. Ardea 90:355–367

Ens BJ, Piersma T, Wolff WJ, Zwarts L (eds) (1990) Homeward bound: problems waders face when migrating from the Banc D’Arguin Mauritania to their northern breeding grounds in spring. (special edition) Ardea 78(1/2)

Gere G, Andrikovics S (1992) Effects of waterfowl on water quality. Hydrobiologia 243–244:445–448

Goss-Custard JD (1977) Optimal foraging and the size selection of worms by redshank, *Tringia totanus*, in the field. Anim Behav 25:10–29

Goss-Custard JD (1980) Competition for food and interference amongst waders. Ardea 68:31–52

Goss-Custard JD, Caldow RWG, Clarke RT, Durell SEA, Urfi AJ, West A (1994) Consequences of habitat loss and change to populations of wintering migratory birds: predicting the local and global effects from studies of individuals. Ibis 137:S56–S66

Goswami BN, Venugopal V, Sengupta D, Madhusoodanan MS, Xavier PK (2006) Increasing trend of extreme rain events over India in a warming environment. Science 314:1442–1445

Green AJ, Elmberg J (2013) Ecosystem services provided by waterbirds. Biol Rev Camb Phil Soc 89(1):105–122. doi:10.1111/brv.12045

Hansen A, Kerekes J (eds) (2006) Proceedings. The 4th Conference of the Working Group on Aquatic Birds of the International Society of Limnology (SIL) "Limnology and Waterbirds 2003" Sackville, New Brunswick, Canada, August 3–7, 2003. (Developments in Hydrobiology). Hydrobiologia. 2006

Hurlbert SH, Chang CCY (1983) Ornitholimnology: effects of grazing by the Andean flamingo (*Phoenicoparrus andinus*). Proc Nat Acad Sci USA 80:4766–4769

Idris MP, Singh P, Johari S (2009) Impact assessment of the Indira Gandhi Canal on the Avifauna of the Thar Desert. In: Faunal ecology and conservation of the Great Indian Desert

Indrawan M, Lawler W, Widodo W, Sutandi (1993) Notes on the feeding behaviour of Milky Storks *Mycteria cinerea* at the coast of Indramayu, West Java. Forktail 8:143–144

Jior RS, Dhindsa MS (1988) Fish fry predation by white breasted and pied kingfishers at a nursery pond. J Bombay Nat Hist Soc 85:425–427

Kalam A, Urfi AJ (2008) Foraging behaviour and prey size of the painted stork (*Mycteria leucocephala*). J Zool (London) 274:198–204

Kerekes JJ, Pollard B (eds) (1994) Symposium Proceedings. Aquatic Birds in the Trophic Web of Lakes. Sackville, New Brunswick, Canada. Aug. 19–22, 1991. (Developments in Hydrobiology). vol 96, 524p. Hydrobiologia 279/280

Krebs JR, Davies NB (eds) (1984) Behavioural ecology: an evolutionary approach. Blackwell, London

Kristiansen J (1996) Dispersal of freshwater algae – a review. Hydrobiologia 336:151–157

Kushlan JA (1978) Feeding ecology of wading birds. National Audubon Society Research Report No. 7. In: Sprunt A, Ogden JC, Winckler S (eds) . National Audubon Society, New York

Lack D (1968) Ecological adaptations for breeding in birds. Chapman and Hall, London

Lampert W, Sommer U (2007) Limnoecology, 2nd edn. Oxford University Press, Oxford

Li ZWD, Bloem A, Delany S, Martakis G, Quintero JO (2009) Status of waterbirds in Asia. Results of the Asian waterbird census: 1987–2007. Wetlands International, Kuala Lumpur

Mahendiran M, Urfi AJ (2010) Foraging patterns and kleptoparasitism among three sympatric cormorants (*Phalacrocorax* spp.) from the Delhi region, North India. Hydrobiologia 638:21–28. doi:10.1007/s10750-009-0002-8

Maheswaran G, Rahmani AR (2002) Foraging behaviour and feeding success of the black-necked stork (*Ephippiorhynchus asiaticus*) in Dudwa national park, Uttar Pradesh, India. J Zool (London) 258:189–195

McWhirter DW (1987) Feeding methods and other notes on the spoon-billed sandpiper *Eurynorhynchus pygmaeus* in Okinawa. Forktail 3:60–61

Middleton BA (1993) Habitat and food preferences of geese overwintering in the Keoladeo National Park, Bharatpur, India. J Trop Ecol 8:181–193

Middleton B, Vander Valk AG (1987) The food habits of Greylag and Barheaded geese in the Keoladeo National Park India. Wildfowl 38:94–102

Moller E (1992) Feeding technique of a white-browed crake *Porzana cinerea*. Forktail 7:154–155

Mooij WM, Janse JH, Domis LNDS, Hulsmann S, Ibelings BW (2007) Predicting the effect of climate change on temperate shallow lakes with the ecosystem model PCLake. Hydrobiologia 584:443–454

Mukherjee AK (1969) Food-habits of water-birds of the Sundarban, 24-Parganas District, West Bengal, India. [Grebe. Cormorant, Darter]. J Bombay Nat Hist Soc 66(2):345–360
Mukherjee AK (1971a) Food-habits of water-birds of the Sundarban, 24- Parganas District, West Bengal. India-II. Herons and bitterns. J Bombay Nat Hist Soc 68(1):37–64
Mukherjee AK (1971b) Food-habits of water-birds of the Sundarban, 24- Parganas District, West Bengal. India- III. Egrets. J Bombay Nat Hist Soc 68(3):691–716
Mukherjee AK (1974) Food-habits of water-birds of the Sundarban, 24 Parganas District, West Bengal, India-IV. Stork, Teal, Moorhen and Coot. J Bombay Nat Hist Soc 71:188–200
Mukherjee AK (1975) Food-habits of water-bird of the Sundarban, 24 Parganas District West Bengal India-V. Lapwing, Sandpiper, Stint, Tern, kingfisher. J Bombay Nat Hist Soc 72(2):422–447
Mukherjee A, Borad CK (2001) Effects of waterbirds on water quality. Hydrobiologia 464:201–205
Mundkur T (1991) Prey items of the great thick-knee *Esacus recurvirostris*. Forktail 6:71–72
Muralidharan S, Jayakumar S (2012) Status of pesticide contamination in birds in India with special reference to threatened species. In: Rahmani AR (ed) Threatened birds of India – their conservation requirements. Bombay Natural History Society, Mumbai, BirdLife International and Royal Society for the Protection of Birds, Sandy
Nagarajan R, Thiyagesan K (2006) The effects of coastal shrimp farming on birds in Indian mangrove forests and tidal flats. Acta Zool Sin 52(Supplement):541–548
Naik RM, Parasharya BM (1987) Impact of the food availability, nesting-habitat destruction and cultural variations of human settlements on the nesting distribution of a coastal bird. *Egularis* in western India. J Bombay Nat Hist Soc 84:350–360
Rahmani AR (1997) The effect of Indira Gandhi Nahar project on the avifauna of the Thar Desert. J Bombay Nat Hist Soc 94:233–266
Rahmani AR (2012) Threatened birds of India and their conservation requirements. Bombay Natural History Society, Mumbai, BirdLife International and Royal Society for the Protection of Birds, Sandy
Sampath K (1990) Food of the spotted sandpiper *Tringa glareola* linn. J Bombay Nat Hist Soc 87:297
Sankhala K (1990) Gardens of God. The waterbird sanctuary at Bharatpur. Vikas Publishing House, New Delhi
Scott DA, Rose PM (eds) (1989) Asian waterfowl census 1989. Mid-winter waterfowl counts in Southern and Eastern Asia. IWRB, Slimbridge
Scheffer M, Van Geest GJ, Zimmer K, Jeppesen E, Søndergaard M, Butler MG, Hanson MA, Scott DA, Rose PM (eds) (1989) Asian waterfowl census 1989. Mid- winter waterfowl counts in southern and eastern Asia. IWRB, Slimbridge second-order effects on biodiversity in shallow lakes and ponds. Oikos 112:227–231
Scheffer M, Van Geest GJ, Zimmer K, Jeppesen E, Søndergaard M, Butler MG, Hanson MA, DeClerck S, De Meester L (2006) Small habitat size and isolation can promote species richness: second-order effects on biodiversity in shallow lakes and ponds. Oikos 112:227–231
Shah GM, Qadri MY (1988) Food of mallard, *Anas platyrhynchos* at Hokarsar wetland, Kashmir. J Bombay Nat Hist Soc 85:325–331
Sodhi NS (1992) Food niche relationships of five sympatric North Indian herons. Forktail 7:125–130
Stephens DW, Brown JS, Ydenberg RC (2007) Foraging: behavior and ecology. University of Chicago Press, Chicago
Swennen C, Marteijn ECL (1987) Notes on the feeding behaviour of the milky stork *Mycteria cinerea*. Forktail 3:63–66
Tonapi GT (1980) Fresh water animals of India (an ecological approach). Oxford & IBH, New Delhi
Tyler SJ (2005) Foraging techniques of the Chinese pond heron *Ardeola bacchus*. Forktail 21:165–166

Urfi AJ (2002) Waders and other wetland birds on Byet Dwarka Island, Gulf of Kutch, Western India. Wader Stud Group Bull 99:31–34

Urfi AJ (2011a) The foraging behavior of painted stork (*Mycteria leucocephala*): a review. Waterbirds 34:448–456

Urfi AJ (2011b) The painted stork: ecology and conservation. Springer, New York

Urfi AJ (2011c) Climate change and its impacts on Indian birds: monsoon phenology and monitoring heronry birds. Curr Sci 101:1140–1142

Urfi AJ (2015) Foraging ecology and conservation of waders along coast of India: need for detailed studies. Wader Stud 122(2):153–159. doi:10.18194/ws.00013

Weller MW (1999) Wetland birds. Habitat resources and conservation implications. Cambridge University Press, Cambridge

Wills KJ, Bhagwat SA (2009) Biodiversity and climate change. Science 326:806–807

Zhengjie Z, Zhengjie P (1998) The foraging behaviour of the scaly-sided Merganser *Mergus squamatus* in the Changbai mountains and Xiao Xingangling mountains of China. Forktail 14:76–77

Ziegler HP, Bischof H (eds) (1993) Vision, brain, and behavior in birds: a comparative review. MIT Press, Cambridge MA

Part III

Limnology, Bio-geochemical Issues and Hydrology

Hydrogeochemistry and Environmental Issues of the Wetlands of Kerala, Southwestern India

8

A. Krishnakumar, P. Saranya, and Revathy Das

Abstract

The geomorphic and geologic evolution of coastal lands of Southwest India is influenced by many local and regional factors, including changes in climate, sea level and local and regional tectonics in the late Quaternary period. The wetlands in Kerala State in Southwestern India, forming an interlacing network, act as an integral part of the socio-environmental frame of the state (Kerala) playing vital roles in the hydrological, biological and biogeochemical features of the environment. However, these systems were mismanaged due to lack of scientific data and proper appreciation of the ecosystem functions. During the recent years, there is a growing concern for conservation and management of the wetlands. This chapter provides some baseline data on the geochemical characteristics of the sediments and the water quality of four important wetlands in the state, namely, Vellayani Lake, Sasthamkotta Lake, Pookot Lake (lacustrine wetlands) and Ashtamudi Lake (estuarine wetland), and provides some insights into the need for their conservation.

Keywords

Hydro-geochemistry • Kerala • Pollution load index • Water quality index • Wetlands

A. Krishnakumar (✉) • P. Saranya • R. Das
Natural Resources and Environmental Management Group, ESSO- National Centre for Earth Science Studies (NCESS), Ministry of Earth Sciences (MoES), Government of India, Akkulam, Thiruvananthapuram 695 011, India
e-mail: drakrishnakumar@gmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_8

8.1 Introduction

India is very rich in wetlands and they have assumed considerable significance in recent years in the country with growing interest in them for their productive and retentive uses. But, the country is losing some of its prime wetlands rapidly due to biotic and anthropogenic interferences. In Kerala State, the total estimated wetland area is 160,590 ha, of which 119,714 ha is ‘inland wetlands’ and 40,876 ha ‘coastal wetlands’ (SAC 2011). The wetlands in the state in total spread over 4.13% of the state’s geographical area (SAC 2011). Kerala State, located in the southwestern part of India, has the imposing Western Ghats as the state’s eastern boundary with its western slopes merging with the midland plains and the western seacoast of the state. This provides an ideal topographic setting for development and sustenance of myriad forms of wetlands in this region (Padmalal et al. 2011). The 44 rivers that originate from the Western Ghats create and maintain almost all the major wetlands of the state.

The majority of wetlands of Kerala are brackish, although there are a few freshwater ones believed to have evolved during the Holocene (Padmalal et al. 2011). Considering their importance in sustaining the hydrodynamic regime and overall economic development of the region, three wetlands of Kerala, *viz*. Vembanad Lake, Ashtamudi Lake (brackish water) and Sasthamkotta Lake (freshwater), were designated as Ramsar Sites as per the Ramsar Convention. Ramsar Convention promotes the concept of ‘wise use’ that stands for ‘sustainable utilization’ for the benefit of human kind in a way compatible with the maintenance of natural properties of the ecosystem. During the recent decades, the emphasis on exploitation and modification for greater economic returns has caused much damage to many Indian wetlands. The major issues are high silt loads causing shrinkage of the waterbody, threat by agricultural chemicals, toxic effluents, insecticide and pesticide residues, domestic sewages, reduction in waterfowl and growth of water hyacinth, decline in fish production, heavy metal accumulation and so on (Unni 2002).

Not much systematic investigations have been carried out so far in evaluating/updating information regarding various freshwater environments in Kerala State for their proper maintenance and management or for sustainable utilization. Some geochemical studies of aquatic sediments have been taken up in the last few decades due to the growing awareness of environmental pollution and its impact on the ecosystem and its relation with ecological service delivery potential of wetlands. Surface sediments act both as sink and source for various kinds of environmental pollutants under different geochemical set-ups. Thus, sediments are often considered as indicators of environmental pollution. Lack of baseline information on various parameters that determines the health of these ecosystems is a major problem before the planners and decision makers for chalking out strategies for environmental management and conservation. Geochemical studies of aquatic sediments are of prime requirement for assessing the pollution load in terms of geochemical constituents and impact on the waterbody, since the sediments are in a complex dynamic relation with the overlying water: while the sediments affect the water chemistry, simultaneously being itself affected by that. In this background, this chapter discusses the hydro-geochemical characteristics of the lacustrine (Vellayani Lake, Sasthamkotta Lake, Pookot Lake) and estuarine (Ashtamudi Lake) wetlands of Kerala in their specific environmental context.

8.2 Lacustrine Wetlands of Kerala

Wetlands are the cradles of civilizations and culture, and they are integral part of the socio-environmental frame of a region. Many of the lacustrine wetlands of the state, such as Sasthamkotta, Vellayani and Pookot (Fig. 8.1), are heading towards degradation due to pollution from various sources and indiscriminate land reclamation. The basic details pertaining to the general profile and geographical delineation of these wetlands are presented in Table 8.1.

Sasthamkotta Lake is listed by the Government of India as a wetland of national importance. It was designated as Ramsar Site in 2002. Its depth varies from 2 to 14 m. A considerable portion of the catchment of the lake and adjacent hillocks are occupied by human settlements (Krishnakumar et al. 2005a) and under a variety of farming practices. This lake serves as source of drinking water to Kollam Municipality and suburbs supplied by the Kerala Water Authority. Recently it is reported that the lake is shrinking at an alarming rate owing to a number of reasons (Das and Krishnakumar 2015). Vellayani Lake, the second largest lacustrine system of Kerala (Table 8.1, Fig. 8.1), is located at the outskirts of Thiruvananthapuram City. The total water spread of the lake is 5.5 km^2. The lake varies in the depth from 2 to 8 m. The watershed of Vellayani Lake is also used for various agricultural activities (Krishnakumar et al. 2006). Pookot Lake, located at the suburbs of Kalpetta town in Wayanad district, is the third largest freshwater lake in the state (Table 8.1). The surroundings of the lake are dominated with thick vegetation.

Textural studies revealed that predominance of silt and clay with very little quantities of sand in Sasthamkotta Lake sediments (Table 8.2). The overall sediment dispersal pattern observed in the Vellayani Lake and Pookot Lake basin indicates intense siltation to which these freshwater basins are subjected. The relative concentrations of various chemical parameters in sediments are in the order OC > Fe > P > Mn > Pb > Cu > Cd in Sasthamkotta Lake and OC > Fe > P > Mn > Cu > Pb > Cd in Vellayani Lake and in Pookot Lake (Das and Krishnakumar 2015).

The physical, chemical and biological parameters of the water in the three wetlands such as odour, total dissolved solids, pH, nitrates, sulphates, chlorides, hardness, calcium and magnesium fall within the prescribed limits of Bureau of Indian Standards (BIS) (Table 8.3). The turbidity and iron values are slightly higher than prescribed standards for drinking water (BIS 2012). Various anthropogenic activities such as disposal of solid waste, household sewage, fertilizer residues and other chemicals seem to result in higher turbidity as observed in Sasthamkotta and Vellayani Lakes (Krishnakumar et al. 2005a). It is observed that phytoplankton community are growing rapidly in the Pookot Lake thereby depleting the DO (Dissolved Oxygen) content. The average values and ranges observed for different parameters, *viz*. pH, turbidity, nitrate, iron, phosphate and faecal coliform contents

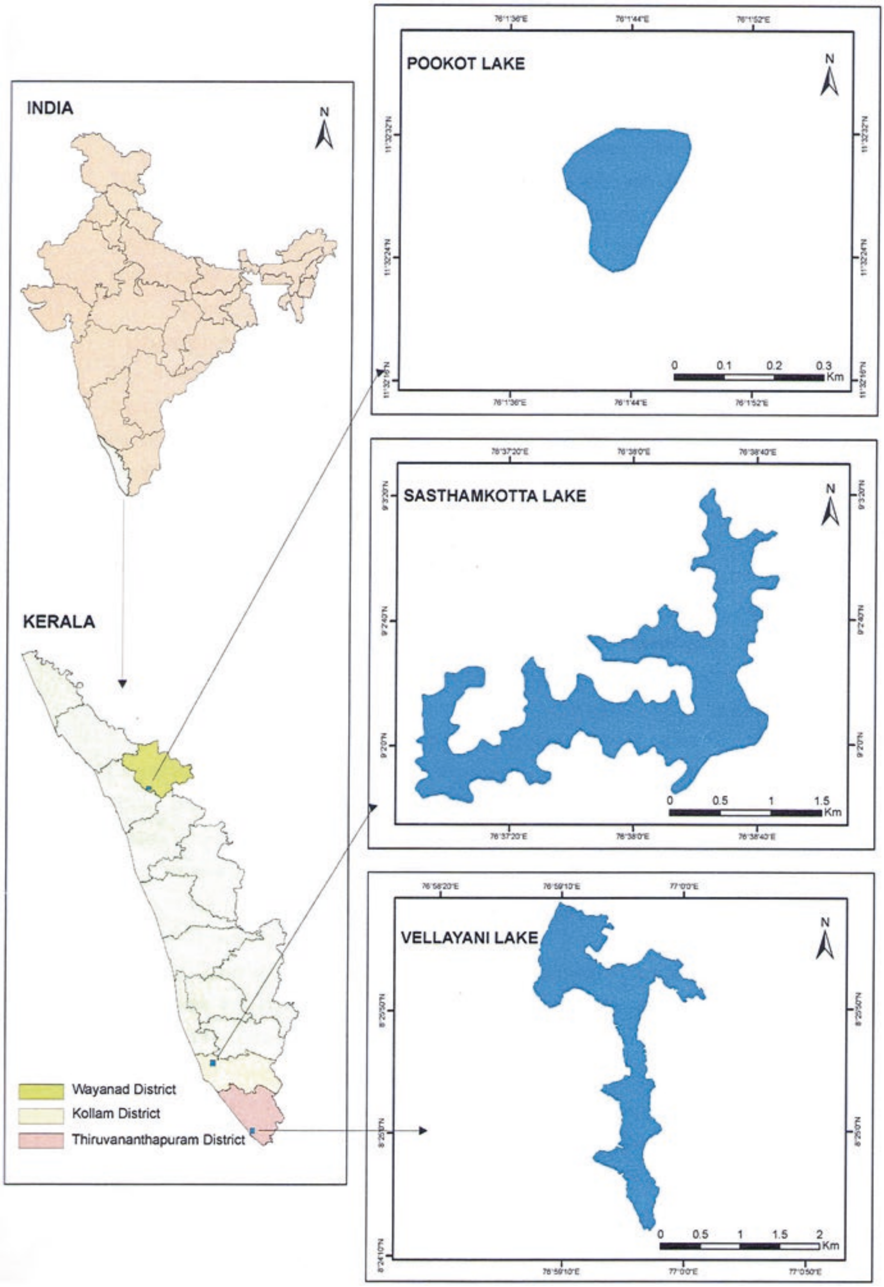


Fig. 8.1 Lacustrine wetlands of Kerala

Table 8.1 Details of Sasthamkotta, Vellayani and Pookot Lakes in Kerala

Particulars	Sasthamkotta Lake	Vellayani Lake	Pookot Lake
District	Kollam	Thiruvananthapuram	Wayanad
Taluk	Kunnathur	Thiruvananthapuram	Vythiri
Block	Sasthamkotta	Nemom, Athiyannur, Thiruvananthapuram Corporation	Kalpetta
Grama panchayats	Sasthamkotta	Kalliyoor, Venganoor, Thiruvananthapuram Corporation	Vythiri
Villages	Sasthamkotta	Kalliyoor, Thiruvallam, Venganoor	Kunnathidavaka
Local name	Sasthamkotta *Kayal*	Vellayani *Kayal*	Pookode *thadakam*
Size (ha)	347.09	230.96	3.70
Location (lat. and long.)	9° 1′ 00″–9° 4′ 00″ N 76° 36′ 30″ -76^0 40′ 00″E	8° 24 ′09″–8° 26 ′33′N 76° 59′ 08″- 76° 59′ 47″E	11° 30′ 20″ -11° 32′ 36″N 76° 1′ 02″ –76° 1′ 43″E
Existing rights and privileges consistent or not consistent with ecological health of the wetland	Fishing Drinking water Settlements Ramsar site	Fishing Boat race Drinking water	Ecotourism

Table 8.2 Textural and geochemical properties of lacustrine wetland sediments

Parameter	Vellayani		Sasthamkotta		Pookot	
	Range	Average	Range	Average	Range	Average
Sand (%)	0.36–26.5	8.53	0.21–78.63	23.4	0.25–19.8	5.73
Silt (%)	54.4–85.8	79.91	0.065–45.9	28.33	58.9–90.4	81.2
Clay (%)	8.28–41.14	18.54	2.4–76.6	44.35	4.03–69.4	12.58
Mud (silt+clay) (%)	73.5–99.7	91.55	14.99–99.8	72.71	74.7–99.4	92.89
OC (%)	0.84–2.55	1.82	0.6–15.8	8.95	0.88–16.4	8.99
P (%)	0.15–0.36	0.214	0.03–0.203	0.17	0.11–0.39	0.24
Fe (%)	0.392–1.887	1.06	0.69–2.99	1.77	0.49–2.49	1.28
Mn (ppm)	32–96	66	45–103	86	37–110	76
Cu (ppm)	4–184	31.7	6–34	24.07	4–98	26.02
Pb (ppm)	0.8–6.2	1.32	28–86	72.6	19–58	39.8
Cd (ppm)	2–6	0.81	1–5	2	2.2–4.8	1.03

Source: Das and Krishnakumar (2015)

Table 8.3 An overview of the observed hydrochemical values in the lacustrine wetlands

Parameter	Drinking water quality standards		Vellayani	Sasthamkotta	Pookot
	BIS	WHO			
pH	6.5–8.5	6.5–8.5	6.5	6.8	5.60
EC (µS/cm)	–	1,500	111.2	108	40.79
Turbidity (NTU)	5	5	4.66	9.3	7.78
TDS (mg/l)	500	1000	129.6	204.3	86.13
HCO_3^- (mg/l)	–	500	84	85.45	18
Cl^- (mg/l)	250	250	13.6	14.73	4.59
SO_4^{2-} (mg/l)	200	250	12.93	3.24	0.79
NO_3^- (mg/l)	45	50	0.56	0.37	0.16
PO_4^{3-} (mg/l)	–	–	0.36	0.5	0.09
Ca^{2+} (mg/l)	75	50	5.53	7.79	2.94
Mg^{2+} (mg/l)	30	75	2.53	7.09	1.93
Na^+ (mg/l)	–	200	16.83	20.11	17.29
K^+ (mg/l)	–	12	2.08	1.37	2.80
Fe^+ (mg/l)	0.3	0.3	0.3	0.5	0.05
Faecal coliforms (CFU/ml)	Shall not be detectable in any 100 ml sample	–	140	260	90

BIS: Bureau of Indian Standards (2012), *WHO*: World Health Organization (1993)

in the lakes, are presented as box-whisker diagrams (Fig. 8.2). Prevalence of coliforms in all the three lakes was indicative of increasing contamination of the surface water by human excreta. Excessive inputs of organic matter from the surrounding areas as domestic waste, manure and agricultural activities result in profuse growth of the microbes (Krishnakumar et al. 2005b). The risk due to water-borne diseases is directly related to the concentration of waterborne pathogens in surface and drinking water. This assumes significance as Sasthamkotta Lake is the source for water for Kollam and adjacent areas, and Vellayani Lake is the source for water for the urban panchayats in Thiruvananthapuram.

8.2.1 Water Quality Index (WQI)

The water quality index (WQI) is calculated based on the standards prescribed by WHO (1993) for drinking water. The WQI is calculated adopting weighted arithmetical index method, considering 11 water quality parameters (i.e. pH, EC, TDS, HCO_3^-, $Ca^{2+,}$ Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-} and NO_3^-) in order to assess the degree of contamination and suitability of human use. If the WQI is 50, the water quality is designated as excellent; 50–100 range indicates good water, while WQI in the range 100–200 indicates poor water. The range of 200–300 is indicative of very poor water quality, and >300 indicates that the water is not at all suitable for drinking.

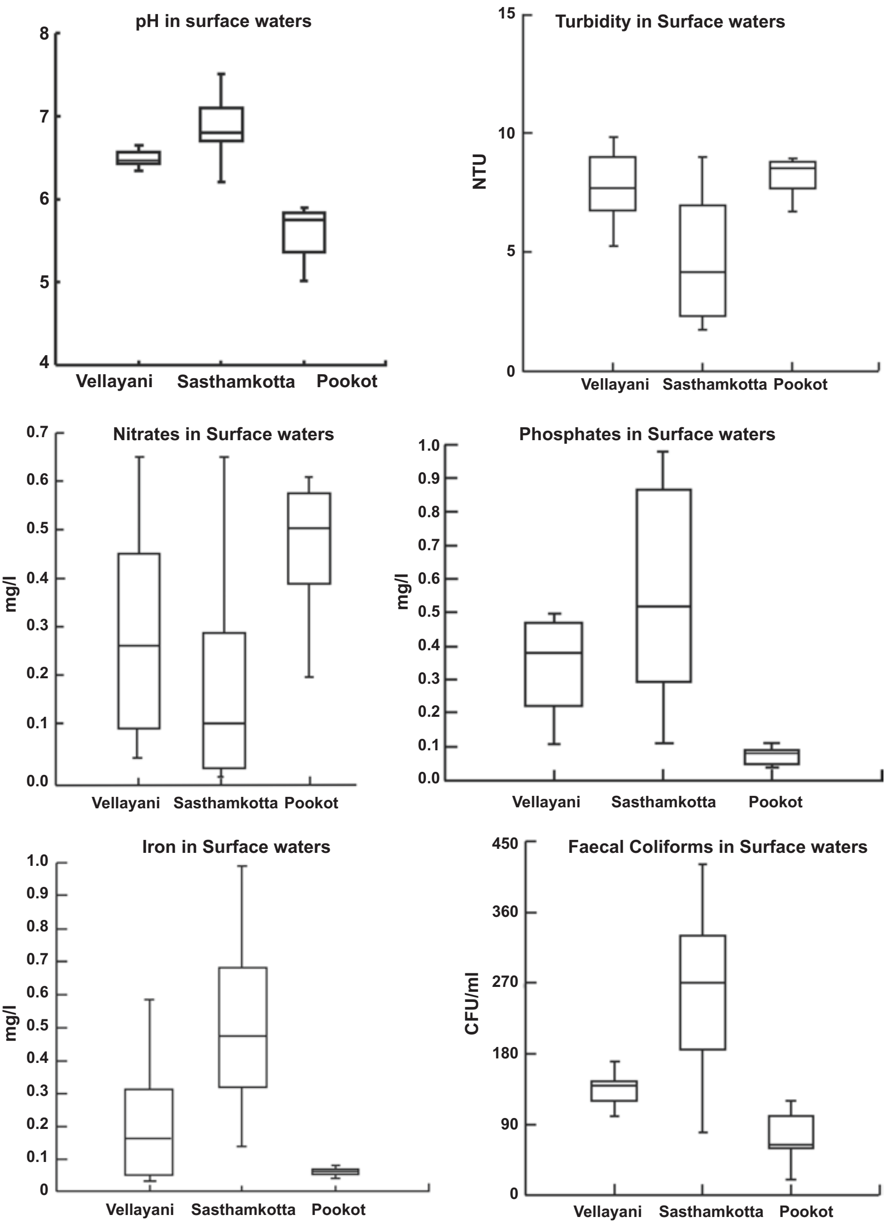


Fig. 8.2 Box-whisker diagrams showing different water quality parameters in the lacustrine wetlands

To calculate the WQI, a weight ranging from 01 to 05 has been assigned for each physico-chemical parameter according to its relative importance in the overall quality of water for drinking purposes. The respective weights assigned are 05 for NO_2 and TDS; 04 for pH, EC, and SO_4; 03 for HCO_3 and Cl; 02 for Ca, Na and K; and 01 for Mg (Vasanthavigar et al. 2010). Then the relative weight is computed by the following equation:

$$W_i = w_i / \sum_{i=1}^{n} w_i \tag{8.1}$$

where *Wi* is the relative weight, *wi* is the weight of each parameter and *n* is the number of parameters.

The quality rating scale (*qi*) for each parameter is assigned as per the equation given below:

$$q_i = \left(C_i / S_i\right) \times 100 \tag{8.2}$$

where *qi* is the quality rating, *Ci* is the concentration of each chemical parameter in each water sample in mg/l and *Si* is the WHO standard for each chemical parameter in mg/L.

For computing the final WQI, the SI is first determined for each parameter, which is then used for estimating WQI for each sample:

$$SI_i = W_i . q_i \tag{8.3}$$

$$WQI = \sum SI_i \tag{8.4}$$

where SI_i is the sub-index of *i*th parameter, *qi* is the rating based on concentration of *i*th parameter and *n* is the number of parameters**.** Then the computed WQI values were classified into five types, from excellent to water unfit for drinking purposes.

The WQI of the each lake was calculated for assessing the influence of natural and anthropogenic activities (Ramakrishnaiah et al. 2009) based on pH, EC, TDS, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+. In total 20 samples from each of the wetlands (Sasthamkotta, Vellayani and Pookot) were analysed. Based on the WQI (Sasthamkotta 23.67, Vellayani 20.30, Pookot 17.84), majority of the samples in the three wetlands were falling under 'excellent' category with respect to the chemical parameters and suitability for drinking purpose after prior treatments (Table 8.3). But, from the bacteriological point of view, the raw waters of the three lakes are unfit for drinking as they all had high coliform counts. Thus, considering the overall water quality evaluation, it can be concluded that the waters of these wetlands should be thoroughly treated prior to consumption. Treatment processes like aeration (precipitates impurities like iron), coagulation and flocculation (removes turbidity), sedimentation (separates suspended solids) filtration (removes very fine particles of silt, clay and microorganisms including algae, bacteria, viruses, etc.) and disinfection (destroys all disease-producing organisms) are suggested prior to its distribution for drinking purposes (Krishnakumar et al. 2014).

8.2.2 Water Types

The water types in all the three freshwater lakes were determined by constructing Piper trilinear diagrams (Piper 1944) using hydrochemical data (Fig. 8.3). These trilinear diagrams are useful in bringing out chemical relationships among surface water samples in definite terms. In the present study, the Piper plots show predominance of Na-HCO_3 with subordinates of sulphates in Vellayani Lake, Na-HCO_3 type in Pookot Lake and Na-Cl with subordinates of Ca and Mg in Sasthamkotta Lake. Vellayani and Pookot Lakes had excess HCO_3^- ions that cause release of alkaline ions, usually Na^+, into solution by exchange reactions with cation exchangers such as clay and other minerals that form part of the aquifer materials, thereby enriching the waters with Na-HCO_3 as observed elsewhere (Sajilkumar 2013). That indicates that simple mineral dissolution or mixing processes are mainly responsible for the

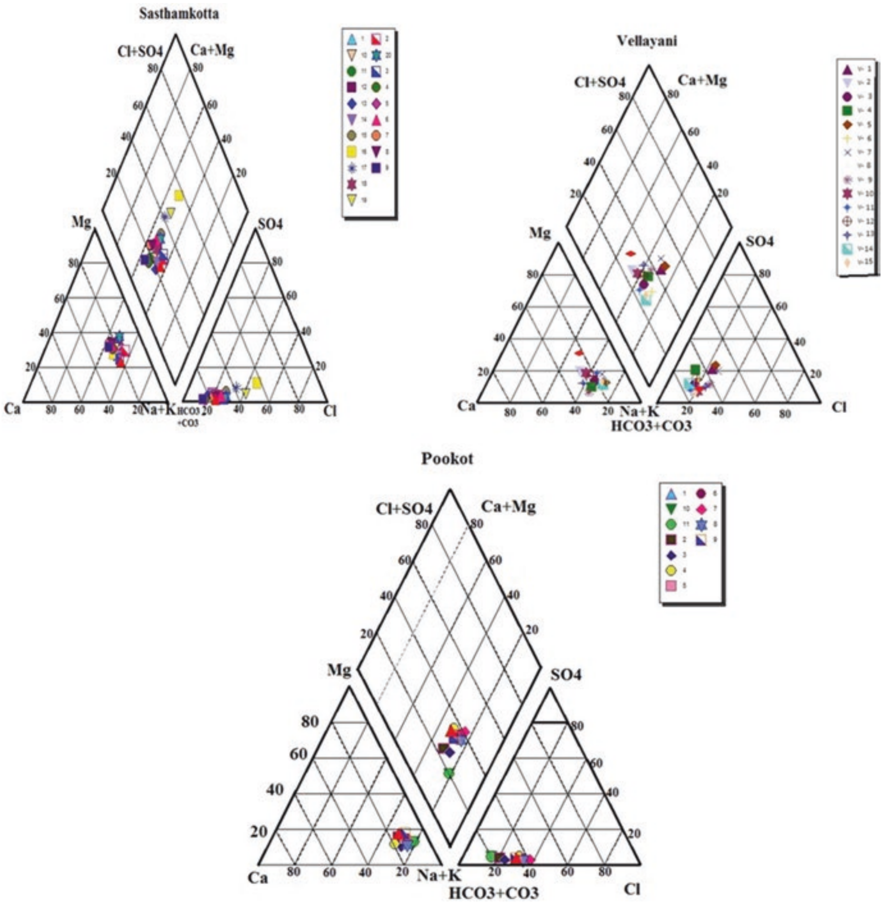


Fig. 8.3 Piper trilinear diagram showing ionic concentration in the lacustrine wetlands

variation of hydro-geochemistry of surface waters in both these lakes. In Sasthamkotta Lake, Piper plots clearly indicate the dominance of Na-Cl species. Due to overextraction of water from the lake, especially in summer, salinity intrusion advances into the lake body, at the same time flushing of the system becoming less effective. The Sasthamkotta Lake is located in the lower stretches of Kallada river basin. Recent studies (Vishnu et al. 2016) reaffirmed that the in-stream and floodplain sand mining in Kallada river basin over the last three to four decades has severely damaged the underground aquifers feeding the lake. Subsequently, seawater intrudes into the coastal aquifers assisted by the overextraction of lake water, as evident from the Piper plot of Sasthamkotta Lake. Earlier studies (Shaji 2013) have also revealed that the rivers of Kerala often experience salinity intrusions into the lower stretches during summer months.

8.2.3 Conservation Implications

The three freshwater lakes (lacustrine wetlands) of Kerala State play vital role in storing rainwater and recharging groundwater. They store large quantities of water during the monsoon and serve as a very useful system in conservation of water, especially in the existing topographical setting of the state. Field investigations reveal degradation of these lakes due to growing problems in and around them. Rapid urbanization is fast shattering the organic structure of the lakes. Fish farming in the lake surroundings is also causing havoc in the ecosystem. Artificial fish feeds and agrochemicals applied in the surrounding agricultural areas of the lakes pollute the lake water. Hence, urgent measures have to be taken to prevent these materials reaching the lakes and for wise use of these precious freshwater resources of the state.

The requirement of water for Thiruvananthapuram City by 2021 is predicted to be around 400 MLD. The existing Aruvikkara and Peppara dams do not have much storage capacity. The Vellayani Lake could be an additional source of drinking water to the capital city and its suburbs. It is inevitable that the Vellayani Lake scheme is undertaken to complement water supply from the existing Aruvikkara scheme. When the scheme materializes, 70 MLD freshwater will be available for distribution in the city, according to the Kerala Water Authority. The future development of Vizhinjam International Seaport is also linked with the better conservation of Vellayani Lake, as it is the prime drinking water source for the same.

8.3 Ashtamudi Lake: An Estuarine Ramsar Site

The Ashtamudi Lake located in Kollam district, a Ramsar Site, is one of the major estuarine wetlands and the second largest backwater system in Kerala (Fig. 8.4). This extensive and deepest wetland of South India, connected to the Arabian Sea, is also important for its hydrological functions and biodiversity. The Ashtamudi

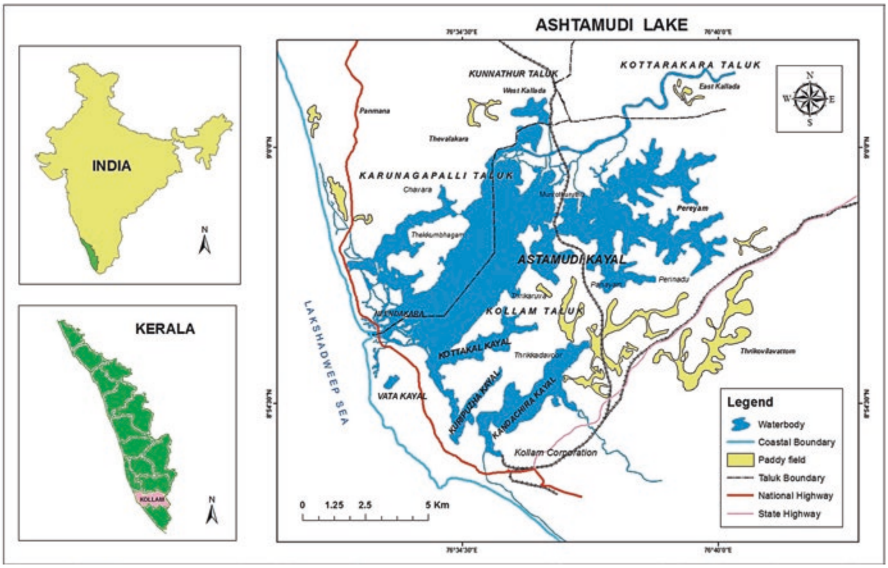


Fig. 8.4 The Ashtamudi Wetland System

Wetland System (AWS) is a palm-shaped waterbody spread over an area of about 32 km^2. It has many creeks and creeklets, of which eight are prominent ones, all of them together constituting the AWS. The Kallada River originating in the Western Ghats flows westerly and after about 120 km, falls into the AWS.

Population pressure, industrialization and rapid urbanization in and around AWS and the proximity to Kollam town are resulting in degradation of this wetland system. Recent developmental activities brought about elevated levels of heavy metals in the waterbody, and the toxicity and persistency of these pollutants made the system a centre of attention for researchers.

Spatial distribution diagrams related to geochemistry and hydrochemistry of the AWS were prepared in GIS platform using interpolation technique. The spatial variations of organic carbon (OC) and Cr in the sediments of AWS during monsoon and non-monsoon seasons are presented in Figs. 8.5 and 8.6, respectively. The contamination factor (CF: the level of contamination of sediment by metal) of metals indicates that Ashtamudi wetland is moderately contaminated with Cr, Fe, Ni and Cu (Table 8.4). The significant pollution load and spatial variation recorded for some parameters are the reflection of negative impacts of anthropogenic activities. To understand the decadal variation of heavy metal contamination in AWS, a comparison was made with previous data (Table 8.5), and it was found that concentrations of Cr and Cu have considerably increased in the AWS. In contrast to this, Zn level has decreased, which may be due to the leaching of metal from the sediments and the subsequent accumulation in the aquatic biota.

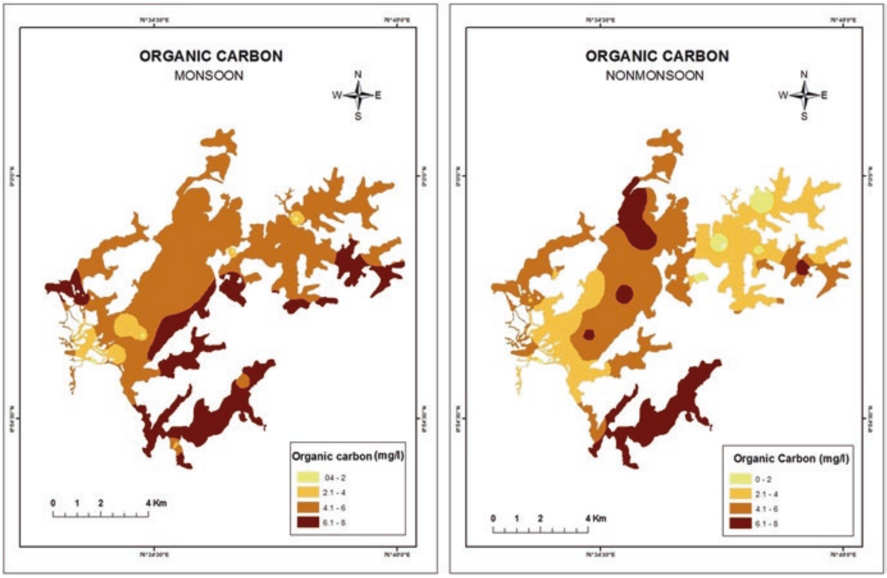


Fig. 8.5 Spatial distribution of Organic Carbon (OC) in surficial sediments of AWS

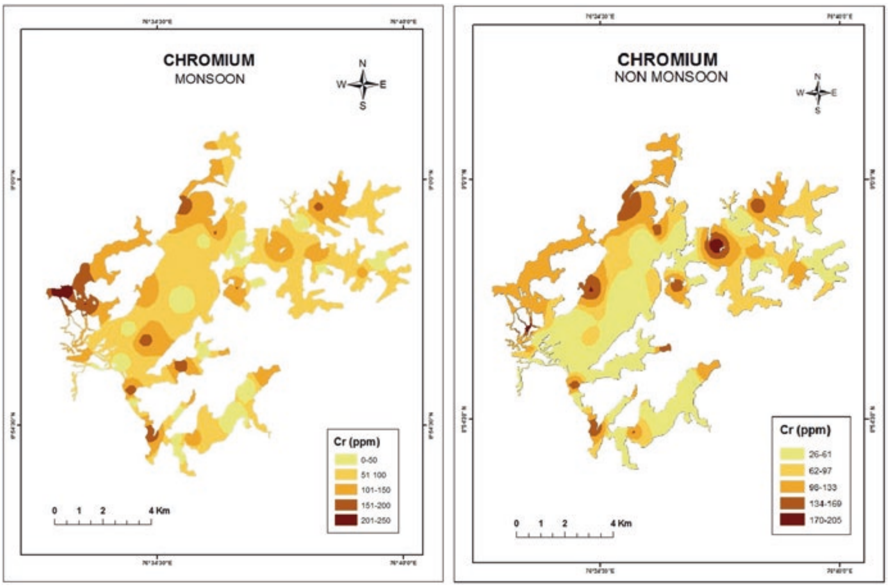


Fig. 8.6 Spatial distribution of chromium in the surficial sediments of AWS

Table 8.4 Observed concentration and contamination factor (CF) of metals in AWS

Sl no.	Elements[a]	Observed ranges of values		World shale average	Contamination factor (CF)		Pollution status
		Monsoon	Non-monsoon		Monsoon	Non-monsoon	
1	Cr	139.4–172.33	126.75–143.66	90	1.55–1.91	1.41–1.60	Moderate
2	Al	0.56–11.58	1.08–10.23	80,000	Negligible	Negligible	NC[b]
3	Mn	0.025–0.08	0.03–0.47	900	Negligible	Negligible	NC[b]
4	Fe	3.72–8.29	3.52–6.88	4.6	0.81–1.80	0.77–1.50	Moderate
5	Co	10–14.2	10–13.2	19	0.53–0.75	0.36–0.77	Low
6	Ni	72.8–99.75	51.4–83.5	68	0.76–1.47	0.76–1.23	Moderate
7	Cu	50.2–70.25	39.4–83.25	45	1.12–1.56	0.88–1.85	Moderate
8	Zn	23.29–73.8	24.7–40	95	0.25–0.78	0.26–0.42	Low
9	Ti	0.56–0.75	0.504–1.08	4,600	Negligible	Negligible	NC[b]

[a]All values are expressed in ppm, except Fe, which is in %
[b]*NC* no Contamination with respect to this element

Table 8.5 Comparative evaluation of heavy metal concentrations in AWS

Elements	Black and Baba 2001 (ppm)	NCESS 2015 (ppm)
Chromium	80–155	136–156
Copper	20–42	59–61
Zinc	57–208	32–49

8.3.1 Water Environment

The nutrient concentration in the AWS is regulated by the freshwater inflow from Kallada River. The nutrient input through the river in non-monsoon season is lesser than that in the monsoon season. However, generally high nutrient inputs from various sources such as coconut husk retting, fish-processing centres, urban sewage and industries located nearby affect the seasonal water quality in the AWS (Table 8.6). In non-monsoon period, reduced freshwater inflow, together with the addition of contaminants in large quantities, depletes the level of DO resulting in subsequent non-oxidation of organic matter. The freshwater inflow into AWS considerably reduces various water quality parameters during monsoon. Earlier studies also have indicated that deterioration in water and sediment quality in AWS is mainly due to input of contaminants through industrial effluents, domestic and municipal sewage, waste disposal and coconut husk retting (Sajan and Damodaran 1981; NarendraBabu

Table 8.6 Water quality of AWS

Parameter	Monsoon	Non-monsoon
pH	5.86–8.38	4–8.04
TDS	83–838	464–2,720
TSS	11.7–135.6	53.2–125.6
EC	3.07–32.45	30.9–47.4
Total hardness	96–1,620	4,000–7,400
Calcium	60.12–400.80	320.64–721.44
Magnesium	2.44–299.02	729–1,552.2
Total alkalinity	100–300	500–900
Salinity	18.68–21.25	20.96–72.72
Sodium	123.10–558.6	624–839.7
Potassium	26.20–1,094	114.2–145
DO	5.12–9.07	1.69–6.78
BOD	0.11–5.85	0.089–6.79
Total phosphorus	0.05–0.58	0.07–1.60
PO_4	0.001–0.08	0.05–0.20
Total nitrogen	0.07–1.75	1.11–2.77
Nitrate, NO_3^-	0.64–5.20	0.01–1.14
Nitrite, NO_2^-	0.002–1.30	0.003–0.05
Ammonia	3.03–3.67	0.87–1.72

All values are expressed in mg/l, except EC and salinity, which are in mS/cm and ppt, respectively

et al. 2009). The spatial variations of DO and ammonia in AWS during monsoon and non-monsoon seasons are presented in Figs. 8.7 and 8.8, respectively.

The Centre for Earth Science Studies (CESS) had taken up a study for developing a management plan for Ashtamudi Estuary during 2001. The study reveals that most of the areas surrounding the AWS are used for coconut husk retting, a major occupation of the people in the area, which reduce the pH and DO in the waters (Black and Baba 2001). The recent report of National Centre for Earth Science Studies (NCESS 2015) also revealed that this occupation is continuing in the environments of AWS, resulting in production of hydrogen sulphide from the rotting husk waste. Even though sparingly soluble in water, hydrogen sulphide lowers the pH. Moreover, due to degradation of organic matter by microbial activity, anoxic conditions prevail in this area, and consequent upon the release of organic acids, further reduction in pH is observed. The DO and BOD levels are also adversely affected due to the oxygen demand associated with the decay and breakdown of the coconut husks. This is a testimony of the unscientific use of wetland systems, in spite of its high potential for providing various goods and services.

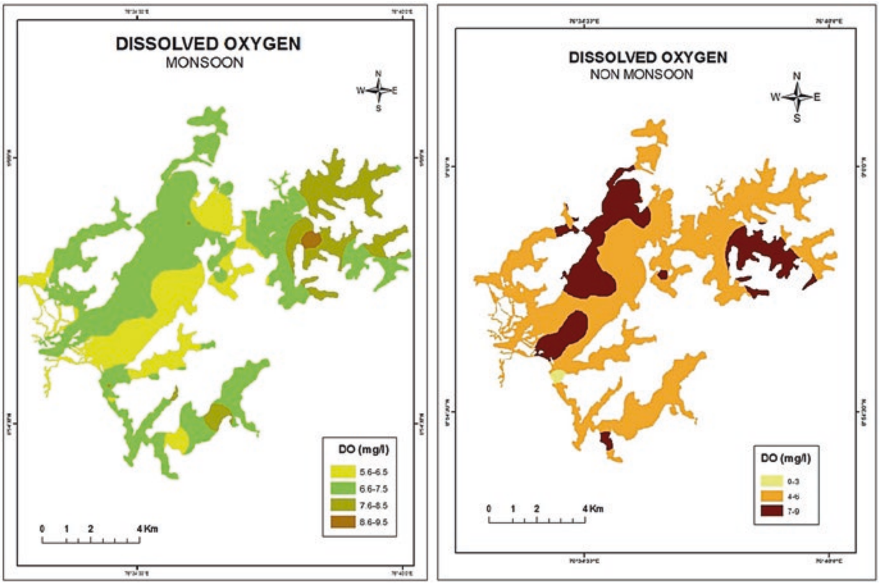


Fig. 8.7 Spatial distribution of Dissolved Oxygen in surface waters of AWS

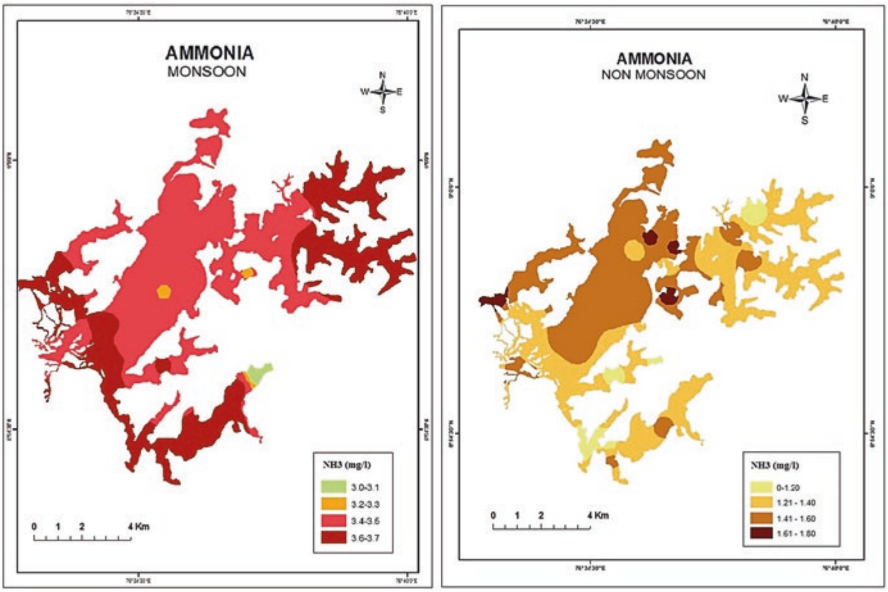


Fig. 8.8 Spatial distribution of ammonia in surface waters of AWS

8.4 Conclusion

Wetlands are the mirrors of nation's ecological wealth and often considered to play a vital role in ensuring social and economic development. The water quality and geochemical characteristics of selected wetlands of Kerala, namely Vellayani Lake, Sasthamkotta Lake and Pookot Lake (three important lacustrine wetlands) and Ashtamudi Wetland System (estuarine wetlands comprising Ashtamudi main lake, Chavara *Kayal*, Kureepuzha-Kandachira *Kayals* and Kumbalathu-Kanjirakottu *Kayals*) in the state have been examined in terms of its hydro-geochemical characteristics and the salient results are highlighted in this chapter. Studies revealed that the pace of urbanization and other anthropogenic activities around the wetlands impose notable changes in the hydro-geochemical characteristics of these natural water bodies, thus deteriorating the health of the ecosystems. Available information emphasizes the need for sustainable management measures for all these wetlands, together with continuous monitoring of sediment and water quality of the different subsystems. Location-specific plans are very much needed for effective conservation and management as well as for sustainable utilization of the important wetland systems in the state.

Acknowledgement The authors wish to express their gratitude to Director T. N. Prakash, NCESS, for the encouragement and support. The help provided by Dr. Anoop Krishnan and Dr. Reji Srinivas during the fieldwork is hereby revered. The financial assistance provided by the Department of Ports and Fisheries, Government of Kerala, for the estuarine wetland studies is gratefully acknowledged.

References

Black K, Baba M (eds) (2001) Developing a management plan for Ashtamudi Estuary, Kollam, India. ASR Limited, New Zealand and Centre for Earth Science Studies, India

Bureau of Indian Standards (2012) Drinking water- specification. http://bis.org.in/. Accessed 15 Jan 2015

Das R, Krishnakumar A (2015) Recent hydrochemical characterization of the tropical lacustrine ecosystems of Kerala. In: Siji VL (ed) REACS-2015: recent and emerging advances in chemical sciences, Thiruvananthapuram, India, 8–9 January 2015, ISBN 978–81–930193-0-6

Krishnakumar A, Baijulal B, Unnikrishnan P, Baiju RS (2005a) Qualitative hydrogeochemical evaluation of two aquatic bodies of Kerala, India with special reference to environmental management. Ecol Environ Conserv 1(3–4):521–526

Krishnakumar A, Sobha V, Padmalal D (2005b) Status of nutrients and heavy metals in the recently deposited sediments of Vellayani freshwater Lake, Kerala, South West coast of India. Ecol Environ Conserv 11(2):235–240

Krishnakumar A, Sobha V, Padmalal D, Baiju RS, Baijulal B (2006) Hydrogeochemical characterization and socio-environmental implications of Vellayani freshwater Lake, Southern Kerala, India. J Eco-Chronicle 1(1):35–46

Krishnakumar A, Vinduja V, Menon SN (2014) Decadal changes of water quality in Vellayani lake, Kerala – implications of climate change, In: Compendium of the National seminar on Spatial technologies for Watershed Planning, Kerala State Land Use Board, Thiruvananthapuram, India, 8–9 Jan 2014

NarendraBabu K, Omana PK, Mohan M (2009) Water and sediment quality of Ashtamudi estuary, a Ramsar site, Southwest coast of India-a statistical appraisal. Environ Monit Assess 165:307–319

National Centre for Earth Science Studies (2015) Environmental studies of Kollam-Neendakara wetlands and associated inlands. Project report submitted to the Department of Port and Fisheries. Govt. of Kerala, India

Padmalal D, Kumaran KPN, Nair KM, Baijulal B, Limaye RB, Vishnu Mohan S (2011) Evolution of the coastal wetland systems of SW India during the Holocene: evidence from marine and terrestrial archives of Kollam coast, Kerala. Quat Int 237(1–2):123–139

Piper AM (1944) A graphic procedure in geochemical interpretation of water analyses. Trans Am Geophys Union 25:914–923. doi:10.1029/TR025i006p00914

Ramakrishnaiah CR, Sadashivaiah C, Ranganna G (2009) Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India. E-J Chem 6:523–530. doi:10.1155/2009/757424

SAC (2011) National wetland atlas. Ministry of Environment and Forest, Ahmedabad, p 334

Sajan K, Damodaran KT (1981) Studies on the distribution of organic matter content in sediments of Ashtamudi lake, Kerala. Bull Dept Mar Sci Uni Cochin 12:155–160

Sajilkumar PK (2013) Interpretation of groundwater chemistry using piper and chadha's diagrams: a comparative study from Perambalur taluk. Elixir Geosci 54:12208–12211

Shaji EJ (2013) Groundwater quality management in Kerala. Int Inte Res J 3:63–68

Unni KS (ed) (2002) Conservation and management of aquatic ecosystems. Daya Publishers, New Delhi

Vasanthavigar M, Srinivasamoorthy K, Vijayaragavan K, Rajiv Ganthi R, Chidambaram S, Anandhan P, Manivannan R, Vasudevan S (2010) Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu, India. Environ Monit Assess 171:595–609. doi:10.1007/s10661-009-1302-1

Vishnu M, John SE, Rajimol TR, Maya K, Sajan K, Padmalal D (2016) Human interventions and consequent environmental degradation of a protected freshwater lake in Kerala, SW India. Geosci J 20(3):391–402

World Health Organization (1993) Guidelines for drinking water quality. www.who.in/. Accessed 15 Jan 2015

9 Distribution of Trace Metals in the Sediments of Estuarine-Mangrove Complex across the Indian Coast

Prabhat Ranjan, Namrata Priya, Alok Kumar, and AL. Ramanathan

Abstract

The present chapter reviews the current knowledge on trace metal distribution and their enrichment and ecotoxicity potential in sediments in Indian estuarine-mangrove complexes. Available literature suggests that the metals like Cd and Fe show very high contamination, whereas Co, Cr, Cu, Mn, Ni, Pb and Zn indicate moderate contamination in Indian mangroves [based on the pollution indices contamination factor (CF), pollution load index (PLI), enrichment factor (EF), geo-accumulation index (I-geo), potential ecological risk index (Eif) and potential toxicity response index (RI)]. The tsunamigenic sediments of Pichavaram mangroves of Southern India indicate very high enrichment of the metals. Low values for Al and As for all indices suggest low degree of risk with respect to these metals across the Indian estuarine mangroves. Cd shows higher enrichment in almost all estuarine-mangrove complexes in India except those at Muthupet and Sundarbans. Of all Indian mangroves, high risk is seen in the case of Pichavaram, Coringa-Gaderu, Manakudy estuary mangrove and Vellar estuary mangrove, while for Sundarbans, Muthupet and Goa, the risk is low. In the light of this, there is a need for effective management strategy for most of the Indian mangrove ecosystems.

Keywords

Contamination • Geo-accumulation • Mangrove • Potential toxicity • Trace metals

P. Ranjan • N. Priya • AL. Ramanathan (✉)
School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India
e-mail: prabhatranjan.jnu@gmail.com; namratapriyarox@gmail.com; alrjnu@gmail.com

A. Kumar
Department of Environmental Science, Central University of Rajasthan, Kishangarh, Ajmer, Rajasthan, India
e-mail: alok_evs@curaj.ac.in

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_9

9.1 Introduction

Mangrove forests are one of the world's most productive tropical ecosystems confined to the coastal deltaic zones of tropics and subtropics, predominantly between 25° N and 25° S with an estimated total coverage of 1.7 to 2.0×10^5 km^2 (Borges et al. 2003). Mangroves are of much significance as they act as a barricade against cyclones, protect coastal erosion and provide habitat for a number of commercially important aquatic organisms (Kathiresan and Bingham 2001).

Pollution of the natural environment by trace metals is a worldwide problem because trace metals have toxic effects on living organisms when they exceed a certain concentration (Chakraborty et al. 2009; Dias and Nayak 2016). Trace metal toxicity holds greater significance as they tend to accumulate in the sediments as well as biota through various physical, chemical and biological processes (Leivouri 1998; Jonathan et al. 2010; Kumar and Ramanathan 2015). Increasing urbanization and industrialization has increased the release of higher domestic sewage, industrial effluents, trace metals and other toxic pollutants to coastal areas (Agoramoorthy and Hsu 2005; Ranjan et al. 2008). Mangrove plants have a special feature to store trace metals without being damaged even at higher concentration than terrestrial flora (MacFarlane et al. 2007). This capacity increases with the increasing age of mangroves (Panda et al. 2013). The present chapter examines the status of major estuarine mangrove complexes (Fig. 9.1) across the Indian coast with reference to occurrence of trace metals in the sediments.

9.1.1 Distribution of Major Indian Mangrove

According to the Forest Survey of India (FSI) report in 2015, the total mangrove cover in the country stands at 4628 km^2. The major Indian mangroves are described in brief as below.

Sundarbans (West Bengal) The Indian Sundarbans at the apex of the Bay of Bengal (between *21°40′ N* and *22°40′ N latitude* and *88°03′ E* and *89°07′ E longitude*) is located towards the northeast coast of India. It is a tide-dominated estuarine wetland at the lower deltaic plains of the Ganges-Brahmaputra Rivers. This wetland is a complex network of tidal creeks, surrounding hundreds of tidal islands exposed to different elevations at high and low semidiurnal tides (Sarkar et al. 2008; Jonathan et al. 2010; Banerjee et al. 2012; Kumar and Ramanathan 2015).

Bhitarkanika (Odisha) Bhitarkanika is located between *20°04′–20°08′ N latitudes* and *86°45′–87°50′ E longitudes* in the Kendrapara district of Odisha. It is the second largest mangrove ecosystem in India comprising mangrove forests, rivers, creeks, estuaries, backwater, accreted land and mud flats. Bhitarkanika mangroves, spread over an area of 672 km^2, were declared as a wildlife sanctuary in 1975. It is a tide-dominated mangrove with areas of high tidal range of semidiurnal nature with mean tide level of 1.5–3.4 m (Sarangi et al. 2002).

Fig. 9.1 Distribution of mangroves in India (Adopted from Kumar 2000)

Coringa and Gaderu (Andhra Pradesh) Coringa and Gaderu mangrove ecosystems are located to the north of Gautami-Godavari River (82° 15′ and 82° 22′ E *latitude*; 16° 43′ and 17° 00′ N *longitude*) with an area of 132 km^2. The Gautami-Godavari River opens into Kakinada bay via the main distributaries Gaderu (length 11 km) and Coringa (length 26 km). The area between Gautami-Godavari and Kakinada bay has dense vegetation of mangrove forests and mudflats belonging to Coringa wildlife sanctuary (Ray et al. 2006).

Pichavaram (Tamil Nadu) Pichavaram mangrove forest is located between Vellar and Coleroon estuaries at 11° 02′ N *latitude* and 79° 47′ E *longitude*. The area has 51 islets, separated by intricate waterways that connect the Vellar and Coleroon estuaries. The southern part close to the Coleroon estuary is mainly mangrove vegetation, while the northern part close to the Vellar estuary is dominated by mudflats. The Vellar estuary opens into the Bay of Bengal at Parangipettai and is connected with the Coleroon River, a distributary of the River Cauvery. The Pichavaram mangrove is influenced by mixing of three types of waters: (1) neritic water from the adjacent Bay of Bengal, (2) brackish water from the Vellar and Coleroon estuaries and (3) fresh water from an irrigation channel (Khan Sahib Canal) and also from the main channel of the Coleroon River. The mangrove covers an area of about 1100 ha, of which 50% is forest, 40% waterways and the remaining sandflats and mudflats (Ramanathan et al. 1999; Ranjan et al. 2013).

Kumarakom Mangrove (Kerala) Kumarakom mangrove is located between *latitude* 09°28′ and 10°10′ N and *longitude* 76°13′ E. Kumarakom mangrove and mangrove-associated forests are seen along the southeastern border of the Vembanad estuary. It was one of the best mangrove ecosystems of Kerala before commissioning of Thannirmukkam barrier constructed on Vembanad estuary to prevent saltwater intrusion during droughts. Now the mangrove ecosystem has severe regeneration problems owing to the drastic changes in the physico-chemical conditions caused by the Thannirmukkam barrier and the intensive shell mining taking place in the areas close to the Kumarakom mangroves (Badarudeen et al. 1996).

Goa Mangrove (Goa) Goa mangrove and associated swamps can be observed along most of the water bodies within the estuarine reaches. It is located on central western coast of India between *14°53′–15°48′ N latitude*s and *73°40′–74°20′ E longitudes*. The most prominent and extensive backwaters with mangroves are located along the east of the capital city Panaji. The total area covered by the estuaries in Goa including the major Mandovi-Zuari estuarine complex is approximately 120 km^2 (Attri and Kerkar 2011).

Mumbai (Maharashtra) The city of Mumbai lies between 18°55′ N and 19°20′ *N latitudes* and 72°45′ E and 73°00′ E *longitudes*. This city has at its northern end the Ulhas River, Thane Creek on the southeastern end and the Arabian Sea on the west. Extensive mudflats and mangroves are present along both estuarine banks. The creek is fringed with mangroves along both banks, along with heavy industrialization and urbanization (Fernandes et al. 2012).

Gulf of Kachchh (Gujarat) The Gulf of Kachchh (GoK) is situated in Saurashtra in the western state of Gujarat. The GoK, occupying an area of 7300 km^2, is biologically one of the most productive and diversified habitats along the western coast of India. The northern shore with numerous shoals and creeks also sustains large stretches of mangroves. The majority of the mangrove cover of Gujarat area is confined to the gulf. Of the 991 km^2 of mangrove cover in the state, those along the gulf contribute 96% of the total. Due to high salinity, grazing and cutting pressure, Kachchh mangroves have stunted growth and are only 1–2 m tall, whereas at untouched patches mangroves gain a height up to 5 m (Ramaswamy et al. 2007; Chakraborty et al. 2014).

Andaman and Nicobar (Andaman and Nicobar Islands, ANI) Andaman and Nicobar archipelago, consisting of over 572 islands and islets, lie in the lap of Bay of Bengal (between *latitude* 6°45′–13°41′ N and *longitude* 92°12′–93°57′ E) to the eastern side of India. The islands, about 1200 km east from the mainland of India, have a total land area of about 8249 km^2 covered by luxuriant tropical rain forest. Fringing reef and barrier reef dominate the Andaman Islands forming a natural barrier to the wave energy from the Bay of Bengal (Ramesh et al. 2006). Coral reefs form the dominant ecosystem creating ground for sea grasses and mangroves in the lagoons and creeks protected by the reef (Nobi et al. 2010).

9.2 Analytical Methods

9.2.1 Contamination Factor (CF)

The CF is the ratio obtained by dividing the mean concentration of each metal in the soil (C_n) by the baseline or background value (concentration in unpolluted soil, Håkanson et al. 1980)

$$CF = C_n / B_n \tag{9.1}$$

C_n in the above formula is the concentration of the examined element '*n*' in the surface sediments, and *Bn* is the geochemical background concentration of the metal '*n*'. *Bn* usually refers to world's average shale or upper continental crust composition as a reference value. CF is categories into four categories, as follows: CF <1 as low level, CF between 1 and 3 as moderate level, CF 3–6 as considerable, and CF >6 as very high level of contamination.

9.2.2 Pollution Load Index (PLI)

The PLI is calculated as the nth root of the product of the contamination factor (CF) of all trace metals. The equation for PLI developed by Tomlinson et al. (1980) is given below:

$$PLI = \sqrt[n]{\left(CF1 \times CF2 \times CF3 \times \ldots \times CFn\right)} \tag{9.2}$$

In the above equation, CF denotes the contamination factors of different metals in the samples. The PLI >1 indicates pollution, whereas <1 indicates no pollution.

9.2.3 Enrichment Factor (EF)

The EF is a geochemical index based on the assumption that, under the natural sedimentation conditions, there is a linear relationship between a reference element and other elements. Elements that are most often used as reference are Al and Fe (Mucha et al. 2003; Esen et al. 2010; Kumar et al. 2016). The EF is defined as given below (Ergin et al. 1991):

$$EF = (M / Fe)_{\text{sample}} / (\mathrm{M} / Fe)_{\text{background}} \tag{9.3}$$

where $(\mathrm{Me/Fe})_{\text{sample}}$ is the metal to Fe ratio in the sample of interest; $(\mathrm{Me/Fe})_{\text{background}}$ is the geochemical background value of metal to Fe ratio. The value of EF denotes the following category of enrichment of trace metals:

- EF < 2 – deficient to minimal enrichment
- EF = 2–5 – moderate enrichment
- EF = 5–20 – significant enrichment
- EF = 20–40 – very high enrichment
- EF >40 – extremely high enrichment

9.2.4 Geo-Accumulation Index (I-geo)

The index I-geo is widely used as a measure of sediment contamination. It denotes contamination by comparing current metal contents with preindustrial levels. The content accepted as background is multiplied by the constant 1.5 in order to take into account natural fluctuations of a given substance in the environment as well as very small anthropogenic influences. The I-geo as per Muller (1981) is described by the following equation:

$$\text{I-}geo = \log_2 \left(\mathrm{C}_n / 1.5\mathrm{B}_n \right) \tag{9.4}$$

The interpretation of the results is as follows:

- I-geo ≤0 – practically uncontaminated
- 0< I-geo <1 – uncontaminated to moderately contaminated
- 1< I-geo < 2 – moderately contaminated
- 2< I-geo <3 – moderately to heavily contaminated
- 3< I-geo < 4 – heavily contaminated
- 4< I-geo <5 – heavily to very heavily contaminated
- I-geo ≥5 – very heavily contaminated

9.2.5 Potential Ecological Risk Index (Eif)

The Eif is used to express quantitatively the potential ecological risk of a given contaminant suggested by Håkanson (1980). It is calculated by the following equation:

$$Eif = CF \times Tif \tag{9.5}$$

where Tif is the toxic response factor for a given substance [toxic response index for different metals are Hg = 40, Cd = 30, As = 10, Cu = Pb = Ni = 5, Cr = 2 and Zn = 1 given by Håkanson (1980)], and CF is the contamination factor. The following terminologies are used to describe the risk factor:

- Eif <40 – low potential ecological risk
- 40≤ Eif < 80 – moderate potential ecological risk
- 80≤ Eif <160 – considerable potential ecological risk
- 160≤ Eif <320 – high potential ecological risk
- Eif ≥320 – very high ecological risk

9.2.6 Potential Toxicity Response Index (RI)

The RI was originally introduced by Håkanson (1980) to assess the degree of heavy metal pollution in soil, according to the toxicity of metals and the response of the environment. The calculation of RI is as given below:

$$RI = \Sigma \text{Eif} \tag{9.6}$$

There are four categories of RI: RI <150 low-grade, 150≤ RI <300 moderate, 300≤ RI <600 severe and 600≤ RI serious risk.

9.3 Scenario of Metal Pollution in Selected Indian Mangrove Ecosystem

Metal distributions are very uneven within mangrove forests; it varies with depth, distance from the coast, anthropogenic activities, types of vegetation and hydrology (Kehrig et al. 2003; Marchand et al. 2006; Chatterjee et al. 2009). The sources are usually difficult to identify as some have natural sources and others have anthropogenic, as point and non-point, sources. The concentration of Al, As, Cd, Cr, Cu, Co, Fe, Mn, Ni, Pb and Zn in mangrove sediments from different studies, published so far, for Indian mangrove is shown in Table 9.1.

The Sundarbans and Pichavaram have higher concentration of Al, As, Cd, Co, Cr, Fe and Mn (Table 9.1). In the tsunamigenic sediments in Pichavaram mangroves, Ranjan et al. (2008) reported higher concentration of almost all trace metals. Coringa-Gaderu, GoK and Manakudy estuary have higher concentration of Zn, Ni and Fe, whereas Coringa and Kumarakom have higher concentration of Cd.

Table 9.1 Trace metal concentration in different mangrove ecosystems of India

Location	Al (%)	As (ppm)	Cd (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Fe (%)	Mn (%)	Ni (ppm)	Pb (ppm)	Zn (ppm)	OC (%)	Sand (%)	Silt (%)	Clay (%)	References
Sundarbans (values in range)						36–82	3.9–5.3	0.424–0.770			55–83	0.601–0.932	2.46–7.62	64.14–73.92	19.60–31.22	Kumar and Ramanathan (2015)
Sundarbans (values in range)		4.12–11.46	0.02–4.4		21.2–60.9	11.6–102.47			19.10–52.6	7.09–183.88		0.47–0.91	0.51–37.40	18.20–66.64	23.18–77.80	Antizar-Ladislao et al. (2015)
Sundarbans		3.82	0.21	7.67	28.3	38.29	0.29	0.06	34.5	15.8	34.42	0.60–0.66	1.80–15.45	32.58–38.93	51.98–59.28	Chowdhury et al. (2015)
Sundarbans			1.88	23.48	44.13	38.47	3.75	0.0574	50.35	30.28	75.87	0.786				Banerjee et al. (2012)
Sundarbans		8.09	0.18		99.01	28.94			51.86	23.01		1.552	28.47			Jonathan et al. (2010)
Sundarbans	6.33	8.3	0.15	10.41	55.98	25.74	3.12	0.58	30.17	65.59	22.8	0.625	15.34	48.24	36.41	Chatterjee et al. (2009)
Sundarbans						90.765				38.175	303.75					Sarkar et al. (2008)
Sundarbans	2.46	3.5	0.1	12.46	36.44	35.47	3.08	0.14	33.46	17.2	74.18	0.457	21.684	56.54	21.76	Sarkar et al. (2004)
Bhitarkanika						3.786	0.003	0.0009			1.01					Sarangi et al. (2002)
Coringa-Gaderu			10.9	28.8	2.2	47.8	0.46	0.11	25.7	55.8						Ray et al. (2006)
Pichavaram			23		152	34	3.80	0.033	51	21	16					Ranjan et al. (2013)
Pichavaram			34.74		6200	132.3	2.50	0.08	252.1		106					Ranjan et al. (2008)
Pichavaram			6.6	35.3	141.2	43.4	3.25	0.09	62	11.2	93					Ramanathan et al. (1999)

Location	Al (%)	As (ppm)	Cd (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Fe (%)	Mn (%)	Ni (ppm)	Pb (ppm)	Zn (ppm)	OC (%)	Sand (%)	Silt (%)	Clay (%)	References
Muthupet			0.24	11	117.3	18.1	3.21	0.0225	53.2	21.6	115.2					Raman et al. (2007)
Muthupet										43.4	261.88		11.9			Natesan et al. (2014)
Vellar estuary mangrove	0.0542		9.15		9.44	16.28	1.00	0.0178	1.64	0.98	39.28					Palpandi and Kesavan (2012)
Kumarakom					9	13	1.83	0.003			84	2.3	45.31	50.75	4.07	Badarudeen et al. (1996)
Sharavati estuary mangrove, Karnataka	3.4			4	52	9	1.6	0.013	11		17	0.4	82	4	14	Fernandes and Nayak (2016)
Goa				114.35		64.99	8.72	0.25	118.565		277.9	1.89	55.27	20.88	24.07	Dias and Nayak (2016)
Goa						49.36	9.94	0.294	64.02	18.74		5.06	44.06	34.48	21.5	Chakraborty et al. (2015)
Goa				24.41	147.75	47.32	19.25	0.154		24.5	66.62		<20			Veerasingam et al. (2015)
Goa	8.38			22.85	271.18	36.26	14.53	0.512	47.15		104.34	2.13	5.82	48.55	45.64	Noronha-D’Mello and Nayak (2015)
Goa				34.36	17.32	45.34	12.18	0.16		22.51	72.853	2.63	26.74	20.69	52.28	Attri and Kerkar (2011)
Gulf of Kachchh			6.113		8.52	5.04	0.19	0.005	2.708	0.37	231					Chakraborty et al. (2014)
Gulf of Kachchh (values in range)			0.173–23.08	18–26	120–255	44–138	0.11–8.23	0.085–0.11	51–78	14–34	0.29–160	1.47–3.25	77.2–97.93	0.60–21.45	0.1–2.5	Kumar et al. (2015)

9.3.1 Contamination Factor (CF)

An overall synthesis of reported CF in sediments from various mangrove habitats in India is presented in Table 9.2. Almost all studies of Indian mangrove ecosystem show most of the trace metals contamination in the range from 'low' to 'moderate'. Few exceptions were 'Fe' in Sundarbans, Pichavaram, Muthupet, Sharavati and Goa and 'Cd' in Coringa-Gaderu, Pichavaram, Vellar and GoK. The CF for Co was high in Sharavati estuary and Goa (Feranandes and Nayak 2016; Dias and Nayak 2016).

9.3.2 Enrichment Factor (EF)

The scenario of trace metal enrichment in various mangrove ecosystems of India is presented in the Table 9.2. In Sundarbans mangrove ecosystem, trace metal enrichment level is deficient to minimal, except for Cd and Ni, in most of the studies (Chowdhury et al. 2015). Enrichment factors for most of the trace metals in the mangroves of Muthupet, Vellar, Sharavati, Kumarakom, Goa, Coringa and Gaderu, Gulf of Kachchh and Vellar were deficient to minimal. Pichavaram also seemed to have somewhat similar enrichment pattern of trace metals except Cd. The mangrove sediment in Vellar had high enrichment of Cd and that in Pichavaram (Tsunamigenic sediment, Ranjan et al. 2008), Coringa-Gaderu and Gulf of Kachchh showed extremely high enrichment of Cd. This extremely high enrichment of Cd is due to the geogenic origin and deposition of marine sediments during the tsunami episode of 2004. This can be attributed to the fact that marine sediments from deep oceans are rich in Cd, which might have been trapped in mangrove sediments after the tsunami.

Extremely high enrichment of Pb in Bhitarkanika mangrove ecosystem indicates that Pb is precipitated at around the redox boundaries (Lee and Cundy 2001); the downward flux of Pb is bound to biogenic particles (Lambert et al. 1991) which increase its concentration. Enrichment of Cd in this estuarine environment can be linked to both natural and non-point anthropogenic sources. The abnormally high enrichment in tsunamigenic sediment can be attributed to various factors (Purvaja and Ramesh 2000; Subramanian 2004), *viz.* anthropogenic wastes from nearby soils brought back by tsunami waves and discharge from nearby industries (aquaculture effluents, domestic sewage). Factors like enhanced organic matter content, flocculation due to varying salinity regimes and transportation of sea sediments to the coastal zone contribute significantly towards the enrichment of heavy metals in sediments.

9.3.3 Pollution Load Index (PLI)

The pollution load of Indian mangrove ecosystem is presented in Table 9.2. With only few exceptions, almost all the mangrove ecosystems seemed to be polluted.

Table 9.2 Contamination factor (*CF*), enrichment factor (*EF*), pollution load index (*PLI*), potential toxicity response index (*RI*) with respect to metals in major Indian mangrove ecosystems

Location	Contamination factor				Enrichment factor					PLI	RI	References
	Low	Moderate	Considerable	High	Deficient to minimal	Moderate	Significant	Very high	Extremely high			
Sundarbans	Al, As, Co, Cr, Fe, Pb, Zn	Cd, Cu, Mn, Ni			As, Co, Cu, Cr, Mn, Pb, Zn	Cd, Ni				Unpolluted	Low grade	Chowdhury et al. (2015)
Sundarbans	Mn	Co, Cr, Cu, Pb, Zn	Ni	Cd, Fe	Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn					Polluted	Serious	Banerjee et al. (2012)
Sundarbans	As, Zn	Cd, Cu, Pb	Cr, Ni							Polluted	Low grade	Jonathan et al. (2010)
Sundarbans	Al, As	Cd, Co, Cr, Cu, Ni	Pb	Fe, Mn	Al, As, Cd, Co, Cr, Cu Mn, Pb, Zn					Polluted	Low grade	Chatterjee et al. (2009)
Sundarbans		Pb	Cu, Zn		Al, As, Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn					Polluted	Low grade	Sarkar et al. (2008)

(continued)

Table 9.2 (continued)

Location	Contamination factor				Enrichment factor					PLI	RI	References
	Low	Moderate	Considerable	High	Deficient to minimal	Moderate	Significant	Very high	Extremely high			
Sundarbans	Al, As, Pb	Cd, Co, Cr, Cu, Mn, Ni, Zn		Fe						Polluted	Low grade	Sarkar et al. (2004)
Bhitarkanika	Fe, Mn Pb, Zn						Zn		Mn, Pb	Unpolluted	Low grade	Sarangi et al. (2002)
Coringa-Gaderu	Cr	Co, Cu, Fe, Mn, Ni, Pb		Cd	Cr, Cu, Mn, Ni	Co, Pb			Cd	Polluted	Serious	Ray et al. (2006)
Pichavaram	Mn, Zn	Cu, Ni, Pb	Cr	Cd, Fe	Cr, Cu, Mn, Ni, Pb, Zn			Cd		Polluted	Serious	Ranjan et al. (2013)
Pichavaram	Cr	Mn, Zn	Cu	Cd, Fe, Ni	Cr, Cu, Mn, Pb, Zn				Cd	Polluted	Serious	Ranjan et al. (2008)
Pichavaram	Pb	Cu, Zn	Co, Cr, Ni	Cd, Fe	Co, Cr, Cu, Mn, Ni, Pb, Zn		Cd			Polluted	Serious	Ramanathan et al. (1999)
Muthupet		Pb	Zn							Polluted	Low grade	Natesan et al. (2014)

Location	Contamination factor				Enrichment factor					PLI	RI	References
	Low	Moderate	Considerable	High	Deficient to minimal	Moderate	Significant	Very high	Extremely high			
Muthupet	Cu, Mn	Cd, Co, Ni, Pb, Zn	Cr	Fe	Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn					Polluted	Low grade	Raman et al. (2007)
Vellar estuary mangrove	Al, Cr, Cu, Mn, Ni, Pb, Zn	Fe		Cd	Al, Cr, Cu, Mn, Ni, Pb, Zn			Cd		Unpolluted	Serious	Palpandi and Kesavan (2012)
Kumarakom	Cr, Cu, Mn	Zn	Fe		Cr, Cu, Mn, Zn					Unpolluted	Low grade	Badarudeen et al. (1996)
Sharavati estuary mangrove, Karnataka		Zn	Mn, Pb	Co, Fe	Co, Cr, Cu, Mn, Ni, Pb, Zn					Polluted	Low grade	Fernandes and Nayak (2016)
Goa		Cu	Mn, Ni, Zn	Co, Fe	Co, Cu, Mn, Ni, Zn					Polluted	Low grade	Dias and Nayak (2016)
Goa	Zn,	Co, Cu, Mn, Pb	Cr	Fe	Co, Cr, Cu, Mn, Pb, Zn					Polluted	Low grade	Veerasingam et al. (2015)

(continued)

Table 9.2 (continued)

Location	Contamination factor				Enrichment factor					PLI	RI	References
	Low	Moderate	Considerable	High	Deficient to minimal	Moderate	Significant	Very high	Extremely high			
Goa		Al, Co, Cu, Ni, Zn		Cr, Fe, Mn	As, Co, Cu, Cr, Mn, Ni, Zn					Polluted	Low grade	Noronha-D'Mello and Nayak (2015)
Goa	Cr	Cu, Mn, Pb, Zn	Co	Fe	Co, Cr, Cu, Mn, Pb, Zn					Polluted	Low grade	Attri and Kerkar (2011)
Gulf of Kachchh	Cr, Cu, Fe, Mn, Ni, Pb		Zn	Cd	Cr, Cu, Mn, Ni, Pb		Zn		Cd	Unpolluted	Serious	Chakraborty et al. (2014)

Pollution of Pichavaram and Goa mangrove can be attributed to fishing, aquaculture, agricultural runoff, shipping, industries, tourism and boating. It was interesting to note that while most of the studies in Sundarbans showed the area to be highly polluted w.r.t. PLI, the recent findings by Chowdhury et al. (2015) were different.

9.3.4 Potential Toxicity Risk Index (RI)

Potential toxicity risk index (RI), presented in Table 9.2, reveals that the RI was in 'low-grade' category in all the studies done so far in Kumarakom, Muthupet, Goa and Bhitarkanika mangroves. Similar was the case with Sundarbans except for the study done by Banerjee et al. (2012). In Pichavaram, Coringa-Gaderu, Vellar and Gulf of Kachchh, the RI fell in 'serious' category.

9.3.5 Geo-Accumulation Index (I-geo)

Geo-accumulation index (I-geo) of various heavy metals in different mangrove ecosystems of India is presented in Table 9.3. Of all the mangroves in India, maximum investigations were undertaken in the Sundarbans. These investigations suggest different accumulation status of heavy metals in the mangrove sediments, ranging from 'practically uncontaminated' (Zn) to 'moderate to strong accumulation' (Fe and Mn). The category of geo-accumulation of metals in Pichavaram mangrove sediments differed from that reported in Sundarbans (practically uncontaminated includes Al, Mn, Pb and Zn; contaminated includes Cu; strongly accumulated includes Cd). However, tsunamigenic sediments showed different patterns of metal accumulation.

In the mangroves of Coringa-Gaderu (Table 9.3), the I-geo for Fe, Cr, and Ni were in 'practically uncontaminated' category, and Cu, Co, Mn and Pb in 'uncontaminated to moderate' category. In Kumarakom mangrove sediments, I-geo values for Cr, Cu, Mn and Zn were in 'practically uncontaminated' category, and Fe was found to be 'moderately accumulated in the sediments'. Most of the heavy metals examined in sediments of GoK and Bhitarkanika mangrove systems were found in "practically uncontaminated"' category. Similarly, Al, Cu and Zn were in 'practically uncontaminated' category in Muthupet and Goa mangroves.

9.3.6 Potential Ecological Risk Index (Eif)

An overall picture of potential ecological risk is presented in Table 9.3 for the Indian mangrove ecosystems. In all the Indian mangrove ecosystems examined, Al, As, Cr, Cd, Ni, Pb and Zn seemed to have 'low potential ecological risk', whereas Cd had 'high potential ecological risk' (in Pichavaram, Coringa-Gaderu, GoK and Vellar).

Table 9.3 Geo-accumulation index (I-geo) and potential ecological risk index (with respect to metals) in major Indian mangrove ecosystems

Location	I-geo							Eif					References
	Practically uncontaminated	Uncontaminated to moderate	Moderate	Moderate to strong	Strong	Strong to very strong	Very strong	Low	Moderate	Considerable	High	Very high	
Sundarbans	As, Co, Cr, Fe, Mn, Pb, Zn	Cd, Cu, Ni						As, Cr, Cu, Ni, Pb, Zn	Cd				Chowdhury et al. (2015)
Sundarbans	Cr, Zn	Co, Cu, Ni, Pb		Fe, Mn	Cd			Cr, Cu, Ni, Pb, Zn	Cd				Banerjee et al. (2012)
Sundarbans	As, Cu, Pb	Cd, Cr, Ni						As, Cr, Cu, Ni, Pb	Cd				Jonathan et al. (2010)
Sundarbans	Al, As, Co, Cu, Zn	Cd, Cr, Ni	Pb	Fe, Mn				As, Cr, Cu, Ni, Pb, Zn	Cd				Chatterjee et al. (2009)
Sundarbans		Pb	Cu, Zn					Cu, Pb, Zn					Sarkar et al. (2008)
Sundarbans	Al, As, Cd, Co, Cr, Cu, Zn	Mn, Ni		Fe				As, Cd, Cr, Cu, Ni, Pb, Zn					Sarkar et al. (2004)
Bhitarkanika	Fe, Mn, Pb, Zn							Pb, Zn					Sarangi et al. (2002)
Coringa-Gaderu	Cr, Fe, Ni	Co, Cu, Mn, Pb					Cd	Cr, Cu, Ni, Pb				Cd	Ray et al. (2006)

Location	I-geo							Eif					References
	Practically uncontaminated	Uncontaminated to moderate	Moderate	Moderate to strong	Strong	Strong to very strong	Very strong	Low	Moderate	Considerable	High	Very high	
Pichavaram	Cu, Mn, Pb, Zn	Ni	Cr				Cd	Cr, Cu, Ni, Pb, Zn				Cd	Ranjan et al. (2013)
Pichavaram	Cr, Mn, Zn		Cu		Pb		Cd	Cr, Cu, Zn	Pb			Cd	Ranjan et al. (2008)
Pichavaram	Pb, Zn	Cu, Mn	Co, Cr, Ni	Fe			Cd	Cr, Cu, Ni, Pb, Zn				Cd	Ramanathan et al. (1999)
Muthupet		Pb	Zn					Pb, Zn					Natesan et al. (2014)
Muthupet	Co, Cu, Pb, Mn	Cd, Ni, Zn	Cr					Cr, Cu, Ni, Pb, Zn	Cd				Raman et al. (2007)
Vellar estuary mangrove	Al, Cr, Cu, Mn, Ni, Pb, Zn	Fe					Cd	Cr, Cu, Ni, Pb, Zn				Cd	Palpandi and Kesavan (2012)
Kumarakom	Cr, Cu, Mn, Zn		Fe				Cd	Cr, Cu, Zn					Badarudeen et al. (1996)
Sharavati estuary mangrove, Karnataka		Zn	Cr, Cu, Mn, Pb	Co, Ni	Fe			Cr, Cu, Ni, Pb, Zn					Fernandes and Nayak (2016)

(continued)

Table 9.3 (continued)

Location	I-geo							Eif					References
	Practically uncontaminated	Uncontaminated to moderate	Moderate	Moderate to strong	Strong	Strong to very strong	Very strong	Low	Moderate	Considerable	High	Very high	
Goa	Co	Cu	Mn, Ni, Zn		Fe			Cu, Ni, Pb, Zn					Dias and Nayak (2016)
Goa	Pb, Zn	Co, Cu, Mn, Pb	Cr				Fe	Cr, Cu, Pb, Zn					Veerasingam et al. (2015)
Goa	Al, Cu, Zn	Co, Ni		Cr, Mn		Fe		Cr, Cu, Ni, Zn					Noronha-D'Mello and Nayak (2015)
Goa	Cr, Pb, Zn	Cu, Mn	Co			Fe		Cr, Cu, Pb, Zn					Attri and Kerkar (2011)
Gulf of Kachchh	Co, Cr, Cu, Fe, Mn, Ni		Pb					Cr, Cu, Ni, Pb, Zn				Cd	Chakraborty et al. (2014)

9.4 Processes Governing the Distribution of Trace Metals

Other than the inputs from the terrestrial runoff and marine inputs (Peters et al. 1997), processes like redox potential, organic matter content, texture of the sediment, flocculation-deflocculation, etc., control the distribution and availability of the trace metals in the mangrove ecosystems. The anaerobic sediments of mangrove with high sulphur content favour trace metal retention, especially Fe and Mn, by combining with sulphides (Silva et al. 1990). Further, the Fe-Mn complex encourages retention of other metals due to the geochemical affinity with other trace metals. Hence, it is also referred as sink of trace metals (Förstner and Wittman 1983). Changing redox potential (oxidation) also causes metal desorption from the sediment to the water column making it mobile and bioavailable (Silva et al. 1990; Marchand et al. 2006). Sediment organic matter acts as a metal carrier (Ray et al. 2006), changing salinity regimes encourages flocculation (Eckert and Slokowitz 1976) and fine particles enhance metal accumulation by precipitation of metals as hydroxide coating over them (Förstner and Wittman 1983; Salomons and Förstner 1984).

The high Cd concentration in surface sediments of Pichavaram mangrove was attributed to the combined effect of both non-point anthropogenic inputs (fertilizers brought in by Vellar, Uppanar and Coleroon river) as well as natural sources, along with inputs of Cd-rich sediment from deep ocean carried by the tsunami (Li et al. 2006; Seralathan et al. 2006). Enrichment of Pb in Pichavaram mangrove indicates that the metal is precipitated around the redox boundaries (Lee and Cundy 2001), and the downward flux of Pb is bound to biogenic particles (Lambert et al. 1991) which increases its concentration. Aquaculture effluents, agricultural runoff and domestic sewage also play a role in Pb enrichment in the area (Purvaja and Ramesh 2000; Subramanian 2004). A higher value of Pb at Manakudy estuary mangrove (161.254 μg/g) were due to the local redox condition that allowed Pb to coprecipitate with Mn during Mn-oxide formation in the superficial segment (Lee and Cundy 2001). Early diagenesis of organic matter in sediments may also cause trace metal redistribution (Prajith et al. 2016).

9.5 Concerns

Accumulations of trace metals have been already reported in many Asian mangroves and associated flora and fauna (Sandilyan and Kathiresan 2014). Trace metals' presence has been reported in more than 30 mangrove species and their various tissues (Lewis et al. 2011). Trace metals have been found in *Avicennia* and *Barringtonia* species of Kerala mangroves showing variable metal accumulation (Thomas and Fernandez 1997). Similarly, trace metals have been reported from stems and leaves of Bhitarkanika mangroves with stem showing higher accumulation (Panda et al. 2013). Bioaccumulation of trace metals in leaves of mangroves from Pichavaram revealed higher concentration of Pb than the normal range of contamination factor reported for plants (Agoramoorthy et al. 2008). Mangroves support various species like fishes and crabs with 60% of commercial fishes in Fiji and India (Lewis et al. 2011). Thus, it may pose threat for many fishes and crustaceans as roots of mangroves have higher accumulation capacity (Sandilyan and Kathiresan 2014). Other bottom dwelling faunal species like crabs, shrimps and filter feeders also face the risk of metal accumulation (Kaviraj and Guhathakurta 2004). Trace metals from mangrove environment can make up their way to human beings directly or indirectly via herbal medicine, honey, seafood and dairy products (Sandilyan and Kathiresan 2014). Recently, Pb and Cr concentration in important edible species of bivalves in the Vellar estuary were reported to be higher than the permitted WHO/EPA limits (Ponnusamy et al. 2014).

Mangrove ecosystems act as a trap for contaminants transported to the coastal ecosystems (Sandilyan and Kathiresan 2014), adversely affecting various species surviving there and ultimately affecting the food chain. Metal stress can weaken the mangrove vivacity (vigour) making it prone to pathological attacks (Awal 2014) and also affecting the general biodiversity in those habitats.

9.6 Summary and Conclusion

The increase of trace metals in the mangrove sediment may be attributed to many factors like the abundance of fine particles having a greater surface area, which increases precipitation of metals as hydroxide coating (mainly Fe and Mn) over them. Factors like high organic matter content, flocculation due to varying salinity and transportation of deep shore sediments to the coastal zone also contribute significantly towards enrichment of heavy metals in sediments. The high values of metals like Fe and Mn in the mangrove sediment could be attributed to the precipitation of the respective metal sulphide compounds in anaerobic sediments. Fe-Mn also shows very close distribution pattern of enrichment in surface/subsurface layers of sediment cores which might be due to the early diagenetic processes as well as the strong association to the geochemical matrix between the two elements. The precipitated Fe in the form of oxyhydroxides has the affinity to scavenge other metals such as Cu and Pb, as they pass through the water en route to the sediment. Many trace metals like Cd, Cu, Pb and Zn have a wide range of sources, mainly anthropogenic, like untreated waste discharge from industries, agricultural runoff, sewage effluent and other surface runoffs. Tsunamigenic sediments show higher contamination factor, enrichment factor and potential ecological risk index than other mangrove sediments, which might be due to higher waste discharge at that time along with tsunami-driven sediments derived from the deep ocean. Thus, it shows that mangrove ecosystem act as the sink for trace metals; many mangrove species also act as a bioaccumulator of trace metals that after dying and degeneration enhances the trace metal concentration in mangrove ecosystem thus increasing its vulnerability.

References

Agoramoorthy G, Hsu MJ (2005) China's battle against escalating environmental pollution. Curr Sci 89:1073–1074

Agoramoorthy G, Chen FA, Hsu MJ et al (2008) Threat of heavy metal pollution in halophytic and mangrove plants of Tamil Nadu, India. Environ Pollut 155(2):320–326

Antizar-Ladislao B, Mondal P, Mitra S, Sarkar SK (2015) Assessment of trace metal contamination level and toxicity in sediments from coastal regions of West Bengal, eastern part of India. Mar Pollut Bull 101(2):886–894

Attri K, Kerkar S (2011) Seasonal assessment of heavy metal pollution in tropical mangrove sediments (Goa, India). J Ecobiotechnol 3(8):09–15

Awal MA (2014) Analysis of possible environmental factors causing top-dying in mangrove forest trees in the Sundarbanss in Bangladesh. Am J Biosci 2(4):135–146

Badarudeen A, Damodaran KT, Sajan K, Padmalal D (1996) Texture and geochemistry of the sediments of a tropical mangrove ecosystem, southwest coast of India. Environ Geo 27(3):164–169

Banerjee K, Senthilkumar B, Purvaja R, Ramesh R (2012) Sedimentation and trace metal distribution in selected locations of Sundarbans mangroves and Hooghly estuary, Northeast coast of India. Environ Geochem Health 34:27–42

Borges AV, Djenidi S, Lacroix G, Theate J, Delille B, Frankignoule M (2003) Atmospheric CO_2 fluxes from mangrove surrounding waters. Geophys Res Lett 30(11):12–14

Chakraborty R, Zaman S, Mukhopadhyay N, Banerjee K, Mitra A (2009) Seasonal variation of Zn, Cu and Pb in the estuarine stretch of west Bengal. Indian J Mar Sci 38(1):104–109

Chakraborty S, Bhattacharya T, Singh G, Maity JP (2014) Benthic macroalgae as biological indicators of heavy metal pollution in the marine environments: a biomonitoring approach for pollution assessment. Ecotoxicol Environ Saf 100:61–68

Chakraborty P, Ramteke D, Chakraborty S (2015) Geochemical partitioning of Cu and Ni in mangrove sediments: relationships with their bioavailability. Mar Pollut Bull 93(1):194–201

Chatterjee M, Massolo S, Sarkar SK, Bhattacharya AK, Bhattacharya BD, Satpathy KK, Saha S et al (2009) An assessment of trace element contamination in intertidal sediment cores of Sundarbans mangrove wetland, India for evaluating sediment quality guidelines. Environ Monit Assess 150:307–322

Chowdhury R, Favas PJC, Pratas J, Jonathan MP, Ganesh PS, Sarkar SK (2015) Accumulation of trace metals by mangrove plants in Indian Sundarban Wetland: prospects for phytoremediation. Int J Phytoremediat 17:885–894

Dias HQ, Nayak GN (2016) Geochemistry and bioavailability of mudflats and mangrove sediments and their effect on bioaccumulation in selected organisms within a tropical (Zuari) estuary, Goa, India. Mar Pollut Bull 105(1):227–236

Eckert JM, Sholkovitz ER (1976) The flocculation of Fe, Al and humates from river water by electrolytes. Geochim Cosmochim Acta 40(7):847–856

Ergin M, Saydam C, Baştürk Ö, Erdem E, Yörük R (1991) Heavy metal concentrations in surface sediments from the two coastal inlets (Golden Horn Estuary and Izmit Bay) of the northeastern sea of Marmara. Chem Geol 91(3):269–285

Esen E, Kucuksezgin F, El U (2010) Assessment of trace metal pollution in surface sediments of Nemrut Bay, Aegean Sea. Environ Monit Assess 160(1–4):257–266

Fernandes MC, Nayak GN (2016) Role of sediment size in the distribution and abundance of metals in a tropical (Sharavati) estuary, west coast of India. Arab J Geosci 9(1):1–3

Fernandes L, Nayak GN, Ilangovan D (2012) Geochemical assessment of metal concentrations in mangrove sediments along Mumbai Coast, India. World Acad Sci Eng Technol 6:1–26

Förstner U, Wittman GTW (1983) Metal pollution in the aquatic environment. Springer Science & Business Media, Berlin

FSI (2015) India state of forest report 2015: mangrove cover, forest survey of India (Ministry of Environment, Forests and Climate Change). Government of India, Dehradun, pp 62–67

Håkanson L (1980) An ecological risk index for aquatic pollution control, a sedimentological approach. Water Res 14:975–1001

Jonathan MP, Sarkar SK, Roy PD, Alam MA, Chatterjee M, Bhattacharya BD, Bhattacharya A, Satpathy KK (2010) Acid leachable trace metals in sediment cores from Sundarbans mangrove Wetland, India: an approach towards regular monitoring. Ecotoxicology 19:405–418

Kathiresan K, Bingham BL (2001) Biology of mangroves and mangrove ecosystems. Adv Mar Biol 40:81–251

Kaviraj A, Guhathakurta H (2004) Heavy metal deposition in some Brackish water ponds of Sundarbans (India) during off-season of shrimp culture. Asian Fish Sci 17:29–38

Kehrig HA, Pinto FN, Moreira I, Malm O et al (2003) Heavy metals and methyl mercury in a tropical coastal estuary and a mangrove in Brazil. Org Geochem 34(5):661–669

Kumar R (2000) Conservation and management of mangroves in India, with special reference to the state of Goa and the Middle Andaman Islands. Unasylva 203(51):41–46

Kumar A, Ramanathan AL (2015) Speciation of selected trace metals (Fe, Mn, Cu and Zn) with depth in the sediments of Sundarbans mangroves: India and Bangladesh. J Soils Sediments 15(12):2476–2486

Kumar G, Kumar M, Ramanathan AL (2015) Assessment of heavy metal contamination in the surface sediments in the mangrove ecosystem of Gulf of Kachchh, West Coast of India. Environ Earth Sci 74:545–556

Kumar A, Ramanathan AL, Prasad MBK, Datta D, Kumar M, Sappal SM (2016) Distribution, enrichment, and potential toxicity of trace metals in the surface sediments of Sundarbans mangrove ecosystem, Bangladesh: a baseline study before Sundarbans oil spill of December, 2014. Environ Sci Pollut Res 23:8985–8999

Lambert C, Veron A, Buatmenard P et al (1991) The role of large biogenic particles in the transport of atmospheric pollutant Pb down to north-Atlantic sediments. Oceanol Acta 14(1):67–76

Lee SV, Cundy AB (2001) Heavy metal contamination and mixing processes in sediments from the Humber Estuary, eastern England. Estuar Coast Shelf Sci 53:619–636

Leivouri M (1998) Heavy metal contaminants in surface sediments in the gulf of Finland and comparison with the gulf of Bothnia. Chemosphere 36:43–59

Lewis M, Pryor R, Wilkin L et al (2011) Fate and effects of anthropogenic chemicals in mangrove ecosystems: a review. Environ Pollut 159:2328–2346

Li XD, Wai OWH, Li YS, Seralathan P, Srinivasalu S, Ramanathan AL (2006) Post tsunami sediments characteristics of Tamilnadu coast. In: Rajamanickam GV (ed) 26th December 2004 tsunami causes, effects remedial measures, pre and post tsunami disaster management, a geoscientific perspective. New Academic Publisher, New Delhi, pp 190–215

Macfarlane GR, Koller CE, Blomberg SP (2007) Accumulation and partitioning of heavy metals in mangroves: a synthesis of field-based studies. Chemosphere 69:1454–1464

Marchand C, Lallier-verges E, Baltzer F, Albéric P, Cossa D, Baillif P (2006) Heavy metals distribution in mangrove sediments along the mobile coastline of French Guiana. Mar Chem 98:1–17

Mucha AP, Vasconcelos MTS, Bordalo AA (2003) Macrobenthic community in the Douro estuary: relations with trace metals and natural sediment characteristics. Environ Pollut 121(2):169–180

Muller G (1981) Die Schwermetallbelastung der Sedimenten des Neckars und Seiner Nebenflusse. Chemiker-Zeitung 6:157–164

Natesan U, Kumar M, Deepthi K (2014) Anthropogenic effects on sediment quality of Muthupet mangroves assessing the sediment core geochemical record. Indian J Mar Sci 43(6):1045–1054

Nobi EP, Dilipan E, Thangaradjou T, Sivakumar K, Kannan L (2010) Geochemical and geostatistical assessment of heavy metal concentration in the sediments of different coastal ecosystems of Andaman Islands, India. Estuar Coast Shelf Sci 87:253–264

Noronha-D'Mello CA, Nayak GN et al (2015) Geochemical characterization of mangrove sediments of the Zuari estuarine system, West coast of India. Estuar Coast Shelf Sci 167:313–325

Palpandi C, Kesavan K (2012) Heavy metal monitoring using *Nerita crepidularia* – mangrove mollusc from the Vellar estuary, Southeast coast of India. Asian Pac J Trop Biomed 2(1):S358–S367

Panda S, Chaturvedi N, Dhal N, Rout N (2013) An assessment of heavy metal accumulation in mangrove species of Bhitarkanika, Odisha, India. Res Plant Biol 3:1–5

Peters EC, Gassman NJ, Firman JC, Richmond RH, Power EA (1997) Ecotoxicology of tropical marine ecosystems. Environ Toxicol Chem 16:12–40

Ponnusamy K, Sivaperumal P, Suresh M, Arularasan S, Munilkumar S, Pal AK (2014) Heavy metal concentration from biologically important edible species of bivalves (*Perna viridis* and *Modiolus metcalfei*) from Vellar estuary, south east coast of India. J Aquacult Res Dev 5(5):1–5

Prajith A, Rao VP, Chakraborty P (2016) Distribution, provenance and early diagenesis of major and trace metals in sediment cores from the Mandovi estuary, western India. Estuar Coast Shelf Sci 170:173–185

Purvaja R, Ramesh R (2000) Human impacts on methane emission from mangrove ecosystems in India. Reg Environ Chang 1:86–97

Raman DJ, Jonathan MP, Srinivasalu S, Armstrong AJS, Mohan SP, Rammohan V (2007) Trace metal enrichments in core sediments in Muthupet mangroves, SE coast of India: application of acid leachable technique. Environ Pollut 145:245–257

Ramanathan AL, Subramanian V, Ramesh R, Chidambaram S, James A et al (1999) Environmental geochemistry of the Pichavaram mangrove ecosystem (tropical), southeast coast of India. Environ Geol 37(3):223–233

Ramaswamy V, Nath BN, Vethamony P, Illangovan D (2007) Source and dispersal of suspended sediment in the macro-tidal gulf of Kachchh. Mar Pollut Bull 54(6):708–719

Ramesh R, Kumar RA, Inamdar AB, Mohan PM, Pritiviraj M, Ramachandran S, Purvaja R, Chinkeri MK, Dolendro TH, Venkataraman G, Khire MV, Gedam SS, Rao YS, Adinarayana J, Nagarajan R (2006) Tsunami characterization and mapping in Andaman and Nicobar islands. In: Rajamanickam GV (ed) 26th December 2004 tsunami causes, effects remedial measures, pre and post tsunami disaster management, a geoscientific perspective. New Academic Publisher, New Delhi, pp 150–174

Ranjan RK, Ramanathan AL, Singh G, Chidambaram S (2008) Assessment of metal enrichments in tsunamigenic sediments of Pichavaram mangroves, southeast coast of India. Environ Monit Assess 147:389–411

Ranjan RK, Singh G, Routh J, Ramanathan AL (2013) Trace metal fractionation in the Pichavaram mangrove–estuarine sediments in southeast India after the tsunami of 2004. Environ Monit Assess 185:8197–8213

Ray AK, Tripathy SC, Patra S, Sarma VV (2006) Assessment of Godavari estuarine mangrove ecosystem through trace metal studies. Environ Int 32:219–222

Salomons W, Förstner U (1984) Sediments and the transport of metals. In: Metals in the hydrocycle. Springer, Berlin, p 63–98

Sandilyan S, Kathiresan K (2014) Decline of mangroves–a threat of heavy metal poisoning in Asia. Ocean Coast Manag 102:161–168

Sarangi RK, Kathiresan K, Subramanian AN (2002) Metal concentrations in five mangrove species of the Bhitarkanika, Orissa, east coast of India. Indian J Mar Sci 31(3):251–253

Sarkar SK, Bilinski SF, Bhattacharya AK, Saha M, Bilinski H (2004) Levels of elements in the surficial estuarine sediments of the Hugli River, northeast India and their environmental implications. Environ Int 30:1089–1098

Sarkar SK, Cabral H, Chatterjee M, Cardoso I, Bhattacharya AK, Satpathy KK, Aftab AMA (2008) Biomonitoring of heavy metals using the bivalve molluscs in Sundarbans mangrove wetland, Northeast coast of bay of Bengal (India): possible risks to human health. CLEAN – Soil Air Water 36(2):187–194

Seralathan P, Srinivasalu S, Ramanathan AL, Rajamanickam GV, Nagendra R, Singarasubramanian SR (2006) Post tsunami sediments characteristics of Tamilnadu Coast. In: Rajamanickam GV (ed) 26th December 2004 tsunami causes, effects remedial measures, pre and post tsunami disaster management, a geoscientific perspective. New Academic Publisher, New Delhi, pp 124–149

Silva CAR, Lacerda LD, Rezende CE (1990) Metals reservoir in a red mangrove forest. Biotropica 22(4):339–345

Subramanian AN (2004) Status of Indian mangroves: pollution status of the Pichavaram mangrove area, southeast coast of India. In: Vannucci M (ed) Mangrove management and conservation. United Nations University Press, Tokyo, pp 59–75

Thomas G, Fernandez TV (1997) Incidence of heavy metals in the mangrove flora and sediments in Kerala, India. In: Asia-Pacific Conference on Science and Management of Coastal Environment, Springer, p 77–87

Tomlinson DL, Wilson JG, Harris CR, Jeffrey DW (1980) Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. Helgoländer Meeresun 33(1–4):566–575

Veerasingam S, Vethamony P, Mani Murali R, Fernandes B (2015) Depositional record of trace metals and degree of contamination in core sediments from the Mandovi estuarine mangrove ecosystem, west coast of India. Mar Pollut Bull 91:362–367

Part IV

Current Issues and Climate Change

Climate Change Impacts on Wetlands of Bangladesh, its Biodiversity and Ecology, and Actions and Programs to Reduce Risks

10

Golam Kibria and A.K. Yousuf Haroon

Abstract

Climate change is projected to increase the intensity and frequency of disasters (floods, increased precipitation), the rise in temperature and sea level in Bangladesh, and the consequences of which will be felt across various sectors including wetlands and wetland-dependent ecosystems, biodiversity, agriculture, fisheries, aquaculture, and livelihoods of people. Hence, this will cause significant economic, social, and environmental challenges/problems for Bangladesh. The major negative impacts of climate change would be damage/destruction of wetland ecosystems and their biodiversity such as, loss or shift of breeding grounds of the Gangetic major carps in the Halda River, Chittagong; loss of Royal Bengal Tiger habitats in the Sundarbans; salinization of rice lands, freshwater aquaculture facilities, and aquifers; water quality problems in wetlands, i.e., algal blooms, low dissolved oxygen, and enhancement of toxins in seafood organisms (fish, prawn); and loss of tourism/recreational business (due to loss of biodiversity). The positive impacts of climate change such as floods would reestablish the connection between rivers and shallow lakes/wetlands, disperse biota/seeds, and enhance spawning and reproduction of native fishes. In order to reduce threats to various sectors, Bangladesh would need to adopt climate resilient development programs/actions including conserving wetlands/mangroves (which are biodiversity "hot spots" and act as major carbon sinks); conserving

G. Kibria (✉)
School of Applied Sciences, Royal Melbourne Institute of Technology (RMIT) University, Melbourne, Australia
e-mail: kibriagolam0@gmail.com

A.K. Yousuf Haroon
Food and Agriculture Organization (FAO) of the UN, Dhaka, Bangladesh
e-mail: dharoon@ymail.com; akyousuf.haroon@fao.org

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_10

species with higher genetic diversity; use of 3F models (simultaneous forestry, food, and fish production in coastal areas) to reduce vulnerabilities in coastal communities; floating agriculture (waterlogged/flood-prone areas); and climate-smart aquaculture, rainwater harvesting, and use of renewable energy. Awareness and education programs including inclusion of climate change in curriculum at primary, secondary, and tertiary educational institutions would be essential. Bangladesh needs to act now, act together, and act differently to enhance development and reduce vulnerability to climate change for a sustainable future.

Keywords
Bangladesh • Climate change impacts • Wetlands • Climate resilient development

10.1 Introduction

Wetlands are areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salty, including areas of marine water, the depth of which at low tide does not exceed 6 m (Ramsar 1971). Wetlands are classified into three broad categories: *inland wetlands* (marshes, swamps, lakes, rivers, streams and creeks, arid wetlands, and floodplains), *marine/coastal wetlands* (shallow marine waters, saltwater marshes, seagrass beds, kelp beds, estuaries, mangroves, coastal freshwater lagoons, and coral reefs), and *human-made wetlands* (fish/aquaculture ponds, irrigation channels, seasonally flooded agricultural land, reservoirs/dams, rice fields, canals, and drainage channels and ditches) (Ramsar 1971).

About three-quarters of the total population live in rural Bangladesh, relying on wetlands and its goods and services for livelihoods. Wetlands play an essential role in rural Bangladesh (agriculture, fishing, duck rearing, aquaculture, snail collection, bird hunting, fuelwood, wild food/vegetable, water for drinking, irrigation, recreation and stock and domestic supply, sand extraction, ecotourism, etc.). The total area of wetlands in Bangladesh is about 7–8 million ha, which is about 50 % of the total land area of the country (Islam 2010). Wetlands of Bangladesh encompass *haors* (freshwater marshes of bowl or saucer-shaped shallow depression), *baors* (oxbow lakes – dead arm of rivers), *beels* (saucer-shaped deeper part of the floodplain landscape), fish ponds and *dighi* (large ponds), flooded rice lands and floodplains, natural lakes, man-made reservoir (Kaptai lake), and coastal/estuarine mangroves (the Sundarbans) and marine areas (St. Martin's Coral Island). Several wetlands in Bangladesh are of national and international significances. Eight wetlands, where ecosystems have reached or threatened to reach a critical state, have been declared as ecologically critical area (ECA) (by the Ecologically Critical Area Ordinance, 2010, under the Bangladesh Environment Conservation Act, 1995). These wetlands are (1) Hakaluki Haor (Moulvibazar and Sylhet districts); (2) Tanguar Haor (Sunamganj district); (3) Marjat Baor (Jhenidah district); (4)

Gulshan-Baridhara Lake (Dhaka city); (5) the Buriganga River, the Shitalakhya River, the Turag River, and the Balu River (Dhaka and Narayanganj districts); (6) the Sundarbans mangrove (Khulna, Satkhira, and Bagerhat districts); (7) Sonadia Island (Cox's Bazar district); and (8) St. Martin's Coral Island (Cox's Bazar district) (http://en.banglapedia.org/index.php?title=Ecologically_Critical_Area; https://en.wikipedia.org/wiki/Ecologically_Critical_Area).

Climate change (the rise in temperatures, carbon dioxide, sea level, ocean acidification, intensity and frequency of extreme events – precipitation, floods, droughts, heat waves/hot extremes, cyclones, bushfire, etc.) is a new and an additional threat to wetlands, its ecology, and biodiversity in Bangladesh (in addition to existing threats posed by pollution, river regulations, dams, overexploitation of resources). Bangladesh can be divided into four climate risk "hot spots" (Box 10.1). This chapter highlights the projected impacts of climate change on wetlands of Bangladesh (world climate risk ranks #1) and suggests actions and climate resilient adaptation and mitigation programs to reduce such impacts on wetlands.

Box 10.1: Climate Change "Hot Spots" in Bangladesh

Bangladesh can be divided into four climate change/natural disaster risk "hot spots" as listed below:

(a) *Cyclone and storm surge risk "hot spot"* – areas close to the Bay of Bengal (southern coastal and marine zone), which are prone to cyclones, storms, and tidal surges including Chittagong, Cox's Bazar, Patuakhali, Barisal, Barguna, Bhola, Hatia, Sandwip, Satkhira, and Khulna and would impact marine fishing, saltwater shrimp farming, aquaculture, agriculture, infrastructure, human settlement, life, and property.

(b) *Flood risk "hot spot"* – most areas of Bangladesh, in particular, areas located in the central and northeastern part of Bangladesh and *char** lands. This would impact agriculture, fisheries (both capture and culture), livestock, water, infrastructure, health, energy, and human settlement *(*char* is a low-lying river island*).*

(c) *Sea-level rise (SLR) and salinity intrusion risk "hot spot"* – southern coastal districts and marine zones where salinity could rise and intrude further inland due to low water flows from the upstream or rise of sea level, in particular, in the southwest region and islands. This would impact agriculture, capture fisheries, aquaculture, water resources, human settlement, electricity supply, and ecological and public health.

(d) *Drought and temperature risk "hot spot"* – northwest region which includes Rajshahi, Kurigram, Nilphamary, Rangpur, and Dinajpur districts and would impact agriculture, fisheries both capture and culture, water availability, electricity supply, and health.

(Based on Rashid et al. 2009; Nishat and Mukherjee 2013a; Kibria 2014a http://www.ldeo.columbia.edu/chrr/research/profiles/pdfs/bangladesh_profile1.pdf)

10.2 Climate Change Impacts on Wetlands of Bangladesh

Climate change [the rise in global temperatures; current 0.8 °C, future – 2 °C by 2040, and 4 °C by 2100 from the preindustrial levels] will cause significant economic, social, and environmental challenges/problems for Bangladesh. Climate change is projected to increase the intensity and frequency of disasters, floods, and sea-level rise (SLR). The consequences of these changes will be felt across various sectors including wetlands and associated ecosystems, biodiversity, water, agriculture, fisheries, aquaculture, human health, and livelihoods (Haque et al. 2010; World Bank 2010; IPCC 2013; Kibria et al. 2013; Rashid and Paul 2014).

10.2.1 Rise of Temperature

Over the past 100 years, Bangladesh has warmed by about 0.5 °C (Ahmad et al. 1996), and the surface temperature from an annual average of 24.46 °C (1969–1990) is projected to reach 28.13 °C (2070–2099) (Cline 2007). In fact, the projected temperature increase will be in the range of 3–3.5 °C by 2100 (http://eprints.nottingham.ac.uk/2040/6/Bangladesh.pdf). The rise in temperature may cause significant impacts on wetland's water quality and biodiversity as discussed below:

The rise in temperature would increase water temperatures in a number of World Rivers including the Ganges-Brahmaputra in Bangladesh by 1.2 °C (van Vliet et al. 2013). Rising water temperatures will reduce dissolved oxygen in water bodies (since oxygen solubility in water is inversely related to temperature) and may cause hypoxic conditions (extremely low level of oxygen <2.8 mg/L) in lakes and rivers. Decreased dissolved oxygen in water can impair fish growth, can alter reproductive success (lower fertilization, hatching success), can cause endocrine disruption (e.g., increased incidence of malformations in fish and may alter fish sex) (Wu et al. 2003; Wu 2009), can affect species diversity, and can create dead zones in coastal/marine systems (Altieri and Gedan 2015). For optimum growth of fish and other aquatic organisms, dissolved oxygen levels in waterbodies should be more than 5.0 mg/L (Kibria et al. 2010).

The expected rise in surface water temperature could accelerate the growth of harmful algal blooms, which produce toxins [microcystins by cyanobacteria/blue-green algae in freshwater, paralytic shellfish poisoning (PSP) and ciguatera fish poisoning (CFP) by dinoflagellates in the marine environment]. For example, increased temperatures may lead to cyanobacterial bloom in freshwater wetlands (Rapala and Sivonnen 1998; Chorus and Bartram 1999; Håkanson et al. 2007). There is a competitive advantage for cyanobacteria to grow better in warmer temperatures since they generally exhibit optimal growth rates at relatively high temperatures, usually in excess of 25 °C (Paerl and Huisman 2008). Cyanobacterial blooms may cause water quality problems (e.g., low dissolved oxygen, unusual tastes and odor, discoloration, and unsightly scum), making such water unfit for irrigation, recreation, livestock and human drinking, fisheries, aquaculture, and other domestic uses (Kibria et al. 2016a). Furthermore, during cyanobacterial blooms, accumulation of microcystins can occur in the gut, liver, kidney, blood, gills and muscle of fish, prawn, crabs, and mussels (Ibelings and Havens 2008) that may damage the vital organs. Cyanobacteria are reported to have caused significant fish kills in ponds in Bangladesh (Kibria 2014b). Several studies reported accumulation of freshwater biotoxins (microcystins) and marine biotoxins (PSP and CFP) in plankton-feeding finfish and filter-feeding shellfish. Microcystins, PSP, and CFP can be transferred to other organisms higher up in the food chain such as humans on eating contaminated seafood (Kibria et al. 2013).

Global warming may enhance bioaccumulation potential of other toxins (pesticides, metals) in aquatic organisms (such as fish). Bioaccumulation is the uptake/accumulation of chemicals by a living organism by all possible routes, including respiratory surfaces (gills), and ingestion (see below). Bioaccumulation of pollutants such as pesticides and heavy metals to aquatic organisms such as fish could be enhanced with increasing temperatures (Noyes et al. 2009; Marques et al. 2010; Anawar 2013; Kibria et al. 2016b). Consequently, there could be a decline of recreational and commercial fisheries in Bangladesh due to lethal and sublethal effects of toxicants on fish growth and reproduction. At higher temperatures, metabolism of aquatic organisms increases, oxygen concentration in water reduces, and the rate of water flow into the aquatic animals (fish) would be higher to extract more oxygen (via gills) resulting in entry of more dissolved pollutants (heavy metals such as cadmium, mercury, and lead and pesticides such as chlorpyrifos, DDT, endosulfan) into the fish and accumulation in fish tissues (Ficke et al. 2007; Marques et al. 2010; Kibria et al. 2016b). These toxins can then be transferred to humans through contaminated seafood (fish, prawn, and shrimp; Kibria et al. 2010, 2013).

Rise in temperature because of climate change may cause significant impacts on biodiversity of wetlands: (i) allow certain species to stay in the environment since they can tolerate/adapt to changes, (ii) cause some species to move out to a suitable environment, (iii) some species may shift to increased depths (e.g., fish) in the oceans to escape heat or warming, or (iv) some species may die out or go extinct (species with restricted distribution and longer generation time may not be able to migrate or adapt to climate change) (Nally et al. 2010). Thus, the rise in temperature may cause some taxa and species (such as fish) to migrate away from coastal Bangladesh to a suitable cooler environment beyond Bangladesh territory. This would affect local seafood catch, local economy, and livelihoods of people associated with fishing (Kibria et al. 2017).

Weeds, insects (pests), and diseases are likely to increase in Bangladesh in a warmer environment (warmer climates are favorable for proliferation of insect pests and vectors), which would potentially reduce crop yields requiring overuse of chemical pesticides (Kibria et al. 2013). In addition, the rise in global temperature will tend to extend shifts and ranges of many invasive aquatic plants, such as the waterweed, *Eichhornia* sp. (water hyacinth), and *Salvinia* sp. (floating fern) (Bates et al. 2008). Water hyacinth is the worst aquatic weed/pest plant in Bangladesh and has already choked many wetlands and waterways. Further invasion of water hyacinth in wetlands of the country would cause extensive environmental, social, and economic problems. Furthermore, changing global temperatures may increase the susceptibility of fish to diseases since the bacterial, whirling disease in aquaculture systems often peaks at high temperatures (Kibria et al. 2010).

10.2.2 Sea-Level Rise (SLR)

Sea-level rise (SLR) is the average increase in the level of world's oceans. Global warming or increases in temperature cause the oceans to warm and expand in volume inducing a rise in the sea levels. Furthermore, warmer climate facilitates melting of glaciers, ice caps, and ice sheets causing further addition of water to the oceans. The average SLR in the Ganges-Brahmaputra delta in Bangladesh (1 inch. or 25.4 mm) has been recorded in sections of the Ganges-Brahmaputra delta (Alam 1996; Ericson et al. 2005), which is much higher than global SLR (0.12 in. or 3.05 mm per year recorded during 1993–2003, IPCC 2007). It is projected that Bangladesh could lose nearly one-quarter of land area it had in 1989 by the end of this century due to SLR in a worst-case scenario (Ericson et al. 2005).

Bangladesh is highly vulnerable to the effects of SLR. It would lead to contamination of both surface and groundwater with chloride (salt), in particular in the low-lying coastal areas, and have the potential to affect thousands of wells that supply freshwater to approximately 17 million people (UNEP 2006). More than 30 % of the cultivable land in Bangladesh is in the coastal area. Because of SLR, agriculture land (rice lands) in coastal districts (Bagerhat, Khulna, and Satkhira) would be salinized, thus, seriously threatening food security in Bangladesh by making water and soil too salty for rice and other crops. Increased salinity inhibits rice growth and reduces yield. Salinization will also affect freshwater aquaculture and reduce the area available for the same (Kibria 2014a). Furthermore, SLR may cause loss/shift of natural breeding grounds of native fish species – the Gangetic major carps (rui, *Labeo rohita*; katal, *Catla catla*; mrigal, *Cirrhinus cirrhosus*) in the Halda River, Chittagong (http://archive.thedailystar.net/newDesign/news-details.php?nid=184249, http://archive.thedailystar.net/newDesign/story.php?nid=121231) *[note: Halda is the only tidal river in the world, from where fertilized eggs of the Gangetic carps are collected].*

SLR of 1 m would cause complete loss of the Sundarbans mangrove of Bangladesh resulting in the loss of heritage, biodiversity, and fisheries (World Bank 2000). A 28 cm SLR is projected to cause a 96 % decline of the Royal Bengal tiger (*Panthera tigris tigris*) habitats in the Sundarbans (Loucks et al. 2010). Nursery and breeding grounds of many estuarine fish and migratory species residing in the Sundarbans mangroves may be affected due to SLR (World Bank 2000), and this would impact aquaculture (shrimps/prawns/fish/crab) seed supply and fisheries in general. The SLR may cause replacement of the most dominant, freshwater-loving important trees in the Sundarbans, *Sundari* trees (*Heritiera fomes*) by salt-tolerant trees such as Goran (*Ceriops decandra*, *C. tagal*) and Keora (*Sonneratia apetala*) (World Bank 2000). *[Note: Sundari trees are most common and important timber producing trees, used for building houses, boats, furniture, electric poles and hardboard, whereas Goran and Keora trees are used as fuel wood and for charcoal production].* As a consequence of SLR, low salinity tolerant species/freshwater-loving mangrove plants of the Sundarbans such as *H. fomes* and *Nypa fruticans* (Goal pata) will most likely be affected (Table 10.1). It is also projected that the distribution and habitat of the globally endangered Ganges river dolphin (*Platanista* *gangetica gangetica*) and Irrawaddy dolphin (*Orcaella brevirostris*) in the Sundarbans offshore areas, preferring lower salinity, may be totally lost due to SLR in Bangladesh (Smith et al. 2009). Loss or damage of ecosystems and biodiversity in the Sundarbans mangroves would affect livelihoods of millions of people dependent on these wetlands for wood, food, timber, water, medicines, honey, fruits, and fisheries.

10.2.3 Ocean Acidification (OA)

The ocean absorbs approximately 30% of CO_2 added to the atmosphere from human activities including fossil fuel burning, industries, cement manufacturing, deforestation, and land use changes. CO_2 dissolves in water, forms carbonic acid (H_2CO_3), and causes decrease in ocean pH (due to increase in hydrogen ion concentration or H^+). This phenomenon is called as ocean acidification (Roessig et al. 2005; Meehl et al. 2007; Turley et al. 2010). The higher absorption of CO_2 has already acidified the surface layers of the ocean causing an overall decrease of 0.1 pH units since the preindustrial period, which is equivalent to a 30 % increase in hydrogen ion concentration or acidity. The surface ocean pH is projected to decrease by 0.3–0.4 pH units by 2100 relative to preindustrial conditions, equivalent to 150 % increase in acidity (H^+) and 50 % decrease in CO_3^{2}- (Meehl et al. 2007; Wittmann and Pörtner 2013).

Ocean acidification will adversely affect many organisms that require calcium carbonate for their skeletons and shells, such as corals, mollusks, pteropods, and some phytoplankton (Kibria 2015a). Ocean acidification has already caused much effect on calcareous animals and plants (e.g., coral bleaching) (Doney et al. 2009; Turley et al. 2010). Wittmann and Pörtner (2013) conducted sensitivities of five living animal taxa (corals, echinoderms, mollusks, crustaceans, fishes) to a wide range of CO_2 concentrations. They found that all animal groups examined were affected negatively by higher CO_2 concentrations; of these, corals, echinoderms and mollusks were very sensitive to a decline in water pH. It is reported that ocean acidification caused tissue damage in many internal organs of cod fish larvae (liver, pancreas, kidney, eye, and the gut) (Frommel et al. 2012) and reduced survival and growth rates of early life stages of silverside fish (Baumann et al. 2012); therefore, it (like other chemical stressors) could cause a decline in valuable wild fisheries (Nugegoda and Kibria 2016). In the case of Bangladesh, ocean acidification may cause significant consequences on biodiversity of St. Martin's Coral Island (the only Coral Island, locally known as *Narikel Jinjira*). St. Martin's Island is a biodiversity "hot spot" with 66 species of corals, 234 species of fish (of which 89 species are coral reef associated), 187 species of mollusks, 12 species of crabs, and 154 species of marine algae including 10 species of seaweeds (Thompson and Islam 2010, http://www.fao.org/docrep/field/003/ab727e/AB727E03.htm). Loss of biodiversity (corals, etc.) in St. Martin's Island due to ocean acidification would mean the loss of seafood security, tourism revenues, and livelihoods of people as fishing and tourism are the main occupations for the Island's 5,500 residents. However, ocean

Table 10.1 Possible threats of SLR on key mangrove plants of the Sundarbans of Bangladesh

Mangrove species	Threats of SLR
Local name: **Sundari**; English name: Sundar; Scientific name*:* *Heritiera fomes;* Conservation status: endangered	**Freshwater loving plants**; found in the upstream estuarine areas; SLR is a major threat if there is no back area to expand and landward movement of the species is blocked due to coastal development. With the rise in sea level, the habitat requirement of this species will be disrupted, will suffer mortality in their present locations, and may establish at higher elevations in areas that were previously landward
Local name: **Gewa**; English name: Gewa; Scientific name: *Excoecaria agallocha;* Conservation status: Least concerned	**Tolerates moderately saltwater**; SLR is a major threat if there is no back area to expand and landward movement of the species is blocked due to coastal development; this species will suffer mortality in their present locations and may establish at higher elevations in areas that were previously landward
Local name: **Goran**; English name: Indian/spurred mangrove; Scientific name: *Ceriops decandra;* Conservation status: Near threatened	Found in the intermediate estuarine zone, **optimal growth at 15 ppt salinity**; with the rise in sea level, the habitat requirement of this species will be disrupted and suffer mortality in their present locations and may establish at higher elevations in areas that were previously landward. If SLR is a continued trend over this century, then there will be continued mortality and new establishment of species zones
Local name: **Goal pata;** English name: Nypa/mangrove palm; Scientific name: *Nypa fruticans;* Conservation status: Least concerned	This species **prefers more freshwater environments**, found in brackish to tidal freshwater creeks and rivers; hypersaline conditions can threaten the species; SLR is a major threat if there is no back area to expand for the species and landward movement is blocked due to coastal development; species will suffer mortality in their present locations and may establish at higher elevations in areas that were previously landward
Local name: **Keora/kewora;** English name: Sonneratia mangrove; Scientific name: *Sonneratia apetala;* Conservation status: Least concerned	Found in the upstream estuarine zone, tolerates **polyhaline condition;** with the rise in sea level, the habitat requirements of the species will be disrupted, will suffer mortality in their present locations, and may establish at higher elevations in areas that were previously landward. If SLR is a continued trend over this century, there will be continued mortality and new establishment of this species zone
Local name: **Baen;** English name: Indian mangrove; Scientific name: *Avicennia officinalis;* Conservation status: Least concerned	**High tolerance of hypersaline conditions**; with the rise in sea level, the habitat requirements of the species will be disrupted, and species will suffer mortality in their present locations and establish at higher elevations in areas that were previously landward. If sea-level rise is a continued trend over this century, then there will be continued mortality and reestablishment of species zones

(continued)

Table 10.1 (continued)

Mangrove species	Threats of SLR
Local name: **Kankara;** English name: Oriental mangrove; Scientific name: *Bruguiera gymnorrhiza;* Conservation status: Least concerned	**Tolerates salinity up to 50 ppt**, optimal growth at 8–34 ppt; with the rise in sea level, the habitat requirements of the species will be disrupted, and species will suffer mortality in their present locations and may establish at higher elevations in areas that were previously landward. If sea-level rise is a continued trend over this century, then there will be continued mortality and new establishment of species zones
Local name: **Garjan;** English name: Red mangrove/Asiatic mangrove; Scientific name: *Rhizophora mucronata; R. apiculate;* Conservation status: Least concerned	**Tolerates salinity up to 40 ppt**, optimal growth at 8–33 ppt; with the rise in sea level, the habitat requirements of the species will be disrupted and species will suffer mortality in their present locations and may establish at higher elevations in areas that were previously landward zones. If SLR is a continued trend over this century, then there will be continued mortality and new establishment of species zones

Based on http://www.iucnredlist.org/details/-IUCN Red List of Threatened species; Aziz 2009

acidification would also enhance the productivity of seaweeds in the Island since CO_2 is a major component for photosynthesis of plants and would help those people engaged in seaweed culture and harvesting business (dry seaweed export to China, Myanmar, and Singapore).

10.2.4 Extreme Events

Climate change would likely increase the intensity and frequency of extreme weather events (heavy precipitation, floods, cyclones, storms, droughts, heat waves, and high sea level) across the globe (IPCC 2007). According to a World Bank report, Bangladesh is threatened by extreme river floods, more intense tropical cyclones, rising sea levels, and very high temperatures (http://www.worldbank.org/en/news/press-release/2013/06/19/warming-climate-to-hit-bangladesh-hard-with-sea-level-rise-more-floods-and-cyclones-world-bank-report-says). Precipitation and fluvial (river) flooding are projected to increase in Bangladesh in the future with climate change (DECCUK 2010). Bangladesh has experienced extreme floods during 1974, 1987, 1988, 1998, 2004, and 2007 and cyclones (Bhola cyclone 1970, Bangladesh cyclone 1991, Cyclone Sidr 2007, Cyclone Aila 2009) in recent times.

Climate change would increase flooded areas in Bangladesh by at least 25 % (range 23–29 %) with a global temperature rise of 2 °C (Mirza 2003; Kundzewicz et al. 2007), which would have both negative and positive effects. Floods may damage wetland ecosystems and their biodiversity. Extreme flood and rainfall events will increase runoff of contaminants/pollutants (pesticides, nutrients, polycyclic aromatic hydrocarbons/oil, human and animal wastes, and pathogens) into waterways and deteriorate water quality. Large floods can injure larval and juvenile fish and other aquatic organisms and may displace adult fish. Floods would cause loss or damage of property, human lives, crops, vegetables, and livestock in the country.

On the other hand, floods would help recharge groundwater and reestablish connectivity between rivers and shallow lakes and wetlands; increase movement of sediments, nutrients and energy, vital for ecosystem functions; enhance migration of aquatic biodiversity and help dispersal of biota and seeds; and enhance spawning of native fishes (flood pulse is a cue for spawning of the Gangetic major carps and many native fishes). Floods will also improve water quality by flushing out salt from coastal rivers/lands, reducing the problem of dissolved oxygen or algal blooms and dilution of chemical and biological pollutants. Projected increase in rainfall would increase the amount of water available for irrigation in Bangladesh.

10.3 Climate Change Adaptation and Mitigation Measures for Bangladesh

To reduce impacts of climate change on wetlands of Bangladesh (to protect/restore/enhance ecology and biodiversity/reduce pressure/enhance livelihoods of people associated with wetlands of Bangladesh), a number of climate resilient/climate-smart adaptation (adjustment/actions to reduce vulnerability and exploit beneficial opportunities) and mitigation (reduce or enhance sinking of Greenhouse Gases – CO_2, CH_4, N_2O) measures would be required. Some simple, low-carbon, low-cost, and environment-friendly adaptation and mitigation models in the context of Bangladesh are proposed in Fig. 10.1a–f. Adaptation and mitigation measures to reduce vulnerability in wetlands and its ecology and biodiversity are briefly discussed in the following sections.

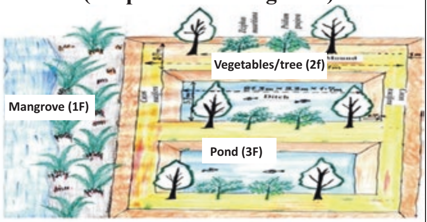
Climate change is now recognized as a major threat to the survival of aquatic species and integrity of wetland ecosystems worldwide. Wetlands that are already being affected by other stressors (dams, pollution, and overexploitation of resources, deforestation, and pest species invasion) are likely to have faster and more acute reactions to climate change. Stress on wetlands can be prevented or reduced by adopting different adaptation strategies as listed below (based on Fischlin et al. 2007; World Bank 2010; Sovacool et al. 2012, Staudinger et al. 2012, Kibria 2015b):

1. Conserving species diversity with higher genetic diversity
2. Conserving wetlands/mangrove habitats (which are biodiversity "hot spots" and act as major carbon sinks; see Fig. 10.1)
3. Restoring habitat structure to increase rare habitat abundance
4. Reducing water stress on water dominant biodiversity
5. Preserving existing and intact floodplain rivers (as strategic global resources such as Ramsar wetlands of the Sundarbans mangrove forest and Tanguar *haor* in Bangladesh)
6. Removing barriers and assisting in the migration of species (to help move species and populations from current locations to those areas expected to become more suitable in the future)
7. Seed banking and captive breeding (conserve live germplasm)

10.1A Afforestation/reforestation/REDD (mitigation)

Afforestation/reforestation/REDD/conservation of mangroves (such as the Sundarban mangroves) would help to reduce CO_2 from the atmosphere (via photosynthesis, carbon sinks in sediments/soils); reduce impacts of disasters (cyclones/ storms/ floods) as forest wall; minimize soil erosion; enhance forest resources/biodiversity, water quality, fisheries; tourism, livelihoods, and mitigate climate change (Kibria et al. 2013); REDD= Reducing Emissions from Deforestation and Forest Degradation (image source: https://www.google.com.au)

10.1B 3F Models (forestry, food and fish) (adaptation & mitigation)



3F models (simultaneous forestry, food, fish production) would reduce the vulnerability of coastal communities of Bangladesh. Mangroves (1F) should be planted along the perimeter of the elevated homesteads to protect against cyclones/ storms; vegetables (2F) at the backyard, and fish/shrimp farming (3F) in dug-out ponds/ gher (Rawlani et al. 2011, Kibria et al. 2013) (image source: Rawlani et al. 2011)

10.1C Floating/hydroponics agriculture (adaptation)

Floating agriculture on beds of rotten water hyacinths stacked together where hyacinth act as compost can be a solution and climate resilient adaptation to regular water logging/prolonged flooding areas in a flood prone country like Bangladesh. It would alleviate poverty, enhance food security, support capacity for poor/ landless people, allow both men and women to work on this simple technology leading to better gender equity (Kibria et al. 2013) (image source: https://www.google.com.au)

10.1D Climate smart aquaculture (adaptation)

Herbivorous fish farming/aquaculture; integrated rice-fish-duck farming; integrated brackish water aquaculture-mangrove etc. have good potential to adapt to and mitigate climate change effects. Such practices would enhance farmer's income, diversify livelihoods, recycle wastes for food production and are energy and resource efficient (Kibria et al. 2013) (image source: https://www.google.com.au)

Fig. 10.1 Examples of climate change/climate-smart adaptation and mitigation models for Bangladesh

10.1E Sustainable water- rainwater (adaptation)	**10.1F Renewable/clean energy (mitigation)**
	
Surface water and groundwater in Bangladesh are contaminated with microbial pathogens and arsenic respectively. Sea-Level Rise would cause salinization of freshwater aquifers and coastal freshwater resources. Bangladesh receives significant amount of rainfall (1,640-2,831 mm/ annum; average 2,347 mm/ annum) (Nishat and Mukherjee 2013b). Rainwater collected from house roofs is a free, natural, sustainable resource and has nil/minimal Greenhouse Gas (GHG) emissions. This can help mitigate scarcity of drinking water along the entire southern coastal areas and reduce pressure on wetland's water resources (Kibria et al. 2013) (image source: https://www.google.com.au)	Renewable Energy (RE) (solar) is a clean energy with nil/minimal GHG emissions and creates opportunity to mitigate climate change/global warming. The availability of plenty of the sunshine in Bangladesh provides potential for solar energy revolution (Kibria et al. 2013). Solar power can be used in rural houses, for irrigation pumping and small transports etc. It would reduce fossil fuels use, carbon pollution and health hazards associated with the use of forest wood, charcoal, cattle dung for cooking in rural Bangladesh. Solar power use reduces impacts on wetlands and biodiversity from climate change/GHG emissions (image source: https://www.google.com.au)

Fig. 10.1 (continued)

8. Reducing non-climate stressors (e.g., habitat fragmentation/destruction, pollution, alien species) to help fish, wildlife, plants, and ecosystems adapt to a changing climate and to enhance resilience to climate change
9. Provision/allocation for environmental water for wetlands to be affected by droughts
10. Increase awareness education to safeguard fish, wildlife, and plants

Other adaptation and mitigation measures to reduce climate change impacts on wetlands of Bangladesh are illustrated in Fig. 10.1b (simultaneous forestry, food, and fish production), Fig. 10.1c (floating agriculture), Fig. 10.1d (climate-smart aquaculture), Fig. 10.1e (sustainable water-rainwater use), and Fig. 10.1f (renewable/clean energy use). In addition, awareness and education programs should be continued so that local communities are more aware of climate change impacts on wetlands and plan for climate resilient adaptation and mitigation-related development programs to reduce impacts on wetlands (as highlighted in Fig. 10.1a–f). It will also be essential to include climate change issues and implications in the curriculum at primary, secondary, and tertiary educational institutions in Bangladesh.

10.4 Conclusion

Climate change will impact Bangladesh severely. Local people do not have the skills/technology/expertise to adapt to climate change efficiently and effectively or manage increasing climate risks. Therefore, Bangladesh needs to act to reduce impacts of climate change on climate-sensitive natural resources like wetlands, its ecology, and biodiversity and wetland-dependent agriculture, fisheries, aquaculture, and water resources on which majority of Bangladeshi people depend for food, water, and their very livelihoods. Some of the adaptation and mitigation models proposed in Fig. 10.1a–f are simple, low-carbon/low-cost technology, environmentally friendly, and easily adaptable to Bangladesh. Secondly, climate change is a global crisis; therefore, Bangladesh would need to act and work unitedly to reduce global emission of GHGs and keep global warming to <2 °C. For example, a 2 °C warming above the preindustrial temperature level could result in permanent reduction in GDP of 4–5 % for South Asia and Africa. Lastly, Bangladesh would have to act differently to build infrastructures/assets, shift cropping patterns and lifestyle, and ensure energy revolution so that the country can withstand new climatic conditions and transit toward low emissions/low-carbon growth paths and climate change and disaster resilient development (e.g., integrating climate risks in all development programs and making development more resilient to climate change) for the foreseeable future while preserving ecosystems. It is imperative that Bangladesh formulates and implements climate-smart policies and programs (based on new information and recent scientific evidence) to enhance climate resilient development and reduce vulnerability to climate-sensitive wetlands, its biodiversity, and ecosystems while significantly reducing its own carbon footprints for a sustainable future.

Acknowledgments We have acknowledged sources of data and information and figures/images both in the reference section and in the texts.

References

Ahmad QK, Warrick RA, Ericksen NJ and Mirza MQ (1996) The implications of climate change for Bangladesh: a synthesis. In: Warrick RA, Ahmad QK (eds) The implications of climate change and sea-level rise for Bangladesh. Chapter 1: p 1–28. Kluwer Academic Publishers, Dordrecht. ISBN-13:978-94-0l0-6591-7 1; DOI:10.1007/978-94-009-0241-1

Alam M (1996) Subsidence of the Ganges-Brahmaputra Delta of Bangladesh and associated drainage, sedimentation and salinity problems. In: Milliman JD, Haq BU (eds) Sea-level rise and coastal subsidence. Kluwer Academic Publishers, Dordrecht, pp 169–187

Altieri AH, Gedan KB (2015) Climate change and dead zones. Glob Chang Biol 21(4):1395–1406

Anawar HM (2013) Impact of climate change on acid mine drainage generation and contaminant transport in water ecosystems of semi-arid and arid mining areas. Phys Chem Earth 58–60:13–21

Aziz M (2009) Coastal and marine plant resources of Bangladesh: management and exploitation. http://www.dhakai.com/botany/Keynote%20paper%20of%20Annual%20Bot.%20Conference%202009.pdf

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water, Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva, p 210

Baumann H, Talmage SC, Gobler CJ (2012) Reduced early life growth and survival in a fish in direct response to increased carbon dioxide. Nat Clim Chang 2:38–41 http://dx.doi.org/10.1038/NCLIMATE1291

Chorus I and Bartram J (eds) (1999) Toxic cyanobacteria in water. A guide to their public health consequences, monitoring and management. Published by WHO, E and FN Spon Press, London, p 416

Cline WR (2007) Global warming and agriculture. Impact estimates by country. Centre for Global Development and the Peterson Institute for International Economics, Washington, DC

DECCUK (2010) Department of energy and climate change, UK. 2011. Climate: observations, projections and impacts: Bangladesh. Research conducted by Met Office, Hadley Centre, The University of Nottingham, Walker Institute, Centre for Ecology and Hydrology, University of Leeds, Tyndall Centre for Climate change http://eprints.nottingham.ac.uk/2040/6/Bangladesh.pdf

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean acidifications: the other CO_2 problems. Annu Rev Mar Sci 1:169–192

Ericson JP, Vorosmarty CJ, Dingman SL, Ward LG, Meybeck M (2005) Effective sea-level rise and deltas: causes of change and human dimension implications. Glob Planet Chang 50:63–82

Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on freshwater fisheries. Rev Fish Biol Fish 17:581–613

Fischlin A, Midgley GF, Price JT, Leemans R, Gopal B, Turley C, Rounsevell MDA, Dube OP, Tarazona J and Velichko A (2007) Ecosystems, their properties, goods, and services. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 211–272

Frommel AY, Maneja R, Lowe D, Malzahn AM, Geffen AJ, Folkvord A, Piatkowski U, Reusch TBH, Clemmesen C (2012) Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. Nat Clim Chang 2:42–46

Håkanson L, Bryhn AC, Hytteborn JK (2007) On the issue of limiting nutrient and predictions of cyanobacteria in aquatic systems. Sci Total Environ 379:89–108

Haque U, Hashizume M, Glass GE, Dewan AM, Overgaard HJ, Yamamoto T (2010) The role of climate variability in the spread of Malaria in Bangladeshi Highlands. PLoS One 5(12):e14341. doi:10.1371/journal.pone.0014341

Ibelings BW and Havens KE (2008) Cyanobacterial toxins: a qualitative meta–analysis of concentrations dosage and effects in freshwater, estuarine and marine biota. In: Hudnell HK (ed) Cyanobacterial harmful algal blooms: state of the science and research needs. Advances in experimental medicine and biology, 1, vol 619. pp 675–732

IPCC (2007) Summary for policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, p 996

IPCC (2013) Summary for policymakers. In: Stocker TF, Qin D, Plattner GK, Tignor MS, Allen K, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

Islam SN (2010) Threatened wetlands and ecologically sensitive ecosystems management in Bangladesh. Front Earth Sci China 4(4):438–448

Kibria G (2014a) Sea-level rise and its impact on wetlands, water, agriculture, fisheries, aquaculture, public health, displacement, infrastructure and adaptation. https://www.researchgate.net/publication/266794121_Sea-level_rise_and_its_impact_on_wetlands_water_agriculture_fisheries_aquaculture_public_health_displacement_infrastructure_and_adaptation

Kibria G (2014b) Global fish kills: causes and consequences. DOI: 10.13140/RG.2.1.1422.8965. https://www.researchgate.net/publication/261216309_Global_fish_Kills_Causes_and_Consequences

Kibria G (2015a) Ocean acidification and its impact on marine biodiversity, seafood security & livelihoods- a short review. DOI: 10.13140/RG.2.1.5138.4808 https://www.researchgate.net/publication/282093645_Ocean_Acidification_and_Its_Impact_on_Marine_Biodiversity_Seafood_Security_Livelihoods-_A_Short_Review

Kibria G (2015b) World wetlands and emerging threats from climate change. https://www.researchgate.net/publication/273948155_World_Wetlands_and_Emerging_Threats_from_Climate_Change

Kibria G, Haroon AKY, Nugegoda D, Rose G (2010) Climate change and chemicals- environmental biological aspects. New India Publishing Agency, New Delhi

Kibria G, Haroon AKY, Nugegoda D (2013) Climate change and agricultural food production: impacts, vulnerabilities and remedies. New India Publishing Agency, New Delhi

Kibria G, Haroon AKY, Nugegoda D (2016a) Climate change and water security: impacts, future projections, adaptations and mitigations. New India Publishing Agency, New Delhi. doi:10.13140/RG.2.1.1848.1528/2 *https://www.researchgate.net/publication/303218799_Climate_Change_Water_Security_-_A_Book_Summary*

Kibria G, Hossain MM, Mallick D, Lau TC, Wu R (2016b) Trace/heavy metal pollution monitoring in estuary and coastal area of bay of Bengal, Bangladesh and implicated impacts. Mar Pollut Bull 105(1):93–402. doi:10.1016/j.marpolbul.2016.02.021

Kibria G, Haroon AKY, Nugegoda D (2017) Climate change impacts on tropical and temperate fisheries, aquaculture, and seafood security and implications - A review. Livestock Research for Rural Development 29(12). http://www.lrrd.org/lrrd29/1/kibr29012.htm

Kundzewicz ZW, Mata LJ, Arnell NW, Doll P, Kabat P, Jimenez B, Miller KA, Oki T, Sen Z, Shiklomanov I (2007) Freshwater resources and their management. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on climate Change. Cambridge University Press, Cambridge, UK, pp 173–210

Loucks C, Barber-Meyer S, Hossain MAA, Barlow A, Chowdhury RM (2010) Sea level rise and tigers: predicted impacts to Bangladesh's sundarbans mangroves a letter. Clim Chang 98:291–298

Marques A, Nunes ML, Moore SK, Strom MS (2010) Climate change and seafood safety: human health implications. Food Res Int 43:1766–1779

Meehl GA, Stocker TF, Collins W, Friedlingstein P, Gaye A, Gregory J, Kitoh A, Knutti R, Murphy A, Noda S, Raper I, Watterson I, Weaver A, Zhao ZC (2007) Global climate change projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp 747–845

Mirza MMQ (2003) Three recent extreme floods in Bangladesh: a hydro meteorological analysis. Nat Hazards 28:35–64

Nally RM, Cunningham RS, Shelly K, Sgro C, Thompson R, Lake S, Sunnuck P, Cavagnaro T, O'Dowd D, Baker P, Beardall J (2010) Biodiversity and climate change. Report prepared by the Australian Centre for Biodiversity. Monash University, Victoria , p 17Australian Centre for Biodiversity, Melbourne

Nishat A and Mukherjee N (2013a) Sea level rise and its impacts in coastal areas of Bangladesh. In: Shaw et al. (eds) Climate change adaptation actions in Bangladesh. Disaster risk reduction, methods, approaches and practices, pp 43–50. DOI 10.1007/978–4–431-54249-0_2, Springer Japan 2013

Nishat A, Mukherjee N (2013b) Climate change impacts, scenario and vulnerability of Bangladesh. In: Shaw et al. (eds) Climate change adaptation actions in Bangladesh. Disaster risk reduction, methods, approaches and practices, pp 15–41. DOI 10.1007/978–4–431-54249-0_2, Springer Japan 2013

Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC et al (2009) The toxicology of climate change: environmental contaminants in a warming world. Environ Int 35:971–986

Nugegoda D, Kibria G (2016) Effects of environmental chemicals on fish thyroid function: implications for fisheries and aquaculture in Australia. Gen Comp Endocrinol. Feb 2016. http://dx.doi.org/10.1016/j.ygcen.2016.02.021

Paerl HW, Huisman J (2008) Blooms like it hot. Science 320:57–58

Ramsar (1971) Convention on wetlands of international importance especially as waterfowl habitat. Ramsar Convention Secretariat, Gland, Switzerland. http://www.ramsar.org/cda/en/ramsar-documents-texts/main/ramsar/1-31-38_4000_0__>

Rapala J, Sivonnen K (1998) Assessment of environmental conditions that favour hepatotoxic and neurotoxic Anabaena spp. Strains cultured under light limitation at different temperatures. Microb Ecol 36:181–192

Rashid H, Paul B (2014) Climate change in Bangladesh-confronting impending disasters. Lexington Books, Plymouth

Rashid AKMM, Singha D and Imam H (2009) Climate change vulnerability in Bangladesh: strategic position of DSK/DCA in the field of climate change adaptation initiatives in Bangladesh. Dustha Shastha Kendra (DSK) and Dan Church Aid (DCA), p 32

Rawlani AK, Benjamin K, Sovacool BK (2011) Building responsiveness to climate change through community-based adaptation in Bangladesh. Mitig Adapt Strateg Glob Chang 16:845–863

Roessig JM, Woodley CM, Cech JJ, Hansen LJ (2005) Effects of global climate change on marine and estuarine fishes and fisheries. Rev Fish Biol Fish 14:251–275

Smith BD, Braulik G, Strindberg S, Mansur R, Diyan MAA, Ahmed BA (2009) Habitat selection of freshwater-dependent cetaceans and the potential effects of declining freshwater flows and sea-level rise in waterways of the Sundarbans mangrove forest, Bangladesh. Aquat Conserv Mar Freshwat Ecosyst 19:209–225

Sovacool BK, D'Agostino AL, Meenawat H, Rawlani A (2012) Expert views of climate change adaptation in least developed Asia. J Environ Manag 97:78–88

Staudinger MD, Grimm NB, Staudt A, Carter SL, Chapin-III FS, Kareiva P, Ruckelshaus M and Stein BA (2012) Impacts of climate change on biodiversity, ecosystems and ecosystem services: technical input to the 2013 national climate assessment. Cooperative report to the 2013 National Climate Assessment 296 p http://assessment.globalchange.gov

Thompson PM, Islam MA (eds) (2010) Environmental profile of St. Martin's Island, United Nations Development Programme, Dhaka http://samiasaif.weebly.com/uploads/1/6/7/9/16797564/environmental_profile_of_st_martins_island.pdf

Turley C, Eby M, Ridgwell AJ et al (2010) The societal challenge of ocean acidification. Mar Pollut Bull 60:787–792

UNEP (2006) United Nations environment programme (2006) potential impact of sea-level rise on Bangladesh: potential impacts of climate change http://www.grida.no/climate/vital/33.htm

van Vliet MTH, Franssen WHP, Yearsley JR, Ludwig F, Haddeland I, Lettenmaier DP, Kabat P (2013) Global river discharge and water temperature under climate change. Glob Environ Chang 23:450–464

Wittmann AC, Pörtner H-O (2013) Sensitivities of extant animal taxa to ocean acidification. Nat Clim Chang. Published Online: 25 Aug, DOI: 10.1038/NCLIMATE1982

World Bank (2000) Bangladesh: climate change and sustainable development report No. 21104 BD, Dhaka.

World Bank (2010) World development report. development and climate change. The International Bank for Reconstruction and Development/The World Bank. Washington, DC 20433; www.worldbank.org

Wu R (2009) Effects of hypoxia on fish reproduction and development. Fish Physiol 27(3):79–141

Wu RSS, Zhou BS, Randall DJ, Woo NYD, Lam PKS (2003) Aquatic hypoxia is an endocrine disruptor and impairs fish reproduction. Environ Sci Technol 37:1137–1141

Wetlands of Tropical Islands under Changing Climate: A Case from Nicobar Group of Islands, India

11

S. Dam Roy, P. Krishnan, A. Velmurugan, A. Anand, Grinson George, R. Kiruba Sankar, and T.P. Swarnam

Abstract

Wetlands have significant value to the tropical islands owing to their significance in terms of biodiversity, coastal protection, and economic values. This chapter highlights the impact of climate change on the wetlands of tropical islands, with Nicobar group of islands in India as a representative case. Nicobar has a prominent tribal group practicing community living by gathering resources available from the terrestrial and coastal waters. The islands are vulnerable to sea level rise and extreme events such as *tsunami*, earthquake, and cyclones that affect their routine life. The receding arable and forest areas also affect their livelihood. The projected changes in mean temperature and precipitation for Nicobar region indicate that the rainfall pattern is all set to change significantly during different seasons and the pattern of change in Nicobar would be different from that in Andaman. The magnitude of climate vagaries is likely to be more prominent in the years to come. This chapter illustrates the vulnerability of tropical island ecosystems in general and the Nicobar Islands in particular, to changing climate

S. Dam Roy (✉) • A. Velmurugan • R. Kiruba Sankar • T.P. Swarnam
ICAR – Central Island Agricultural Research Institute (CIARI), Port Blair, Andaman, India
e-mail: sibnarayan@gmail.com; vels_21@yahoo.com; rkirubasankar@gmail.com; swarna_8@yahoo.com

P. Krishnan
National Centre for Sustainable Coastal Management (NCSCM), Ministry of Environment Forest & Climate Change, Anna University Campus, Chennai 600 025 Tamil Nadu, India
e-mail: krishnanars@yahoo.com

A. Anand
Regional Centre of National Remote Sensing Centre (NRSC), Nagpur, India
e-mail: anand_isro@rediffmail.com

G. George
ICAR-Central Marine Fisheries Research Institute (CMFRI), Kochi, Kerala, India
e-mail: grinsongeorge@gmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_11

and calls for incorporating sea level rise into coastal planning and development of appropriate decision-support systems for taking adaptive action, in order to mitigate the impacts of climate change on these islands and their wetland ecosystems.

Keywords
Climate change • Digital elevation model • Resource depletion • Vulnerability

11.1 Introduction

Wetlands are one of the most productive and biologically diverse ecosystems, which provide essential habitats for many species and play crucial role in hydrological cycle. Wetlands play important roles in nutrient cycle, climate change (climate mitigation and adaptation), food security (provision for crops and nurseries for fisheries), job security (maintenance of fisheries, soil quality for agriculture), and a range of cultural benefits, including knowledge (scientific and traditional), recreation and tourism, and formation of cultural values, including identity and spiritual values (ten Brink et al. 2013). Even though wetlands cover only 7 % of the earth's surface, they deliver 45 % of the world's natural productivity and ecosystem services (Panigrahy et al. 2010).

In an island ecosystem, wetlands are very important, and they range from marine to freshwater systems. Wetlands of small islands assume even greater significance, because they are the largest component of such island ecosystems in terms of area and species composition. Further, they regulate water quantity, facilitate groundwater recharge and floods, and at times resist the impacts of storms. Most importantly, wetlands help in erosion control and sediment transport, thereby contributing to land formation and increasing resilience to storms (ten Brink et al. 2013). All these ecosystem services improve water security including those from natural hazards and help in climate change adaptation of small islands. However, in recent times, wetlands in most of the islands have come under increased pressure from anthropogenic activities, climate change events, sea level rise (SLR), and extreme events, affecting the very existence of these important ecosystems. The SLR and sea surges will have significant and profound effects on settlements, living conditions, and island economies more than any other casual factors because of concentration of human populations, agricultural lands, and infrastructures in the coastal zone. This in turn makes the coastal communities rely more on the wetland resources for their livelihood resulting in further degradation of wetlands habitat and shrinking of their geographical extent. These changes are manifested by way of decrease in their ecosystem services that are a major cause of concern for island communities across the world.

Even though total submergence of the islands is not an immediate event due to climate change (IPCC 2007), the decreasing ecosystem services of the island wetlands may trigger socioeconomic consequences including large-scale migration of people in the near future. Such migrating population, termed as climate refugees, from small islands to large or developed countries would undermine the socioeconomic fabric of many islands in the tropical region. Therefore, proper understanding of the climate change and variability over these tropical islands with an emphasis on the wetland resources of Nicobar group of islands will assist in devising appropriate strategy for wetland management and improve their ability to provide continued ecosystem services.

11.2 Importance of Wetlands in the Tropical Islands

As majority of Small Island Developing States (SIDS) are situated in the tropics, they are bestowed with vast expanses of coastally sensitive ecosystems, which include coral reefs, mangrove forests, and sea grass beds with rich marine biodiversity. A typical wetland ecosystem of an island has several components from the seafront to the center of the island (Fig. 11.1). The mangroves and corals in the seafront protect shorelines and serve as nursery grounds to fish seed and juveniles, which is vital for sustainability of the fishery sector. There are few fishes such as groupers and snappers which require a primary spawning area near corals. They are much valued in the food market also. Therefore, a reduction in island wetland areas may affect such fishes which have habitat preferences to coral reefs, mangroves, and other low-lying wetlands. Apart from raising the shores of the islands and protecting them against SLR, mangroves and coral reefs also act as a barrier and natural breakwater to small islands. This provides a natural protection to islands against storm surges and *tsunamis* as evidenced from the variations in impact of 2004 *tsunami* in Andaman and Nicobar Islands (ANI), India. Coral reefs are the main habitat for a variety of marine life and together with lagoons are integral component of the island tourism sector. Hence, the contributions of wetlands are significant in sustaining the economy of small islands. Further, the freshwater component of island wetlands is limited in size, yet they are very important to meet the vital freshwater requirement. The freshwater wetlands not only provide drinking water but also play

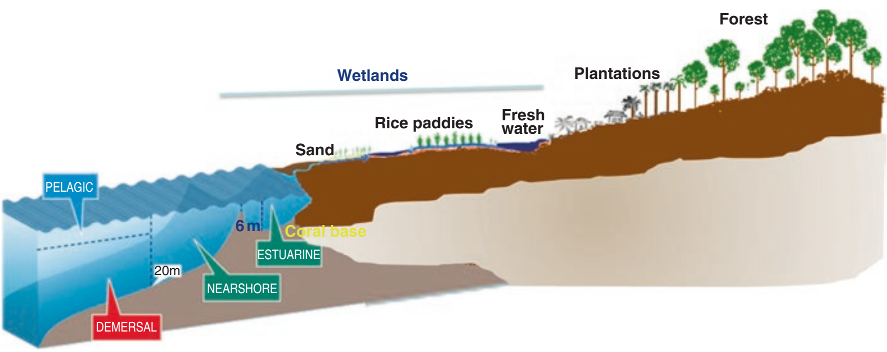


Fig. 11.1 Schematic diagram showing wetlands in a typical tropical island landscape

a key role in maintaining the salt balance in the groundwater resources of the islands by pushing back the seawater. The schematic diagram of the wetlands in an island ecosystem is shown in Fig. 11.1.

In the tropical Indian Ocean region, ANI are considered a biological paradise, with 8425 species of fauna, of which 846 species are endemic. The coral reefs of these islands rank next only to the Australian Great Barrier Reef, in terms of their global biodiversity. The sea grass beds in ANI occur in shallow coastal waters and sheltered bays, where the clear water allows penetration of sunlight down to the bottom. It is widely recognized that ecologically and economically, wetlands are the most important component of an island ecosystem and are vital for sustaining livelihood of island communities.

11.3 Impact of Climate Change on the Wetlands of Tropical Islands

11.3.1 Climate Change: An Overview

Climate change is a significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years. It may be a change in average weather climatic conditions or the distribution of events around that average (e.g., more or fewer extreme weather events). In general, climate change means a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere often referred as global warming and which is in addition to the natural climate variability observed over comparable time periods (UNFCC 1994). The interlink between different processes involved in climate change and response is depicted in Fig. 11.2. It shows that the human causes of climate change can be reduced by mitigation efforts, while the impact of climate change can be reduced by adaptation activities. This is more important for protecting the wetlands of islands and sustaining their ecosystem services.

Global warming continues steadily every decade. Each of the last three decades has been warmer than the preceding decades since 1850. Analysis of observational data showed a global mean temperature increase of around 0.6 °C during the twentieth century (IPCC 2007). It is clear that several trends associated with global warming of anthropogenic origin are intensifying and that specific rates of their intensification can be quantitatively estimated. Although global warming is not spatially uniform across the globe, probably there is no region in the world that is not experiencing some rise in average temperature.

The increase in mean temperature and SLR is of greater concern for the small islands (independent or part of continental states) than the continents. New observations and reanalyses of temperatures averaged over land and ocean surfaces show consistent warming trends in all small island regions during 1901–2004 (Trenberth et al. 2007). Besides, mean sea level rose by about 2 mm/year that is also affected by the local tectonics and El Niño-Southern Oscillation (ENSO) events that

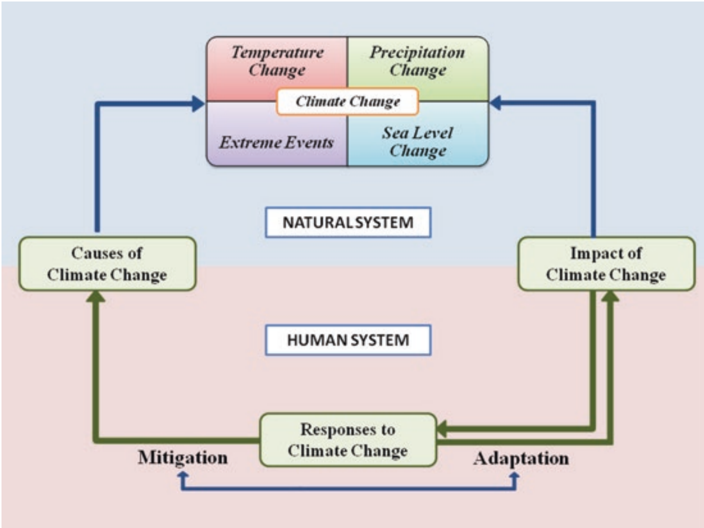


Fig. 11.2 Components of climate change process

originate in the sea. Intergovernmental Panel on Climate Change (IPCC 2007) also found much of the rainfall variability to be closely related to ENSO events, combined with seasonal and decadal changes in the convergence zones.

11.3.2 Climate Change and Its Impact on the Tropical Islands

11.3.2.1 Climate Change Events

The climate regimes of small islands are quite variable, generally characterized by large seasonal variability in precipitation and by small seasonal temperature differences in low-latitude islands and large seasonal temperature differences in high-latitude islands (IPCC 2007). In the Indian Ocean, the climate regimes of small islands in tropical regions are predominantly influenced by the Asian monsoon, the seasonal alternation of atmospheric flow patterns that results in two distinct monsoon patterns influenced by the ENSO events (IPCC 2007). Thus, wetlands are highly influenced by the occurrences of extreme climate and weather events in the region. In addition, the inherent characteristics of isolation, relatively small population and limited domestic land-based resources of small islands, bring about their own environmental and social challenges.

Reconstructed sea levels based on tide gauge data and TOPEX/Poseidon altimeter records in the Indian Ocean during 1950–2001 (Church et al. 2006) indicated relative SLR of 1.5, 1.3, and 1.5 mm/year (with error estimates of about 0.5 mm/year) at Port Louis, Rodrigues, and Cocos Islands, respectively. The situation appeared to be very grim for the Maldives as the available data suggested SLR of 4 mm/year measured at Male and Gan sea level sites (Khan et al. 2002). However, Church et al. (2006) noted that the SLR records from the Maldives has shown high variability in the SLR values between sites, and a 52-year reconstruction of SLR range suggested a common rate of rise of only 1.0–1.2 mm/year. In spite of this variability in measurements, SLR and the potential for stronger increase in storms surges pose an increasing threat to these islands by affecting the coastline, shoreline, infrastructures, sandy beaches, coastal wetlands, and their ecosystems.

11.3.2.2 Vulnerability of Wetlands in Tropical Islands to Changing Climate

The coastal wetlands of tropical islands are threatened by SLR, increase in sea surface temperature, sea surges, and possible increases in extreme weather events arising from a combination of human activity and climate change. The major impacts, as a consequence, are accelerated coastal erosion, saline intrusion into freshwater lenses, increased flooding from the sea, and loss of wetlands.

Sea level rise is arguably the most certain and potentially devastating climate change impact on these islands. Coastal inundation caused by SLR will decrease the land area of these islands with further consequence to inland wetlands and coastlines. It has long been recognized that islands on coral atolls are especially vulnerable to SLR, and the long-term viability of some atoll states are thus threatened. However, coasts particularly of islands respond dynamically in different ways to SLR which depends on factors such as the geological setting, coastal type, whether soft or hard shores, the rate of sediment supply relative to rate of submergence, sediment type (sand or gravel), presence or absence of natural shore protection structures such as beach rock or conglomerate outcrops, presence or absence of biotic protection such as mangroves and other strand vegetation, and the health of coral reefs (Mimura et al. 2007).

Apart from SLR and consequent coastline changes, the threat is likely to be amplified by increasing sea surface temperature and changes in tropical cyclones. Interestingly, several studies concluded that chemical, rather than geomorphological changes, could reduce the habitability and adaptive capacity of the low-lying islands. Oceanic absorption of atmospheric carbon dioxide as a result of increase in atmospheric CO_2 leads to ocean acidification (Caldeira and Wickett 2003; Royal Society 2005), which is likely to have detrimental effects on coral islands by reducing the productivity of corals and increasing the dissolution of calcium. Nevertheless, the impacts on coral reefs emanating from the events associated with climate change will not be uniform throughout the small island realm with lots of uncertainty expected in the combined effect.

Under the Special Report on Emissions Scenarios (SRES), small islands are seen to be particularly vulnerable to coastal flooding and decreased extent of coastal vegetated wetlands (Nicholls 2004). The expected changes in climate will also result in ecological problems of the coastal wetlands such as that from invasive alien species (Wilkie 2002). Due to the adverse living conditions brought out by changing climate in islands located at lower altitude, many species would migrate to islands located at higher latitudes. It is anticipated that mid-latitude and high-latitude islands are likely to be colonized by invasive species posing threat to the native species.

11.3.2.3 Water Resources

In an island ecosystem, freshwater from surface water bodies and groundwater are very important natural resources that may be seriously compromised due to climate change, particularly by decrease in precipitation and SLR. The freshwater aquaculture ponds, along the coast of these islands, provide livelihood security to small and marginal farmers. Coastal groundwater is a dynamic and replaceable resource, which plays a significant role in the overall circulation of water through the hydrologic cycle. In those areas away from the coast, groundwater will be impacted less directly and more slowly by climate change as compared to surface water, but in coastal areas groundwater will be directly affected by SLR (Ranjana et al. 2013). Sea level rise would directly affect the coastal river basin areas and increase saline water intrusion to the coastal areas of islands. Owing to factors of limited size, availability, and geology and topography, water resources in small islands are extremely vulnerable to changes and variations in climate, especially rainfall (IPCC 2001). Atolls and islands with limestone/coral as base have no surface water or streams and are fully reliant on rainfall and groundwater harvesting. Many small islands are experiencing water stress due to reduced rainfall and increased extraction of groundwater, which is often more than its recharge. Moreover, pollution of groundwater is emerging as a major problem especially on low-lying islands due to the rising human population and consequent developmental activities.

Rainfall is the only source of freshwater in small islands, and any variation in the amount of rainfall and its distribution would affect the availability of freshwater. Lower than the average rainfall leads to reduction in the amount of water flow in the streams and the rate of recharge of the groundwater while it increases the instances of drought. Further, it will heavily impact fisheries, coral reefs, and other wetland ecosystem resources and associated livelihoods. The dependency on rainfall significantly increases the vulnerability of small islands to future changes in amount and distribution of rainfall.

11.3.2.4 Agricultural Production Systems

Most of the tropical islands are dependent on subsistence farming for survival and cash crops for economic development apart from tourism. While subsistence agriculture provides local food security, cash crops such as sugar cane, bananas, and minor forest products (MFPs) are exported in order to earn foreign exchange. The situation has been changing as many island states are experiencing decrease in gross domestic product (GDP) contributions from agriculture, partly due to the drop in competitiveness of cash crops, cheaper imports from larger countries, increased costs of maintaining soil fertility, and competing uses for water resources, especially from tourism (FAO 2011). The projected impacts of climate change include extended periods of drought and / or loss of soil fertility and degradation as a result of increased precipitation, both of which will negatively impact on agriculture and food security. In addition, these islands have to invest heavily to rebuild their infrastructure affected by events associated with SLR. Together they increase the cost of production and decrease the seasonal availability of perishable agricultural commodities. But not all effects of climate change on agriculture are expected to be negative. For example, increased temperatures in high-latitude islands are likely to make conditions more suitable for agriculture and provide opportunities to enhance resilience of local food systems.

11.3.2.5 Fisheries

Wild capture fisheries practiced in coastal wetlands contribute sizeable portion of the GDP in the islands. However, in contrast to agriculture, the mobility of fish makes it difficult to estimate future changes in marine fish resources. Since the life cycles of many species of commercially exploited fishes extend from freshwater to ocean water, land-based and coastal activities will also affect the populations of such species. As the coral reefs and other coastal wetland ecosystems are sensitive to increase in sea surface temperature and other climate change events, consequent impacts would be felt on fishery production, which in turn will adversely affect the GDP as well as livelihood of people living in these islands (Graham et al. 2006). Further, these islands may experience loss of biodiversity in coastal wetlands due to inhospitable environmental conditions and its associated migration of some of the sensate fish species.

11.4 A Case Study of Nicobar Islands Under Changing Climate

11.4.1 The Background

The islands of the Andaman and Nicobar are similar to other tropical islands in several features such as remoteness, limited physical size, wetlands diversity, vulnerability to climate change, and developmental needs. The ANI are situated in the Bay of Bengal off the eastern coast of India in north to south orientation (Fig. 11.3) and connect with Indo-Malaysian realm, thereby forming a part of south as well as Southeast Asia. The Nicobar group of islands is separated from the Andaman group by 10° channel. The Nicobar group has 22 islands of which 13 are inhabited and are divided into three subdivisions, *viz.*, Car Nicobar, Nancowry group, and Great Nicobar. Many of these islands are coralline in origin. These islands are mainly inhabited by the tribals (Nicobarese and Shompens) and a large number of non-tribal settlers from mainland. Among the tribals, Nicobarese are the largest tribal group inhabiting 12 islands with major population in Car Nicobar. They were the last indigenous people to arrive in these islands and have racial mixture with the natives of Southeast Asia. A vast majority of the Nicobarese still pursue their traditional occupation of coconut plantation and pig rearing. The livestock of the tribals comprises of pigs (82 %) and goats (18 %), reared in extensive open semi-feral system (Swarnam et al. 2015). The tribals also utilize the vast coastal fishery resources of these islands. Many of the mangrove patches around the uninhabited islands are still in pristine stage, and in other islands it is largely intact.

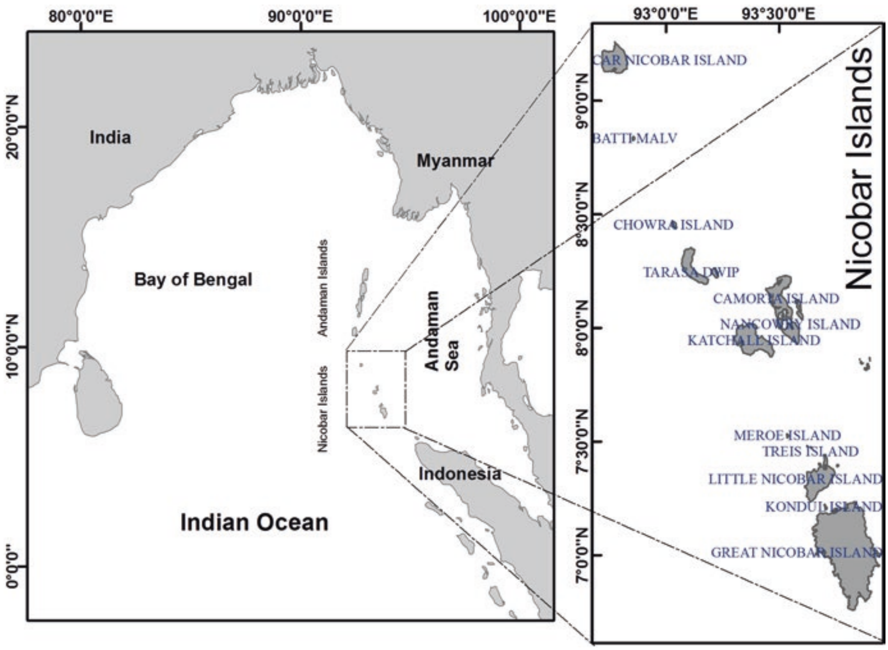


Fig. 11.3 Andaman and Nicobar Islands and Bay of Bengal region

11.4.2 Physiography and Land Use in Nicobar Islands

The physiography of an island is one of the most important factors influencing the land cover and land use. Wetlands in different physiographic locations have different characteristics and biodiversity composition. In addition, coastal erosion, stream flow, vulnerability to increase in sea level, and sea surges are influenced by the physiography of this island group. The Nicobar Islands are generally surrounded by shallow seas and coral reefs. Baring a few, the terrain in the islands is mostly undulating with the main ridges running north–south. In between the main ridges, deep inlets and creeks are formed by submerged valleys. Great Nicobar has five perennial rivers.

Among the Nicobar group of islands, Car Nicobar is flat except for some cliffs in the north and small hilly areas in the center. It is bordered by a flat ground consisting of coralline diluvium. Nancowry and Kamorta have a hilly terrain covered with grass, forming undulating meadows. In the central group, Katchal is slightly hilly in the center but has a remarkable flat area, like Car Nicobar. Trinket is a flat island, while Chowra is almost flat, except for a hill that is located at its southern tip. The other islands, *viz.*, Teresa, Tillangchong, and Bompoka have hilly terrain. The Great Nicobar Island, hilly and undulating, is the southernmost landmass of the Nicobar group of islands. The physiography of each island has profound influence on the distribution of crops and type of farming within and between the islands.

Table 11.1 Area estimates of wetlands in Nicobar

Wetland category	Number of wetlands	Total wetland area	% of wetland area
Inland wetland – natural			
Lakes/ponds	2	32	0.13
River/stream	4	367	1.48
Total – inland	6	399	1.61
Coastal wetlands – natural			
Lagoons	1	2	0.01
Creeks	11	75	0.3
Sand/beach	156	6858	27.74
Intertidal mud flats	94	6541	26.46
Salt march	38	2454	9.93
Mangroves	12	209	0.85
Coral	59	8158	33
Total – coastal	371	24,297	98.28
Subtotal	377	24,696	99.9
Wetlands (2.25 ha), mainly Tanks	25	25	0.1
Total	402	24,721	100

Source: SAC (2009)

In Nicobar group of islands, more than 90 % of reported area is under forest cover, and only the remaining is available for other uses including agriculture. However, the proportion of agricultural land to total area significantly varies from island to island. In Car Nicobar and Katchal, over 40 % of the total geographical area is under crops, and the rest of the islands has cultivable area ranging between 1 % and 19 %. The climate is very congenial for the growth of plantation crops; consequently, coconut occupies 84 % of area under agriculture (Swarnam et al. 2015). The dense canopy cover of coconut trees reduces the striking velocity of raindrop, the thick surface roots enable maximum infiltration of runoff water, and hence the rate of erosion is minimized. The existing land use favors accumulation of water in the shallow aquifers, which is the major source of freshwater.

11.4.3 Status of Wetlands in Nicobar

Area estimates of various wetland categories for Nicobar Islands were carried out by Space Applications Centre (SAC), Ahmedabad, India, using remote sensing and geographical information system (GIS). It revealed enormous diversity in wetlands according to their genesis, geographical location, water regime and chemistry, dominant plants, and soil or sediment characteristics (Table 11.1). The major wetland types in Nicobar are corals (8158 ha), followed by sand/beaches (6858 ha) and intertidal mud flats (6541 ha). Compared to the 4.6 % intertidal mud flats of Andaman group of islands, Nicobar mud flats occupy 26.5 % of wetland area (SAC

2009). The inland wetlands account for only 2 % when compared to coastal wetlands (24,297 ha) that account for 98.5 % of total wetland area. Similarly mangroves, which dominated the wetland area in Andaman Islands (51.47 %), account for less than 1 % of wetland area in Nicobar Islands. Similar is the case with creeks and paddy fields. The salt marsh and mangrove ecosystems in Nicobar Islands are subject to increase in water levels following the monsoon. Wetlands of Nicobar Islands support a large number of plant and animal species adapted to fluctuating water levels, making the wetlands of critical ecological significance. With the relevance of carbon footprint gaining momentum in a climate change perspective, wetlands are going to contribute largely to the green carbon indices of various commodities relevant to the islands. Further, the fishery, a major livelihood and nutrition related activity, in the islands, is dependent on the wetlands. Reduction in wetlands will reduce the area for nursery growth phase of fishes and may result in less marine fish production.

11.4.4 Climate Change Projections for Nicobar Islands

The Nicobar group of islands experience hot and humid climate because of their location in equatorial zone surrounded by Andaman Sea and Bay of Bengal. The islands receive good rainfall, ranging from 2750 to 3000 mm each year, from both southwest and northeast monsoons. Maximum amount of rainfall is received during the monsoon (June–November) and minimum in dry season (January–April). The rainwater quantity during the showers decides the water lens formed on the seawater around the islands which in turn decides the groundwater recharging. Therefore, rainfall projections are done to understand the vulnerability of islands with respect to rainfall. The historical climatic data shows the mean relative humidity as 79 %, maximum temperature as 30.2 °C, and minimum temperature as 23.0 °C.

The analysis of historical rainfall data pertaining to these islands since 1951 showed no significant change in the average decadal rainfall, but the pattern of rainfall has changed with increase in the number of extreme rainfall events. The change in pattern of extreme rainfall events over Nicobar Islands during winter and post-monsoon seasons when there is a decreasing trend has consequences for the inland wetlands particularly of freshwater aquifers (Velmurugan et al. 2015). Lal (2004) also indicated increase in daily rainfall intensity for many of smaller islands.

In an effort to understand future climate patterns, Intergovernmental Panel on Climate Change (IPCC) approved model; MAGIC/SCENGEN software (ICAR 2015) was used to generate two possible scenarios for the years 2025 and 2050 for rainfall and temperature in four seasons for Andaman and Nicobar group of islands. We looked into the seasonal variations also because of the typical rainfall-associated livelihood pattern, which is embedded in the cultural practices of the tribals residing in the islands. The projected rainfall for 2025 showed significant differences among the four seasons and between the two island groups of Andaman and Nicobar. The rainfall modeled for 2050 also significantly differed among the seasons, but not between the island groups. A decrease in precipitation (lower than mean seasonal

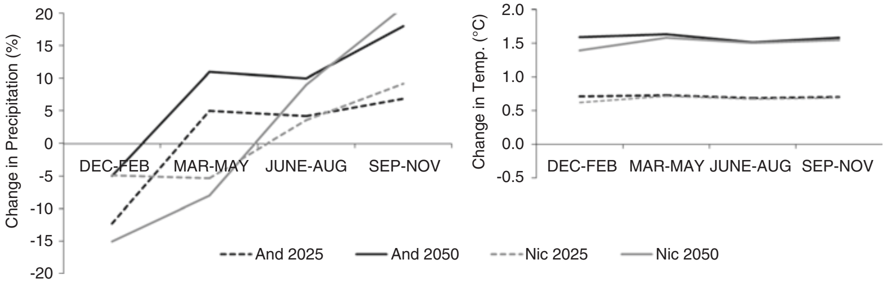


Fig. 11.4 Change in precipitation (%) and temperature (°C) in Andaman and Nicobar Islands during 2025 and 2050 as projected by MAGICC/SCENGEN software (Source: Velmurugan et al. 2015)

rainfall) was projected for December–February for Andaman Islands and for December–May for Nicobar Islands, with the rest of the seasons to have increase in precipitation (Fig. 11.4). The decrease in winter monsoon and summer monsoon showers can affect ecosystems such as coral reefs and mangroves. The surplus rains during the rest of the seasons can compensate for drinking water-related issues. The temperature projected for 2025 showed significant change among seasons and between the island groups. In contrast, the temperature for 2050 period significantly differed among the seasons but was similar between the two island groups. The plot of mean temperatures for the two projected years, 2025 and 2050, illustrates a similar projected increase in mean temperatures for all the seasons and between the two island groups. Increasing temperatures have indicated ecological/weather problems in the islands with increasing incidents of extreme events such as cyclones, coral bleaching, droughts, floods, and erratic monsoons. The possibility of further increasing temperature trends in our simulations exposes the need for proper adaptation strategies for the islands to mitigate such weather events.

Similarly, the long-term average of mean temperature also shows increasing trend in the post-monsoon season (Fig. 11.5). The recent observation of change in average temperature (2013–2014) for these islands shows 15 % higher than the decadal average. During that period, drying up of many of the freshwater ponds and falling groundwater level in the islands was reported (ICAR-CIARI 2015). The climate change projections (Lal et al. 2002; Ruosteenoja et al. 2003) report a gradual warming of sea surface temperature (SST) and a general warming trend in surface air temperature in all small island regions and seasons.

An important aspect of climate change more relevant to the islands is change in SST. The average monthly SST extracted from different locations around the Nicobar Islands for 2010 was higher than the corresponding monthly average SST of each of the three different decadal averages (1981–2010, 1991–2010, and 2001–2010), between January and July (Fig. 11.6). During April to July, the increase was higher (0.75–1.25 °C) than the rest of the months. This anomalous increase in SST resulted in mass bleaching of corals (Krishnan et al. 2010). Previously, anomalous SST events and subsequent coral bleaching were recorded in 1998, 2002, and 2005 (Arthur 2000; Krishnan et al. 2010).

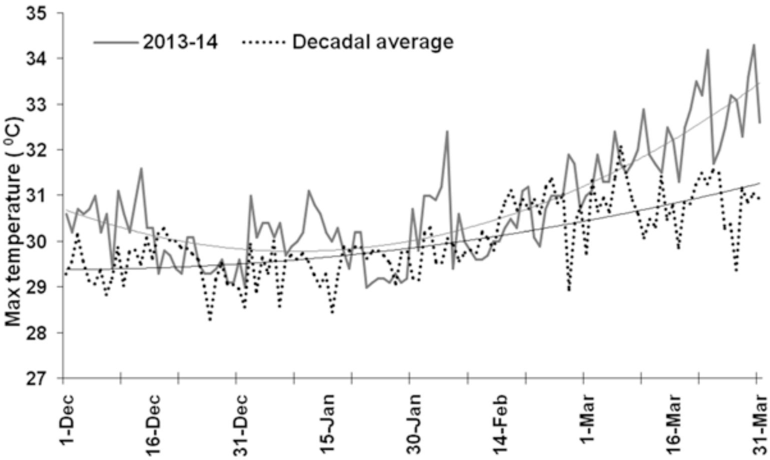


Fig. 11.5 Temperature of 2013–2014 compared with the decadal average (2000–2010) (*Only the period with significant difference, Dec–Mar, is plotted.*)

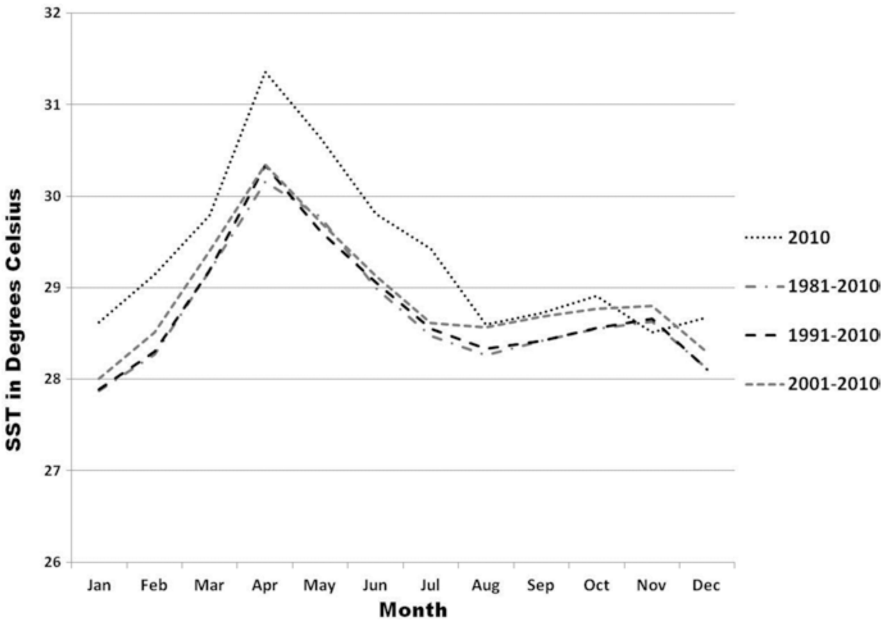


Fig. 11.6 Comparison of sea surface temperature (SST) in 2010 with decadal averages

11.4.5 Impact of Changing Climate on the Wetlands of Nicobar Islands

In spite of uncertainty in magnitude of occurrence, in recent times, the impacts of climate change and weather extremes are certainly felt in Nicobar Islands in the form of increasing monsoon period depressions, dry spell during post-monsoon period, intrusion of seawater into the freshwater aquifer and coastal lowlands, loss of agricultural land, and coastal erosion. A large number of non-climate change factors and disturbances, mainly driven by human activities, can also affect coral reefs (Nyström et al. 2000; Hughes et al. 2003). The "coral reef crisis" is almost certainly the result of complex and synergistic interactions among global-scale climatic and local-scale human-imposed stresses (Buddemeier et al. 2004). This may pose serious threat to the livelihood of tribals inhabiting these islands and trigger other ecological consequences in which the wetlands particularly the mangroves, corals, and inland water bodies are at the receiving end. Hatchery production and farming of groupers and snappers have not yielded good results so far. Decreasing reef areas are going to bring down their population in the sea, as reefs are critical in their life cycle as spawning, nursery, and fishing grounds. Further, the stress on existing resources such as water, mangroves, and reefs will lead to depletion or overexploitation of other island resources. Islands have a unique lifestyle of generating and utilizing resources within the islands. Unstable supply gaps in the resources available within the islands will result in catastrophes. There are historical examples of complete devastation of island civilization in ancient human history such as the collapse of Easter Islands. Unless proper adaptation strategies are devised for Nicobar, there is a life-threatening situation as predicted by the simulations in weather forecasting models.

11.4.5.1 Mangroves

Mangroves are considered to be the natural protective cover for islands toward the seafront which are also known to provide habitat for several important species. Andaman and Nicobar group of islands together have the second largest area under mangroves in India after West Bengal, as far as density and growth are concerned, and furthermore mangroves of ANI are the best in the country (Planning Commission 2008). It is found along the creeks; the width ranges from 0.5 to 1 km, and in some locations, it can be found several meters inside the islands from the coast (Dam Roy and Krishnan 2005). Ecological conditions in a mangrove ecosystem exert pressure on non-mangrove plant species. However, following the disturbance to the mangrove ecosystem, during storm or cyclones, other plant species may encroach and dominate the area. One known opportunistic plant species in the Andaman and Nicobar is the giant fern, *Acrostichum aureum*, that inhabits as small patches in dry mangrove areas under normal conditions. Under the SRES scenarios, small islands are shown to be particularly vulnerable to coastal flooding and decreased extent of coastal vegetated wetlands (Nicholls 2004). Similarly, in the event of natural disasters such as cyclones (hurricanes), the coastal biodiversity of these islands could be severely affected, and as the adaptation responses of some of these islands are expected to be slow, the impacts of storms would be more pronounced.

During the Indian Ocean tsunami of December 2004, Nicobar group of islands experienced subduction of landmasses, while North Andaman was uplifted. Though earthquake and subsequent subduction are not attributed to climate change, the effects on these islands were similar to that of SLR associated with climate change. Nearly 4200 ha coastal wetlands, mostly rice paddies, were permanently inundated. Withdrawal of tidal water from the mangrove habitats triggered a renewed ecological succession, changes in shorelines, and drying of mangrove stands.

11.4.5.2 Coral Reefs and Associated Biodiversity

Oceanic islands often have a unique biodiversity through high endemism caused by ecological isolation. The ANI are bestowed with the richest coral diversity among all Indian reefs (Krishnan et al. 2011). In total 228 species of hard corals, falling under 58 genera and 15 families, have been reported from these islands (Venkataraman et al. 2003). Recent surveys indicate that the numbers could be close to 80 % of the global maximum (Krishnan et al. 2011). Estimates by Zoological Survey of India (ZSI), India, suggest that over 400 species of corals are found around these islands. The nearshore waters are rich in finfish, shellfish, and other economically important species such as seashells, sea cucumbers, crabs, lobsters, etc.

Changes in the physical and biological structure of benthic reef habitats are likely to have detrimental effects on reef-associated organisms particularly on organisms that depend on corals for food, shelter, or recruitment. Mass coral bleaching, ocean acidification, and intense cyclones due to climate change will cause fundamental changes to the reef habitat, including reduced coral cover, changes to the composition of coral assemblages, and reduced structural complexity (Hoegh-Guldberg et al. 2007). The anomalous increase in SST in Andaman waters during 2010 resulted in mass bleaching of corals. Short-term exposure to such SST anomalies induces bleaching and subsequent recovery; however, prolonged exposure to elevated SST causes chronic stress which can lead to irreversible bleaching. Anomalous elevations in SST by at least 1.0 °C above the expected climatology during the warmest months of the year have been associated with coral bleaching hotspots (Reaser et al. 2000). Available evidence suggests that widespread bleaching would lead to significant reduction in the abundance of many reef fishes around these islands. Many of the butterfly fishes are obligate or facultative coral feeders and are dependent on live coral cover, and damsel fishes depend to a great extent on the structural complexities of the reef for protection. Such coral-dependent species will be most seriously affected, but many other species could suffer long-term population declines due to loss of settlement habitat and essential habitat structure for post-settlement survival (Graham et al. 2006).

11.4.5.3 Water Resources

The freshwater wetlands are vital not only to provide drinking water but also for maintaining the salt balance in the groundwater by pushing back the saline seawater. Water resources of these islands are directly affected by seasonal changes and variations in climate, especially in rainfall, whereas other factors like smaller size, geology, and topography increase the risk of freshwater resources due to SLR. The SLR is projected to inundate several low-lying areas of Nicobar Islands with flat topography. Consequently, several coastal freshwater ponds and other water bodies may turn saline affecting the freshwater biodiversity of these islands.

As these islands are not suitable for large-scale development of surface storage facilities, decentralized rainwater harvesting and recharging the shallow water table are the only options, which directly depend on the rainfall and its distribution. Groundwater is the main source of drinking water supply in these islands. About 90 % of the dry borewells were in compressed sedimentary deposits, which act as aquiclude or even as aquitard, whereas rocky subsoil formation was found to be more successful (Srivastava and Ambast 2011). However, the coralline limestone formations form potential aquifer in shallow horizon in many islands that can be utilized through dug wells of 4–5 m diameter with 6 m depth. As in the case of other small islands, the scarcity of freshwater is often a limiting factor for social and economic development of Nicobar.

11.4.6 Vulnerability of Wetlands to Changing Climate

Climate vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change. Climate vulnerability depends on exposure, sensitivity, and adaptive capacity. Climate exposure is the extent and magnitude of a climate and weather event, which is almost certain on all the wetlands existing in the island located in the Indian Ocean region. While sensitivity is the degree to which the area of concern is susceptible to a climate impact, in this context, islands with maximum areas with lower elevation are highly sensitive as in the case of Nicobar Islands. Adaptive capacity is defined as the ability of the area of concern to adjust or respond to the changing conditions. But, it depends on the resources and technology available with the community (IPCC 2012).

The digital elevation model (DEM) of the islands shows that among the Nicobar Islands, Trinket and Chowra have over 15 % of the total land area with an elevation less than 10 m above mean sea level (AMSL) and are thus significantly vulnerable to climate change events. About 70 and 93 % of the total land area in Car Nicobar and Great Nicobar have an elevation >20 m above MSL, respectively. Tidal wave in the aftermath of the 2004 tsunami affected such low-lying areas. Similarly, storm surges associated with cyclones would have similar effects, as that of the tsunami, in these areas. The height of storm surge increases when the coastal crossing of storm is associated with high tide. The maximum storm surge disaster for the islands under the worst hypothetical scenario involving a super cyclone with maximum wind speeds of 80 m/s has been determined to be 3.7 m under neap tide conditions (Kumar et al. 2008). Both Andaman and Nicobar group of islands have smaller shelf widths and steeper slopes than the mainland coasts, so the impact of tsunami and storm surges for these islands would be low compared to that of east coast of India under similar conditions (Sadhuram et al. 2006; Kumar et al. 2008). However, Nicobar group of islands are more vulnerable to SLR due to their flat topography, limited space for retreat, and dense coastal settlements. This is the case with most of the coral islands in the Indian Ocean region.

Ramanamurthy et al. (2005) studied the inundation of seawater in Car Nicobar and Great Nicobar during the 2004 tsunami and concluded that the run-up (usually expressed in meters above normal tide or mean sea level) which can be used for determining the extent of vulnerability of human settlement varied from 3 to 7 m with a distance of penetration ranging from 50 to 1000 m. Coastal land in Car Nicobar is characterized by a gentle slope interrupted by streets and houses. As per the tsunami run-up subsector database for Indian Ocean between 1750 and 2007, seven tsunamis have been reported in the Indian Ocean region, and the extent of run-up recorded was 0.76 m in Car Nicobar during 1881. Nicobar Islands lie in the seismic zone V as the expected intensity of seismic activity would be IX or greater on the Medvedev-Sponheuer-Karnik intensity scale (Rai and Murty 2005). Further, massive earthquakes also result in the alteration of island topography leading to subduction of the islands. Analysis of the estimated area that will be affected with 0–5 and 5–10 m increase in sea level reveals that the loss of land would be greatest in Chowra where about 13.34 % of island will be inundated with 0–10 m rise in sea level.

11.5 Adaptation of Wetlands to Changing Climate

Small islands are subjected to a range of climatic and oceanic impacts and that these impacts will be exacerbated by the projected climate change and SLR. In general, both global and local drivers may show increases in the future and will interact to impact small islands and the coastal wetlands in the future. These will probably impact on island environments and their biogeophysical conditions, as well as the socioeconomic well-being of island communities (Clark 2004). Unless adaptation measures are put in place to reduce impacts, it is foreseen that the drivers will certainly impact the islands. Therefore, it is essential to improve the adaptive capacity of these islands aimed at increasing the ability of the built, natural, and social systems to adjust to climate change, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

The adaptation to climate change and restoration of coastal wetlands include (a) protecting those ecosystems that are projected to suffer as a consequence of climate change and sea level rise and (b) rehabilitating ecosystems degraded or destroyed as a result of socioeconomic developments. The coastal natural resources such as coral reefs and mangrove forests possess a natural ability to adapt to changing environmental conditions, a phenomenon called as natural or autonomous adaptation. Further, they are also rehabilitated and restored as part of resource management that is termed as planned adaptation mechanism, aimed to increase natural protection against SLR resulting in sea and storm surges. This is more relevant to the smaller islands as that of Nicobar Islands in the Indian Ocean region.

With respect to the adaptive capacity of smaller islands, Sutherland et al. (2005) suggest that enhancing adaptive capacity will only be successful when it is integrated with other policies such as disaster preparedness, land-use planning, environmental conservation, coastal planning, and national plans for sustainable development. It is essential to build the capacities of individuals, communities, and governments with regional and international cooperation so that they are able to make informed decisions about adaptation to climate change and to enhance their adaptive capacity in the long run. Therefore, encouraging active participation of local communities in capacity building and environmental education should become an objective of many development programs in small islands. The locals should also be encouraged to identify local options for adaptation.

11.6 Conclusion

From the foregoing discussions, it is evident that the small islands and SIDS are more vulnerable to the perceived climate change though there are variations in effect and uncertainty in estimations. In these islands, wetlands constitute the most important component in terms of biodiversity, coastal protection, and economic values. The coastal and inland wetlands of tropical islands, in particular, are facing the threats posed by climate change. Sea level rise can affect coastal communities and habitats in various ways, including submerging low-lying lands, eroding beaches, converting wetlands to open water, intensifying coastal flooding, and increasing the salinity of estuaries and freshwater aquifers, which would mainly manifest in the form of habitat and biodiversity loss. Climate change leads to increasing sea surface temperature, SLR, and tropical cyclones, which in turn result in possible decreases in growth rates and physical damage of coral reefs around islands.

Some impacts of SLR are already being observed in many Indian Ocean islands, underscoring the immediate need for improving scientific understanding and the ability to predict the effects of rising sea level to improve upon the adaptation measures. Incorporating SLR into coastal planning, in combination with the development of decision-support tools for taking further adaptive action, could lessen the economic and environmental impacts of climate change on these islands and their wetland ecosystems.

References

Arthur R (2000) Coral bleaching and mortality in three Indian reef regions during an El Niño southern oscillation event. Curr Sci 79:1723–1729

Buddemeier RW, Kleypas JA, Aronson RB (2004) Coral reefs & global climate change: potential contributions of climate change to the stresses on coral reef ecosystems. Pew Center on Global Climate Change, Washington, DC. Available at http://www.pewclimate.org/global-warming-in-depth/all_reports/coral_reefs/. Accessed 8 Jan 2016

Caldeira K, Wickett ME (2003) Anthropogenic carbon and ocean pH. Nature 425:365

Church JA, White N, Hunter J (2006) Sea level rise at tropical Pacific and Indian Ocean islands. Glob Planet Chang 53:155–168

Clark E (2004) The ballad dance of the faeroese: island biocultural geography in an age of globalization. Tijdschr Econ Soc Geogr 95(3):284–297
Dam Roy S, Krishnan P (2005) Mangrove stands of Andamans vis-à-vis tsunami. Curr Sci 89(11):1800–1804
Food and Agriculture Organization (2011) FAO water reports: climate change, water and food security. Available at http://www.fao.org/docrep/014/i2096e/i2096e.pdf. Accessed 8 Jan 2016
Graham NAJ, Wilson SK, Jennings S, Polunin NVC, Bijoux JP (2006) Dynamic fragility of oceanic coral reef ecosystems. Proc Natl Acad Sci 103:8425–8429
Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatziolos ME (2007) Coral reefs under rapid climate change and ocean acidification. Science 318(5857):1737–1742
Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nyström M, Palumbi SR, Pandolfi JM, Rosen B, Roughgarden J (2003) Climate change, human impacts, and the resilience of coral reefs. Science 301:929–933
Indian Council of Agricultural Research (2015) Vision 2050. Available at http://www.icar.org.in/Vision%202050%20CIARI,%20Port%20Blair.pdf. Accessed 8 Jan 2016
Indian Council of Agricultural Research-Central Island Agriculture Research Institute (2015). ICAR-CIARI research achievements. Available at http://icar-ciari.res.in/achievemnts.htm. Accessed 8 Jan 2016
IPCC (2001) Intergovernmental panel on climate change – third assessment report, volume I. Cambridge University Press, Cambridge
IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. In: Parry M, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 976
IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 582
Khan TMA, Quadir DA, Murty TS, Kabir A, Aktar F, Sarker MA (2002) Relative sea level changes in Maldives and vulnerability of land due to abnormal coastal inundation. Mar Geod 25:133–143
Krishnan P, Dam-Roy S, George G, Anand A, Murugesan S, Kaliyamoorthy M, Vikas, Soundararajan R (2010) Elevated Sea Surface Temperature (SST) induces mass bleaching of corals in Andaman. Curr Sci 100:1800–1804
Krishnan P, Dam Roy S, George G, Srivastava RC, Anand A, Murugesan S, Kaliyamoorthy, Vikas N, Soundararajan (2011) Elevated sea surface temperature during May 2010 induces mass bleaching of corals in the Andaman. Curr Sci 100(1):111–116
Kumar VS, Babu VR, Babu MT, Dhinakaran G, Rajamanickam GV (2008) Assessment of storm surge disaster potential for the Andaman Islands. J Coast Res 24:171–177
Lal M (2004) Climate change and small island developing countries of the South Pacific. Fijian Stud 2:15–31
Lal M, Harasawa H, Takahashi K (2002) Future climate change and its impacts over small island states. Clim Res 19:179–192
Mimura N, Nurse L, RF ML, Agard J, Briguglio L, Lefale P, Payet R, Sem G (2007) Small islands. In: Parry M, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 687–716 Available at http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter16.pdf. Accessed 8 Jan 2016
Nicholls RJ (2004) Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. Glob Environ Chang 14(1):69–86

Nyström M, Folke C, Moberg F (2000) Coral reef disturbance and resilience in a human-dominated environment. Trends Ecol Evol 15:413–417

Panigrahy S, Murthy TVR, Patel GJ, Suthar NM, Kundu N, Paul M, Basu N (2010) National wetland atlas: Bihar. Space applications centre (ISRO). Ahmedabad and Institute of Environmental Studies and Wetland Management (IESWM), Kolkata, p 222

Planning Commission (2008) Andaman and Nicobar islands development report. Available at http://planningcommission.nic.in/plans/stateplan/sdr/sdr_andaman.pdf. Accessed 8 Jan 2016

Rai DC, Murty CVR (2005) Engineering lessons not learnt from 2002 Diglipur earthquake – a review after 2004 Sumatra earthquake. Curr Sci 89:1681–1689

Ramanamurthy MV, Sundaramoorthy S, Pari Y, Rao VR, Mishra P, Bhat M, Usha T, Venkatesan R, Subramanian BR (2005) Inundation of seawater in Andaman and Nicobar Islands and parts of Tamil nadu coast during 2004 Sumatra tsunami. Curr Sci 88:1736–1740

Ranjana U K, Piyadasa KDN, Weerasinghe JA, Liyanage LMJR, Wijayawardhana. (2013) Role of sea level rise on the groundwater quality in coastal areas of Sri Lanka. Climate change and island and coastal vulnerability, Springer, Dordrecht, pp 209–216

Reaser JK, Pomerance R, Thomas PO (2000) Coral bleaching and global climate change: Scientific findings and policy recommendations. Conserv Biol 14:1500–1511

Royal Society (2005) Ocean acidification due to increasing atmospheric carbon dioxide. Policy Document 12/05. The Royal Society, London, p 60

Ruosteenoja K, Carter TR, Jylhä K, Tuomenvirta H (2003) Future climate in world regions: an inter-comparison of model-based projections for the new IPCC emissions scenarios. The Finnish Environment 644, Finnish Environment Institute, p 83

Sadhuram Y, Murthy TVR, Rao BP (2006) Hydro-physical manifestations of the Indian Ocean tsunami. Tsunami 17:365–372

Space Applications Centre (2009) National Wetland Atlas: Andaman & Nicobar Islands, SAC/RESA/AFEG/NWIA/ATLAS/04/2009, Space Applications Centre (SAC-ISRO). Ahmedabad, p 190

Srivastava RC, Ambast SK (2011) Water policy for Andman and Nicobar islands: a scientific perspective. Central Agricultural Research Institute, Port Blair

Sutherland K, Smit B, Wulf V, Nakalevu T (2005) Vulnerability in samoa. Tiempo 54:11–15

Swarnam TP, Velmurugan A, Saravana Kumar A (2015) Studies on tribal farming in Nicobar Islands, India. IOSR J Agr Vet Sci 8(1):41–49

ten Brink P, Russi D, Farmer A, Badura T, Coates D, Förster J, Kumar R, Davidson N (2013) The economics of ecosystems and biodiversity for water and wetlands. Executive summary. Available at http://www.zaragoza.es/contenidos/medioambiente/onu/1024_eng_sum_teeb_water_and_wetlands.pdf. Accessed 8 Jan 2016

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

UNFCC (1994) The United Nations framework convention on climate change http://unfccc.int/essential_background/convention/background/items/1349. php Accessed 8 Jan 2016

Velmurugan A, Dam Roy S, Krishnan P, Swarnam TP, Jaisankar I, Singh AK, Biswas TK (2015) Climate change and Nicobar Islands: impacts and adaptation strategies. J Andaman Sci Assoc 20(1):1–12

Venkataraman K, Sathyanarayana C, Alfred JRB, Wolstenhome J (2003) Hand book on hard corals of India. Zoological Survey of India, Kolkata, p 266

Wilkie ML (2002) Climate change, forests and SIDS. Int Forest Rev 4(4):313–316

Climate Change Impacts and Adaptations in Wetlands

12

Md Sarwar Hossain, Alamgir Kabir, and Persia Nargis

Abstract

Despite the substantial contribution of wetland resources to support human well-being and the threats of climate change on wetland resources, climate studies have paid less attention to wetlands in South Asia. Hence, this chapter explores the impacts and adaptation to climate change on the wetlands of southwest coastal Bangladesh using the time series (e.g. Mann–Kendall) analysis of climate data and survey data analysis for the adaptations to climate change. We have also reviewed the literature to explore whether the local development projects in wetlands integrates climate change adaptations according to the national adaptation plan. The trends of temperature in pre-monsoon, monsoon and post-monsoon are increasing over the period 1948–2012. Pre-monsoon rainfall trend is decreasing, in contrast to the increasing rainfall trends in monsoon and post-monsoon seasons. In response to the changes in climate, 78% of respondents have adopted multiple adaptation options, and 94% of respondents have adopted expensive boring methods to support agriculture. The production cost has increased three-fold in response to the changes in crop varieties to cope with climate change. The bivariate probit regression (BPR) reveals that loan taking is the determinant of climate change adaptation. Though the review of literature suggests that the impacts of climate change will be severe in the future, adaptation planning is yet not integrated into the wetlands' development plans. Some of the adaptation

Md Sarwar Hossain (✉)
Geography and Environment, University of Southampton, Southampton, UK
e-mail: Koushikadd@yahoo.com; Sarwar.Sohel@soton.ac.uk

A. Kabir
Department of Environmental Science, Faculty of Science and Technology,
Bangladesh University of Professionals (BUP), Dhaka, Bangladesh

P. Nargis
Department of Geography and Environment, University of Dhaka, Dhaka, Bangladesh

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_12

options (e.g. access to credit and innovating crop varieties with low production cost) may be included in the global development goals to strengthen climate change adaptation at global and regional scales.

Keywords
Adaptation planning • Climate change • Time series • Wetlands

12.1 Introduction

Wetlands are one of the most productive biological systems, which provide enormous ecosystem services to support human wellbeing (EPA 2016). About 6% of the total global land is covered by wetlands (IPCC 1995), which store ~11,000 km^3 global water (Shiklomanov and Rodda 2003). The total economic value of wetlands is about 70 billion USD year^{-1} and is the source of two-thirds of global fish consumption (IWMI 2010). However, wetland ecosystem services and biodiversity rich systems are highly threatened by climate change. Impacts of climate change on wetlands include alternation of hydrology and water quality, increase in natural hazards, decrease in water resource quantity and decrease in food production (Erwin 2009; Ramsar 2014). It has been estimated that ~1% global wetlands' stock was lost each year in the late twentieth century, and the projection shows that ~46% wetlands and more than 200 million people would be threatened by 1 m sea level rise in wetlands. About 75% South Asian wetlands would be inundated due to 1 m sea-level rise (SLR), affecting 95 million people in the region (Hoozemans et al. 1993; Nicholls 2004).

Bangladesh is known as land of rivers, and wetlands are the major (~8 million ha) land use type in the country (Khan 1993). Wetlands are the main sources of rice production (Byomkesh et al. 2009), biodiversity (~5000 flowering plants, ~1500 vertebrates) and water resources (Khan et al. 1994) in Bangladesh. It is estimated that the mangrove wetlands alone produce ~800,000 USD per year through provisioning services (e.g. forest product) and tourism industry (Uddin et al. 2013). However, this highly productive system is threatened by climate change, similar to the whole of the country, due to SLR, temperature increase, decreased water flow and other human interventions (World Bank 2000; Byomkesh et al. 2009; Hossain et al. 2013). Therefore, we need to investigate how climate change is affecting wetland resources to develop adaptation strategy for these systems. Despite the high economic contribution to human wellbeing of Bangladesh, wetlands received less attention than other natural systems such as rivers, coastal areas and forests in climate change adaptation plans. Hence, we aimed in this chapter to explore the recent trends and impacts of climate change, the adaptation processes through time series and survey data analysis and literature review. This chapter also includes a case study to provide insight in to mainstreaming climate change adaptation into the wetlands' development planning at local level.

12.2 Case Study: Bangladesh

We selected the wetlands in Narail District (Fig. 12.1) at the southwestern part of Bangladesh for the study. This area is highly influenced by wetlands, which are connected to the rivers (Chitra and Nabaganga) through canals and watercourses (ADB 2005). A large population (730,000) is dependent on wetlands as ~70% of people are dependent on agriculture. Although only 2% of people are fishermen, ~30–50% of people are engaged in fishing during wet season. These wetlands provide huge amount of provisioning services (e.g. crops, fish) worth ~173 million USD year^{-1} and also accumulate 1800–3600 t CO^2 e km^{-2} year^{1} (Hossain and Sazbo 2016). In addition, the wetlands also contribute to the cultural values of human livelihood in this area. However, half of the population of the area is below the poverty line (Saadat and Islam 2011). Besides the challenges of poverty alleviation, climate change and hydraulic engineering are making the social-ecological system of this area more vulnerable (Hossain et al. 2010; Moni and Hossain 2010). However, this region is not salinity affected compared to the other southwestern part of Bangladesh. Besides all these socioecological-economic motivations, availability of time series data and

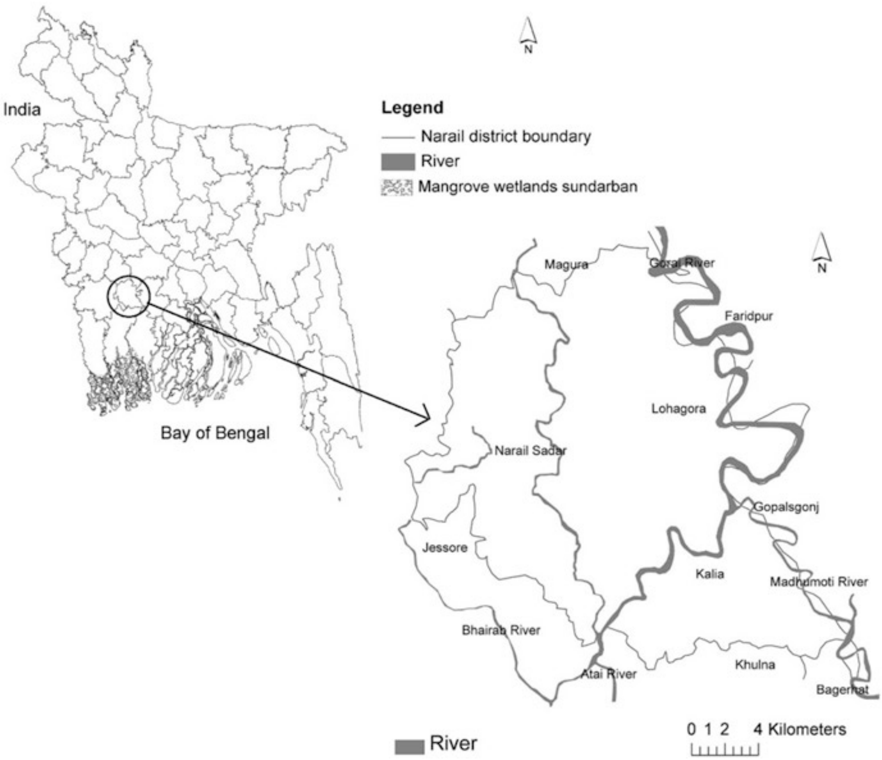


Fig. 12.1 Southwest coastal district of Narail, the case study area in Bangladesh

availability of relevant literatures about climate change impacts and adaptation for the wetlands of this area are the reasons to select the area as a case study to understand the impacts and adaptation in wetlands.

12.3 Methods

Time series (1948–2012), temperature (monthly) and rainfall (daily) data for the nearest meteorological station (Jessore) were collected from the Bangladesh Meteorological Department (BMD). Monthly mean rainfall was calculated from the daily rainfall data. Each year was classified into four seasons: monsoon (June–July–August), post-monsoon (September–October–November), winter (December–January–February) and pre-monsoon (March–April–May). Besides analysing the trends for the period 1948–2012, we have also analysed data by dividing the total time period into three segments: 1948–1970, 1971–1990 and 1991–2012. We have applied the nonparametric Mann–Kendall test and linear regression in order to discriminate trends (increasing, decreasing or stable) in the time series data. Mann–Kendall test is applied widely to detect trends in highly variable and nonlinear systems such as temperature and precipitation (Vitale et al. 2010; Hossain et al. 2014). Similar tests were also applied to analyse the trends in the Bengali months, which coincide with the panicle and spikelet initiation time of local crops. These panicle and spikelet initiation times of local crops were collected using a farmer's perception during the focus group discussion (FGD) in the study area. We conducted five FGDs, in which 50% of the respondents were women. FGDs were also used to collect information on the production costs for the current crop varieties and the previous crop varieties. We have also surveyed 103 farmers to collect the information on their perception on climate and adaptation practices and to investigate the determinants of climate change adaptation. We used bivariate probit model (BPM) to analyse the determinants of adaptation methods to climate change in the wetlands of Bangladesh. The reason why we used this model was as we have two binary response (i.e. dummy) variables, adaptation in agriculture (y_1) and water resources (y_2), which vary jointly and are assumed to have correlated disturbances (Greene 2003). This method can also be used when both dependent variables are seemingly unrelated. Previously, multinomial logit models, i.e. where the discrete outcomes are more than two, have been used in climate change literature to analyse adaptation methods such as choice of crop (Hassan and Nhemachena 2008; Kurukulasuriya and Mendelsohn 2008) and livestock (Seo and Mendelsohn 2008). We have also used relevant literature to investigate future trends in climate change, impacts and possible adaptation planning in the study area. We also aimed at exploring briefly how the government is integrating national adaptation plan into the wetlands' development plans.

12.4 Recent Trends in Climate

We have analysed rainfall (Table 12.1) and temperature (average, maximum and minimum; Tables 12.2, 12.3 and 12.4) data for the pre-monsoon, monsoon, post-monsoon and winter seasons for the period from 1948 to 2012. Pre-monsoon rainfall shows nonsignificant (50%) decreasing trend (MK stat −0.82, −63 mm/season/year) since the 1990s. Similarly, winter rainfall also follows significant (90%) decreasing trend (MK stat −0.82, −62 mm/season/year) since the 1990s. However, the winter rainfall trend shows significant (90%) increasing (MK stat 1.74, 9.9 mm/season/year) trend over the period 1948–2012. Similar to the winter rainfall trend, post-monsoon rainfall also shows significant (99%) increasing trend (MK stat 2.92, 93 mm/season/year) for the period 1948–2012. However, the trend is not significant since the 1990s.

In pre-monsoon, the average and minimum temperatures show (Tables 12.2, 12.3 and 12.4) significant (99–95%) increasing trend (MK stat 1.87 and 3.14, respectively) at a rate of change of 0.9 °C $year^{-1}$ and 0.02 °C $year^{-1}$, respectively, over the period 1948–2012. Although the temperature (average, minimum and maximum) shows increasing trends in all the three periods, 1948–1970, 1971–1990 and 1991–2012, the trends are not significant. Monsoon temperature (average, minimum and maximum) also shows significant (99%) increasing (MK stat 4–5) trend (0.2–0.7 °C $year^{-1}$) for the period 1948–2012. Though the trends are positive for the periods 1948–1970, 1971–1990 and 1991–2012, test statistics are significant (99%) only since the 1990s. Similarly, post-monsoon maximum and average temperature showed an increasing trend (MK stat 4.14 and 3.09, respectively) at 99% significant level with a rate of change of 0.02 and 0.01 °C/year, respectively, over the periods 1948–2012. Test statistics (Tables 12.2, 12.3 and 12.4) also found positive for post-monsoon temperature (average, minimum and maximum) since the 1990s, although the trend is significant only for maximum temperature. The winter temperature shows nonsignificant increasing trends, except the decreasing (MK stat −1.41, 0.05 °C/year) trend for minimum temperature since the 1990s. Besides analysing weather station data, we have also investigated people's perception (Table 12.5) about the recent climatic trends. While 96% of respondents reported that the temperature is increasing, 92% of respondents reported that rainfall trend is decreasing (Table 12.5).

12.5 Impacts, Adaptation Practices and Determinants of Adaptation

Discussions with the farmers in the wetlands reveal that rising temperature and decreasing trends in rainfall negatively affect the panicle and spikelet initiation time of crops. Table 12.6 depicts the time of panicle and spikelet initiation in crops collected during the FGDs with farmers. Famers reported panicle and spikelet initiation time according to the Bengali months of the year. Therefore, we have also analysed the trends of Bengali months, as it does not coincide with the season as per the English

Table 12.1 Trend statistics for rainfall at Narail for the period 1948–2012

Rainfall	Nonmiss	Test stat	Std. dev.	MK-stat	*p*-value	Covariance	Correlation	Rate of change (mm/year)	*r*
Monsoon									
1948–2012	64.00	135.00	172.60	0.78	0.43	2,9791.00	1.00	0.12	0.00
1948–1970	23.00	11.00	37.86	0.29	0.77	1433.67	1.00	0.08	0.00
1971–1990	19.00	19.00	28.58	0.66	0.51	817.00	1.00	0.44	0.00
1991–2012	22.00	−1.00	35.46	−0.03	0.98	1257.67	1.00	0.13	0.00
Post-monsoon									
1948–2012	64.00	504.00	172.59	2.92	0.00	29,788.00	1.00	1.04	0.08
1948–1970	23.00	41.00	37.86	1.08	0.28	1433.67	1.00	3.05	0.13
1971–1990	19.00	33.00	28.58	1.15	0.25	817.00	1.00	0.58	0.00
1991–2012	22.00	17.00	35.46	0.48	0.63	1257.67	1.00	1.84	0.03
Pre-monsoon									
1948–2012	62.00	67.00	164.61	0.41	0.68	27,097.67	1.00	0.03	0.00
1948–1970	22.00	−38.00	35.45	−1.07	0.28	1256.67	1.00	−2.65	0.11
1971–1990	18.00	21.00	26.40	0.80	0.43	697.00	1.00	2.63	0.09
1991–2012	22.00	−29.00	35.46	−0.82	0.41	1257.67	1.00	−0.70	0.02
Winter									
1948–2012	64.00	299.00	172.10	1.74	0.08	29,619.00	1.00	0.11	0.02
1948–1970	23.00	71.00	37.64	1.89	0.06	1417.00	1.00	0.35	0.06
1971–1990	19.00	26.00	28.53	0.91	0.36	814.00	1.00	0.41	0.01
1991–2012	22.00	−57.00	35.34	−1.61	0.11	1249.00	1.00	−0.69	0.15

Table 12.2 Trend statistics for maximum temperature at Narail for the period 1948–2012

Maximum temperature	Nonmiss	Test stat	Std. dev.	MK-stat	*p*-value	Covariance	Correlation	Rate of changes (°C/year)	*r*
Monsoon									
1948–2012	64.00	765.00	172.53	4.43	0.00	29,766.33	1.00	0.03	0.26
1948–1970	23.00	−17.00	37.86	−0.45	0.65	1433.67	1.00	−0.01	0.01
1971–1990	19.00	34.00	28.57	1.19	0.23	816.00	1.00	0.05	0.04
1991–2012	22.00	89.00	35.23	2.53	0.01	1241.00	1.00	0.07	0.31
Post-monsoon									
1948–2012	63.00	698.00	168.50	4.14	0.00	28,391.34	1.00	0.02	0.23
1948–1970	22.00	−8.00	35.42	−0.23	0.82	1254.67	1.00	−0.02	0.03
1971–1990	19.00	−19.00	28.55	−0.67	0.51	815.00	1.00	−0.03	0.05
1991–2012	22.00	66.00	35.38	1.87	0.06	1252.00	1.00	0.03	0.16
Pre-monsoon									
1948–2012	62.00	151.00	164.58	0.92	0.36	2,7087.00	1.00	0.00	0.00
1948–1970	22.00	48.00	35.45	1.35	0.18	1256.67	1.00	0.05	0.04
1971–1990	18.00	−13.00	26.36	−0.49	0.62	695.00	1.00	−0.05	0.04
1991–2012	22.00	18.00	35.42	0.51	0.61	1254.67	1.00	0.02	0.01
Winter									
1948–2012	63.00	−248.00	168.53	−1.47	0.14	28,401.34	1.00	0.01	0.03
1948–1970	23.00	−84.00	37.79	−2.22	0.03	1428.00	1.00	−0.06	0.26
1971–1990	18.00	−51.00	26.40	−1.93	0.05	697.00	1.00	−0.05	0.16
1991–2012	22.00	51.00	35.40	1.44	0.15	1253.00	1.00	0.06	0.17

Table 12.3 Trend statistics for average temperature at Narail for the period 1948–2012

Average temperature	Nonmiss	Test stat	Std. dev.	MK-stat	*p*-value	Covariance	Correlation	Rate of changes (°C/year)	*r*
Monsoon									
1948–2012	63.00	919.00	168.54	5.45	0.00	28,405.67	1.00	0.02	0.40
1948–1970	22.00	0.00	35.42	0.00	1.00	1254.67	1.00	0.00	0.00
1971–1990	19.00	21.00	28.58	0.73	0.46	817.00	1.00	0.05	0.13
1991–2012	22.00	132.00	35.45	3.72	0.00	1256.67	1.00	0.05	0.53
Post-monsoon									
1948–2012	61.00	496.00	160.64	3.09	0.00	25,806.67	1.00	0.01	0.13
1948–1970	22.00	9.00	35.46	0.25	0.80	1257.67	1.00	0.00	0.00
1971–1990	17.00	−26.00	24.23	−1.07	0.28	587.33	1.00	−0.04	0.09
1991–2012	22.00	33.00	35.44	0.93	0.35	1255.67	1.00	0.02	0.05
Pre-monsoon									
1948–2012	62.00	308.00	164.60	1.87	0.06	27,094.00	1.00	0.01	0.03
1948–1970	22.00	58.00	35.45	1.64	0.10	1256.67	1.00	0.07	0.16
1971–1990	18.00	10.00	26.38	0.38	0.70	696.00	1.00	−0.01	0.00
1991–2012	22.00	28.00	35.45	0.79	0.43	1256.67	1.00	0.01	0.01
Winter									
1948–2012	63.00	200.00	168.56	1.19	0.24	28,414.00	1.00	0.01	0.03
1948–1970	22.00	−8.00	35.45	−0.23	0.82	1256.67	1.00	0.00	0.00
1971–1990	19.00	37.00	28.55	1.30	0.19	815.00	1.00	0.05	0.12
1991–2012	22.00	12.00	35.45	0.34	0.73	1256.67	1.00	0.01	0.01

Table 12.4 Trend statistics for minimum temperature at Narail for the period 1948–2012

Minimum temperature	Nonmiss	Test stat	Std. dev.	MK-stat	*p*-value	Covariance	Correlation	Rate of change (°C/year)	*r*
Monsoon									
1948–2012	64.00	700.00	172.49	4.06	0.00	29,754.00	1.00	0.02	0.20
1948–1970	23.00	41.00	37.81	1.08	0.28	1429.67	1.00	0.02	0.06
1971–1990	19.00	56.00	28.57	1.96	0.05	816.00	1.00	0.05	0.13
1991–2012	22.00	96.00	35.29	2.72	0.01	1245.33	1.00	0.04	0.25
Post-monsoon									
1948–2012	62.00	16.00	164.56	0.10	0.92	27,079.34	1.00	0.00	0.00
1948–1970	23.00	30.00	37.82	0.79	0.43	1430.00	1.00	0.02	0.02
1971–1990	17.00	−53.00	24.26	−2.19	0.03	588.33	1.00	−0.08	0.20
1991–2012	22.00	8.00	35.45	0.23	0.82	1256.67	1.00	0.00	0.00
Pre-monsoon									
1948–2012	63.00	530.00	168.54	3.14	0.00	28,404.67	1.00	0.02	0.16
1948–1970	23.00	99.00	37.86	2.61	0.01	1433.67	1.00	0.09	0.27
1971–1990	18.00	28.00	26.29	1.06	0.29	691.33	1.00	0.04	0.03
1991–2012	22.00	12.00	35.38	0.34	0.73	1252.00	1.00	0.02	0.05
Winter									
1948–2012	63.00	499.00	168.57	2.96	0.00	28,414.33	1.00	0.02	0.16
1948–1970	23.00	37.00	37.84	0.98	0.33	1431.67	1.00	0.03	0.06
1971–1990	18.00	69.00	26.40	2.61	0.01	697.00	1.00	0.15	0.41
1991–2012	22.00	−50.00	35.42	−1.41	0.16	1254.67	1.00	−0.05	0.14

Table 12.5 Farmers perception on climate change impacts and adaptation in wetlands (N = 103)

Variable	Percentage (%)
Changes in temperature	
Increasing	96
Decreasing	4
Stayed the same	0
Changes in rainfall	
Increasing	5
Decreasing	92
Erratic	1
Stayed the same	2
Impact of rainfall and temperature changes in production	
Yes	99
No	1
Adaptation in agriculture	
Changes of crop varieties	12
High quantity of fertilizer	5
Increase in irrigation	3
Multiple coping strategies	80
Adaptation in water sector	
Use of boring methods	94
River water	1
Prevent saline water	1
Doing nothing	4
Loan taken	
Yes	8
No	92
Concern about climate change	
Yes	75
No	25

Table 12.6 Panicle and spikelet initiation time for the local crops

Crop types	Panicle and spikelet initiation time
Til	*Chaitra* (mid-March to mid-April)
Aus	*Ashar-Joistha* (mid-June to mid-August
Aman	*Ashin-Kartik* (mid-September to mid November)

months. The trend analysis revealed that, though the rainfall trends are decreasing only for the *Joistha* (May–June) and *Kartik* (October–November), the mean and maximum temperatures are following significant increasing trends from 1948 to 2012. This rising temperature and decreasing rainfall coincide with the panicle and spikelet initiation time of local crops such as *Aus* (autumn/pre-kharif rice crop), *Aman* (winter/kharif rice crop) and *Til* (sesame seed). The rising temperature negatively affects agriculture by burning out the production. The rising temperature in monsoon, post-monsoon and pre-monsoon seasons and decreasing rainfall trends in pre-monsoon season are the reasons for changing the crop varieties in the wetlands. Although the growing demands of food due to the rising population forced the government to develop policies friendly to high-yielding varieties (HYV), the changes in climate are also a reason for adopting HYV crops. During the survey, ~99% of farmers perceived that changes in rainfall and temperature negatively affected crop production in the wetlands. While coping with these negative effects of climate change, 80% of farmers have adopted multiple adaptation methods that include changes in crop varieties and excessive use of fertilizers, whereas ~12% of farmers adopted only changes in crop varieties as an adaptation option. Furthermore, 94% of farmers are adopting expensive borewells as an adaptation in water resources required for crop production in wetlands. Farmers reported that the local crops cultivated before the 1990s did not require such borewells, as means of adaptations, whereas the new HYV crops' production costs are very high. Figure 12.2 shows that the production cost has increased 2.5–3.5-fold within 10 years of time due to the shift from local crops to HYV crops.

We explored the determinants of adaptation by running bivariate probit regression (BPR) with age, education and income as explanatory variables. Table 12.7 shows that education positively ($\beta = 0.06$, $p < 0.05$) influenced adaptation practices in agriculture, whereas the rest of the variables exhibited no influence. Further, we added some more explanatory variables such as access to credit, climate change concerns (e.g. yes or no) and impact of rain and temperature on agriculture along with the earlier three explanatory variables. This exhibited no influence of education on adaptation; however, adaptation exhibited ($\beta = 1.00$, $p < 0.1$) significant relationship with loan taken. This possibly implies that adaptation to climate change is influenced mostly by the loan, as the farmers are depending on loan to cope with increase in production cost.

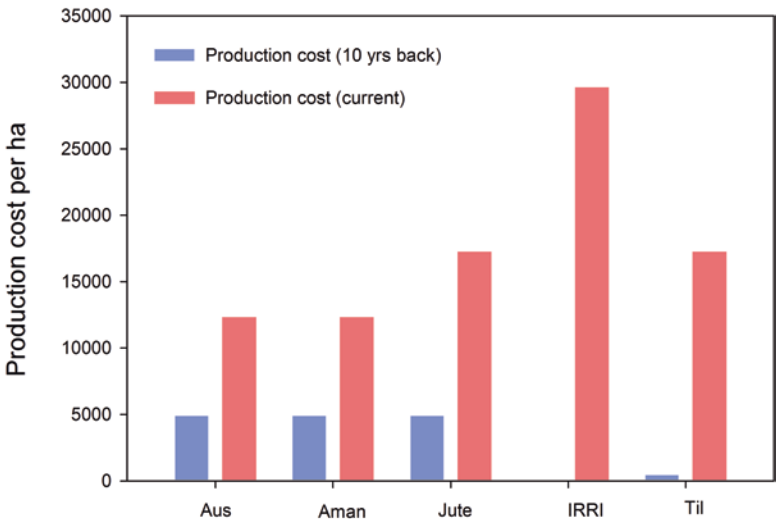


Fig. 12.2 Production costs of local crop varieties in wetlands

Table 12.7 Determinants of climate change adaptation

Variables	(1) Adapt dummy	(2) Water dummy	(3) Adapt dummy	(4) Water dummy
Age	−0.00	0.01	−0.00	0.01
	(0.01)	(0.01)	(0.01)	(0.01)
Educational	0.06*	−0.05	0.04	−0.05
	(0.03)	(0.04)	(0.03)	(0.04)
Income	−0.07	0.10	−0.08	0.11
	(0.16)	(0.22)	(0.16)	(0.23)
Loan			1.00*	−0.40
			(0.52)	(0.64)
Concern about climate change			0.36	−0.47
			(0.39)	(0.61)
Impact of rainfall and temperature changes			5.22	−4.06
			(1678)	(3095)
Constant	−0.20	0.26	−5.73	4.74
	(1.66)	(2.30)	(1678)	(3095)
Observations	93	93	93	93

Standard errors in parentheses
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

12.6 Future Impacts and Adaptation to Climate Change in Wetlands

Our previous work (Hossain et al. 2013) projected climate change for the same study area using MAGICC (Model for the Assessment of Greenhouse Gas Induced Climate Change)–SCENGEN (SCENario GENerator) model. This study also investigated the plausible impacts of future climate using expert judgement and literature review. The model projection shows that monsoon and post-monsoon rainfall will increase 10–23% by 2100. Similarly, temperature will increase 2–5 °C in all seasons by the year 2100. For the predicted changes in temperature and rainfall, crop production will decline by 30–35% for *Aus* (autumn/pre-kharif rice crop) and 22–63% for wheat. The fall in production will influence food security of this region, as these crops are the staple food not only for the wetland-based people but also the whole population of the country. The changes in climate will also increase irrigation demand, which in turn will increase production cost in agriculture. In addition, salinity and water scarcity will also increase due to the changes in climate, which will also increase production cost, with a possibility of production loss in wetlands at Narail. Moreover, natural hazards such as floods will also increase (25–50%) in the region.

Hossain et al. (2013) also identified adaptation and mitigation options using interdisciplinary framework DPSIR [driver-pressure-state-impact-response], (Fig. 12.3) to adapt to climate change in these wetlands. They recommended maintaining water flow required in dry season and construction of barrage to store water in dry season. Mitigation options such as dredging rivers and excavating canals in wetlands were also identified as the possible mitigation options to climate change. In case of adaptation to current state and future impacts, fair trade policy at least could ensure recovery from the loss of high production cost and other impacts due to climate change. In addition, increasing the capacity of farmers through training and education could enhance their capacity to adapt with climate change. Adaptation options such as new varieties with low production cost and increase in the access of fertilizers and energy could help the community to cope with climate change. Moreover, low-cost technology such as rainwater harvesting could help in storing water during wet season for the use in dry season for household and irrigation purposes. These recommendations were for ecosystem service-based adaptation (ESbA) concerning the social–ecological system of wetlands.

12.7 Mainstreaming Climate Change in Development Planning

Adaptation to climate change is highly challenging for the development in low-income countries. Despite greater emphasis on mainstreaming climate change adaptation into development planning (Schipper 2007; OECD 2009), it is in relatively early stage in many countries (UNEP 2011). One of our previous works (Hossain et al. 2010) is focused on mainstreaming climate change adaptation in the same wetlands that we are focusing in this chapter. Hossain et al. (2010) investigated whether the government was concerned about climate change while planning water resource management project in wetlands. Surveys and FGDs were used to collect the impacts of climate change in the study area. National Adaptation Programme of Action (NAPA) and the project documents of water resources were reviewed to investigate whether climate change was one of the concerns while planning and implementing the project. As we have already discussed about climate change impacts using trends and survey data analyses, we will now focus only on the mainstreaming of climate change adaptation in this section. Although the water resource management project adopted some of the initiatives such as canal excavation and embankment construction to increase water availability in wetlands, the project was not concerned about climate change while in its planning stage. National Adaptation Programme of Action (NAPA 2005) identified the wetland area as drought prone area; however, the project did not consider the mitigation and adaptation to drought in the wetlands. The project also did not consider the current and future impacts of climate change, or it did not consider how it would adapt to climate change. Though the project claimed that water demand would increase after the implantation of the project, water scarcity in wetlands may increase because of not linking climate change with water demand and feedbacks from society such as extraction of more groundwater in response to increasing water demand due to climate change. Moreover, the important question is how the water resource management initiatives will adapt with the excess of water in the wet season and scarcity of water in the dry

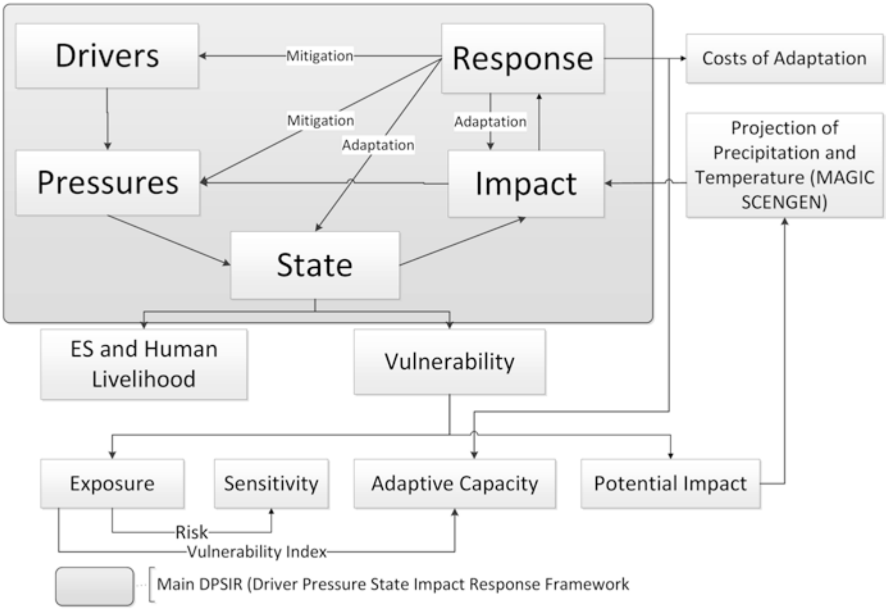


Fig. 12.3 Modified DPSIR to demonstrate integration of climate change adaptation into development plans (Source: Hossain et al. 2013)

season in the future. NAPA (2005) and Bangladesh Climate Change Strategy and Action Plan 2009 (MoEF 2009) emphasized mainstreaming of climate change in the country and provided guideline for climate change adaptations. However, previous studies did not provide insight on how we can integrate adaptation planning in the real word. Hossain et al. (2013) provided a conceptual model to integrate climate change adaptation within development plans. In brief, the modified versions of DPSIR framework (Fig. 12.3) identify the drivers and pressures using secondary data and community engagement and also identify the state by analysing the vulnerability of the wetlands. The future impacts were then assessed by using MAGICC/SCENGEN model to project future climate. The response part of the DPSIR integrates how we can mitigate the drivers and pressures and how we can adapt with current state and future impacts using ecosystem service-based adaptation.

12.8 Why We Still Need to Know About Local Climate Change Adaptation?

Despite the significant contribution of wetlands to the national and regional (South Asia) economy, impacts and adaptation to wetlands were given low attention in Bangladesh in particular, and South Asia in general. Therefore, this study explores the opportunity for adaptation planning at local and national level through local knowledge on climate change in wetlands. Engaging with the community to understand their perception on climate change impacts and adaptations has been recognized as an intuitive way to get insight into climate information and as a tool for communication with local people (Reyes-García et al. 2016). The real-world example of not integrating climate change adaptation into development planning despite emphasis on mainstreaming climate change adaptation in national planning provides indication that there is a need for developing robust and more effective planning to cope with climate change at local level. In addition, the influence of loan on adaptation to climate change also suggests to increase the access to credit and microfinance for promoting sustainable agriculture and to tackle climate change impacts. Although the microfinance and access to credit are set among the Sustainable Development Goals (SDGs) for ending poverty, these are not included for promoting sustainable agriculture and achieving climate change goals identified in the SDGs. In addition, the dependency of agriculture production on subsidy and the necessity of shifting to crop varieties with low production cost have been neglected while setting the SDGs. Without including these issues in local and global agenda, the rising production cost may demotivate farmers in the long run, and it could jeopardize in achieving some of the SDGs such as ending poverty by 2030. Therefore, the local adaptation study not only can influence adaptation planning at different scales but also can contribute in developing global targets such as SDGs. This study can be extended by increasing sample size and extending this study to other wetlands. Moreover, answering some of following research questions can provide insight into the impacts of climate change on wetlands and ways to develop effective adaptation plans. The research questions may include:

- Do the wetland management plans integrate national adaptation planning?
- How can we reduce cost of production using wetland resources?
- How the wetland ecosystem services can play a role in adaptation to climate change?
- How to develop tools/framework/model to integrate adaptation planning into development planning?
- How local wetlands can contribute to the mitigation of climate change at global and national scale?
- What are the limits of adaptation to climate change concerning the social–ecological systems of wetlands?

Acknowledgement Authors would like to acknowledge Abu Siddique from the University of Southampton for supporting us in the survey data analysis.

References

Asian Development Bank (2005) Summery environmental impact assessment: South West Area Integrated Water Resources Planning and Management Project in Bangladesh. Asian Development Bank (ADB), Manila

Byomkesh T, Nakagoshi N, Shahedur RM (2009) State and management of wetlands in Bangladesh. Landsc Ecol Eng 5:81–90. doi:10.1007/s11355-008-0052-5

Environmental Protection Agency (2016) Why wetlands are important? Environmental Protection Agency (EPA), Washington, DC. Available at https://www.epa.gov/wetlands/why-are-wetlands-important. Accessed 21 May 2016

Erwin KL (2009) Wetlands and global climate change: the role of wetland restoration in a changing world. Wetl Ecol Manag 17:71–84. doi:10.1007/s11273-008-9119-1

Greene WH (2003) Econometric analysis. Pearson Education India, New Delhi

Hassan R, Nhemachena C (2008) Determinants of African farmers' strategies for adapting to climate change: multinomial choice analysis. Afr J Agric Resour Econ 2(1):83–104

Hoozemans FMJ, Marchand M, Pennekamp HA (1993) A global vulnerability analysis: vulnerability assessment for population, coastal wetlands and rice production on a global scale, 2nd edn. Delft Hydraulics, The Hague

Hossain MS, Sazbo S (2016) Understanding the socio-ecological system of wetlands. In: Prusty BAK, Chandra R, Azeez PA (eds) Wetlands science: perspective from South Asia. Springer Nature, New Delhi. (in Press)

Hossain MS, Roy K, Hauqe M, Khan HM (2010) Climate change and development: a research on mainstreaming of climate change in National Policy Development using Environmental Impact Assessment (EIA) in Water Resource Management at Narail, Bangladesh. Ulashi Sreejony Sangha (USS) and NGO Forum on ADB

Hossain MS, Hein L, Rip FI, Dearing JA (2013) Integrating ecosystem services and climate change responses in coastal wetlands development plans for Bangladesh. Mitig Adapt Strateg Glob Chang. doi:10.1007/s11027-013-9489-4

Hossain MS, Roy K, Datta D (2014) Spatial and temporal rainfall variability of rainfall over the south west coast of Bangladesh. Climate 2:28–46. doi:10.3390/cli2020028

Intergovernmental Panel on Climate Change (1995) Climate change 1995 – impacts, adaptations and mitigation of climate change: scientific technical analysis. Contribution of working group II to the second assessment report of the IPCC. Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge

International Water Management Institute (2010) Wetland, agriculture and poverty reduction. Research report. International Water Management Institute (IWMI), Colombo. Available via: http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB137/RR137.pdf. Accessed 21 May 2016

Khan AA (1993) Fresh water wetlands in Bangladesh: opportunities and options. In: Nishat A, Hussain Z, Roy MK, Karim A (eds) Freshwater wetlands in Bangladesh – issues and approaches for management. IUCN, Dhaka, pp 1–7

Khan SM, Haq E, Huq S, Rahman AA, Rashid SMA, Ahmed H (1994) Wetlands of Bangladesh. Bangladesh Centre for Advanced Studies (BCAS), Dhaka knowledge and working memory: a study among three contemporary hunter-gatherer societies. PLoS One 11(1):e0145265. doi:10.1371/journal.pone.0145265

Kurukulasuriya P, Mendelsohn R (2008) Crop switching as a strategy for adapting to climate change. Afr J Agric Resour Econ 2(1):105–126

MoEF (2009) Bangladesh Climate Change Strategy and Action Plan 2009. Ministry of Environment and Forests, Goverment of the People's Republic of Bangladesh, Dhaka Bangladesh. HYPERLINK http://www.climatechangecell.org.bd/Documents/climate_change_strategy2009.pdf

Moni AH, Hossain MS (2010) Response of environmental changes (Climate) in wetlands. Proceedings 3rd international conference on Bangladesh environment 2010 by BEN and BAPA, Dhaka

NAPA (2005) Bangladesh National Adaptation Program of Action. Bangladesh Ministry of Environment and Forest, Government of Peoples Republic of Bangladesh, Dhaka

Nicholls RJ (2004) Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. Glob Environ Chang 14:69–86. doi:10.1016/j.gloenvcha.2003.10.007

Organization for Economic Co-operation and Development (2009) Integrating climate change adaptation into development co-operation: policy guidance, Organization for Economic Co-operation and Development (OECD). Available via: www.oecd.org/dataoecd/0/9/43652123.pdf. Accessed 21 May 2016

Ramsar (2014) Wetlands & agriculture partners for growth. Available via: http://www.ramsar.org/sites/default/files/wwd14_leaflet_en.pdf. Accessed 21 May 2016

Reyes-García V, Pyhälä A, Díaz-Reviriego I, Duda R, Fernández-Llamazares Á, Gallois S et al (2016) Schooling, local knowledge and working memory: a study among three contemporary hunter-gatherer societies. PLoS One 11(1):e0145265. doi:10.1371/journal.pone.0145265

Saadat MA, Islam AKMS (2011) Impact of climate change on rural livelihood: a case study. Paper presented at the International Conference on Water & Flood Management (ICWFM-2011), Dhaka, Bangladesh

Schipper L (2007) Climate change adaptation and development: exploring the linkages. Tyndall Centre working paper 107, Tyndall Centre for Climate Change Research, Norwich, UK

Seo SN, Mendelsohn R (2008) Climate change impacts on Latin American farmland values: the role of farm type. Revista de Economia e Agronegócio 6(2):159–176

Shiklomanov IA, Rodda JC (2003) World water resources at the beginning of the 21st century. UNESCO, Paris

Uddin MS, de R van Steveninck E, Stuip M, MAR S (2013) Economic valuation of provisioning and cultural services of a protected mangrove ecosystem: a case study on Sundarbans Reserve Forest, Bangladesh. Ecosyst Serv 5:88–93

UNEP (2011) Mainstreaming climate change adaptation into development planning: a guide for practitioners. United Nations Environmental Program (UNEP). Available via: http://www.unep.org/pdf/mainstreaming-cc-adaptation-web.pdf. Accessed 21 May 2016

Vitale JD, Vognan G, Ouattarra M, Traore O (2010) The commercial application of GMO crops in Africa: Burkina Faso's decade of experience with Bt cotton. AgBioforum 13(4):320–332

World Bank (2000) Bangladesh: climate change & sustainable development. Sector report no. 21104, Dhaka

Carbon Dynamics, Processes and Factors Regulating Greenhouse Gas Emissions from Wetlands

13

Akhilesh Vijay and Sivasankaran Bijoy Nandan

Abstract

Wetlands are prominent ecosystems lying at the interphase between terrestrial and aquatic ecosystems storing nearly 20–30% of the global carbon pool and are considered as the first ecosystem to experience the impact of climate change. Carbon storage in wetlands depends on the balance between carbon input and output influenced by several environmental and micro-meteorological factors such as temperature, moisture, pH, redox conditions, topography, geological position, the hydrological regime and type of vegetation. Globally rice paddies share a significant portion of the wetlands functioning as a major sink or source of carbon micromanaging the emissions of major greenhouse gases. Studies conducted by the authors in selected paddy wetlands of Kerala, India, have established that they are net source of methane during the flooded paddy growth period (92.638 mg m^{-2} h^{-1}), whereas they act as sink during the summer fallow period (−2.0176 mg m^{-2} h^{-1}). The carbon dioxide fluxes in the paddy act as a source (−0.45 to 2.3 g m^{-2} h^{-1}) during the entire study period. Seasonal carbon dioxide was higher in the summer fallow period than in the flooded cultivation period. Fallow period facilitates the aeration of soil, thereby resulting in net loss of soil organic carbon by oxidizing it to carbon dioxide. Highest nitrous oxide emission (0.76 mg m^{-2} h^{-1}) was observed during the end of first crop season whereas lowest (−0.017 mg m^{-2} h^{-1}) was during summer fallow months of April. During the study, the global warming potential determined for the paddy wetlands of Palakkad was 337.16 g m^{-2}. Wetlands having considerable role in carbon sequestration levels and greenhouse gas (GHG) emissions have a potential bearing on the effective management for mitigating climate change.

A. Vijay • S.B. Nandan (✉)
Department of Marine Biology, Microbiology & Biochemistry, School of Marine Sciences, Cochin University of Science and Technology, Kochi, Kerala, India
e-mail: akhileshvijay@cusat.ac.in; bijoynandan@yahoo.co.in

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_13

Keywords
Carbon sequestration • Climate change • Greenhouse gases • Global warming potential • Wetlands

13.1 Introduction

Wetlands are transitional zones between terrestrial and aquatic systems recognized as an important component of the global carbon cycle ever related to climatic factors both at global and regional scale. Prevailing unique biogeochemical processes facilitate wetlands as major reservoirs of carbon (C), storing nearly 20–30% of the global carbon pool. As carbon stored in the wetland sediments are highly sensitive to climate-driven environmental changes, including changes in inundation, temperature, nutrient regime and microbial activity, they act as a major source of carbon especially major greenhouse gases (GHG), *viz.*, methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) (Mitra et al. 2005). During 1750–2011, atmospheric CO_2 increased from 278 to 390.5 ppm, CH_4 from 722 to 1803 ppb and N_2O from 271 to 324.2 ppb (IPCC 2013). This unprecedented rate of change in the atmospheric concentrations of physically and chemically important trace gases over the last century along with increase in global temperature made it increasingly important to understand the climatic factors and processes regulating the sink and source of carbon and major GHGs function of wetlands in the context of the climate change. This chapter discusses the mechanism and major factors regulating C storage and release from wetlands, with a case study of the paddy wetlands of Kerala.

13.2 Wetlands as Sink and Source of Carbon

Wetlands occupy 12% of the global carbon pool having a carbon density of 723 t ha^{-1} (Ma et al. 2016) and store approximately 2500 Pg (Note: 1 Pg = 10^{15} gm) of the earth's carbon pool (Lal 2008; Mitsch et al. 2013). The major carbon reserves of wetland include (a) plant biomass carbon (PBC), (b) particulate organic carbon (POC), (c) dissolved organic carbon (DOC), (d) microbial biomass carbon (MBC) and (e) gaseous end products such as CO_2 and CH_4. Active biomass comprises wetland vegetation, which transforms the inorganic carbon such as CO_2 to organic carbon through photosynthesis. Particulate organic carbon consists of decaying plant materials present on the soil surface or in water column. Dissolved organic carbon comprises of dissolved carbon compounds such as trihalomethane (THM), microbial exudates contributing to biochemical oxygen demand. Microbial biomass carbon occurs in heterotrophic microflora, transforming organic carbon to inorganic carbon and mineralizing particulate organic carbon and dissolved organic carbon (Kayranli et al. 2010).

Carbon storage in the wetland is the balance between carbon input (organic matter production) and release (decomposition, respiration and methanogenesis). Organic matter, entering the wetlands as plant remnants, contributes 45–50% of carbon (Kayranli et al. 2010). The biomass undergoes complex processes of aerobic and anaerobic decomposition. The key processes are respiration in the aerobic zone and fermentation, methanogenesis, sulphate, iron and nitrate reduction in the anaerobic zone. The combination of elevated water table, high productivity and slower or incomplete decomposition of organic matter under anaerobic conditions allows significant storage of carbon in the wetland soil, making it a carbon sink (Dieleman et al. 2015). Even though wetlands are considered as a sink of atmospheric carbon, they are also ecosystems that significantly contribute to emissions of major GHG (Smith et al. 2007). GHG emissions from wetland soils are complex heterogeneous processes in which CO_2 is released from autotrophic and heterotrophic respiration (Janzen 2004). The ecosystem CO_2 balance depends on the net ecosystem exchange (NEE), comprising of input of carbon from photosynthesis and losses from ecosystem respiration. Ecosystem respiration includes respiration by the plants and soil. Soil respiration comprises of autotrophic respiration originating from roots and their associated mycorrhizal fungi and rhizosphere microbes and heterotrophic respiration from microbial decomposition of soil organic matter (Hanson et al. 2000). Methane is produced by methanogenesis under strict anoxic conditions and low redox potential of ≤150 mv by transmethylation or decarboxylation of acetic acid and by the reduction of CO_2 (Wang et al. 1997; Singh et al. 2000). Nitrous oxide emission from wetlands is a result of (a) nitrate or nitrite-reducing processes of denitrification, (b) nitrate ammonification, (c) ammonia oxidation and (d) nitrifier denitrification (Baggs 2011). The complex process of N_2O emission from wetlands is regulated not only by N input and the water regime but also by several other factors such as soil texture, soil pH, redox potential and C/N ratio (Akiyama and Tsuruta 2003). Thus, the dynamics of three GHG emissions regulate and control the biogeochemical processes in wetlands.

13.3 Carbon Sequestration Process

Carbon sequestration is the natural or anthropogenic process by which the atmospheric CO_2 is captured and stored in the soils, vegetation, ocean and geologic basalts, for a specific duration (Lal 2004). In the present scenario, carbon sequestration technique is being incorporated along with various geoengineering processes to fix and thereby mitigate atmospheric CO_2. Abiotic and biotic processes are involved in sequestering carbon. In abiotic process, CO_2 is sequestered following physical, chemical reaction and engineering techniques devoid of living organisms (e.g. plants, microbes, etc.). Theoretically, abiotic sequestration has larger sink capacity than biotic sequestration making it considerable among oceanic and geological structures (Freund and Ormerod 1997). In the biotic process, the atmospheric CO_2

is fixed into the terrestrial/aquatic ecosystem by photosynthesis, and carbon is stored in plant components including trunks, branches, leaves and roots (Kishwan et al. 2009). The incorporation of these materials into the soil via the actions of different soil organisms (Kemmitt et al. 2008) and inhabitants of the litter, together with the carbon exudates from roots that are utilized by microbial populations, constitutes the natural pathway of incorporating biomass carbon into the soil.

13.4 Carbon Sequestration Potential of Wetlands

Globally wetlands store nearly 44.6 Tg C $year^{-1}$ (Note: 1 Tg = 10^{12} gm) (Patil et al. 2012) with an average carbon sequestration rate of 20–30 g C m^{-2} $year^{-1}$ (Roulet et al. 1993) in which tropical, temperate and boreal wetlands sequester about 0.56 Pg C $year^{-1}$, 0.16 Pg C $year^{-1}$ and 0.11 Pg C $year^{-1}$, respectively. On accounting the sequestration potential, it varies widely among wetlands and climatic regime as sequestration is a function of both biomass production and respiration. Coastal wetlands, comprising of more than 226,000 km^2 of mangroves and salt marshes (Patra et al. 2013), have the potential to sequester 4.77 g C m^{-2} $year^{-1}$ (Chmura et al. 2003). Along with mangroves, tidal wetlands of San Francisco Bay sequester nearly 79 g C m^{-2} $year^{-1}$ (Callaway et al. 2012). It is estimated that the northern and tropical peat-based wetland systems store up to 510 Gt C that equates to approximately 30% of the total global organic soil carbon stock (Saunders et al. 2014). Based on carbon density, carbon storage of temperate and tropical peatlands was estimated to store nearly 256 Gt C and 19.3 Gt C, respectively, whereas boreal and subarctic peatlands alone store nearly at 460 Gt C (Mitra et al. 2005). Globally soil organic carbon (SOC) in most of the agricultural pools is below their ecological potential prone to soil erosion and other degradable processes. Wetland under cultivation has 0.2–7.6 g C m^{-2} $year^{-1}$ under improved crop management and 8–10 g C m^{-2} $year^{-1}$ through restoration of wetlands (Lal 2008). The carbon sequestration potential of restored wetlands, under the ongoing national wetland conservation action plan in China, was estimated at 6.57 Gg C $year^{-1}$ (Note: 1 Gg = 10^9 gm). North American prairie pothole restored wetlands also have an estimated annual sequestration rate of 27 g C m^{-2} $year^{-1}$. The carbon sequestration potential of selected wetlands around the world is given in Table 13.1.

India accounts for nearly 757 wetlands contributing to nearly 4.64% of the total geographical area of the country. Of the total wetland area, coastal and inland wetlands constitute 27% and 69%, respectively (SAC 2011). The total extent of coastal ecosystems (including mangroves) in India is around 43,000 km^2 and sequesters about 1.5 Mt C ha^{-1} $year^{-1}$ (Kathiresan and Thakur 2008). The total area under wetlands in Kerala is 1279.3 km^2, of which 341.9 km^2 and 937.3 km^2 are constituted by inland and coastal wetlands, respectively. Studies on the sequestration of carbon from the wetlands of India are scanty and largely deal with GHG emissions.

Table 13.1 Carbon sequestration potential of selected wetlands of the world

Wetland types	g C m^{-2} $year^{-1}$	References
General range for wetlands	20–140	Mitra et al. (2005)
Northern peatlands		
Peatlands (North America)	2	Gorham (1991)
Boreal peatlands	15–26	Turunen et al. (2002)
Temperate peatlands	10–46	Turunen et al. (2002)
Temperate/tropical wetlands		
Coastal wetlands, North America		
Mangroves	180	Chmura et al. (2003)
Salt marshes	220	Chmura et al. (2003)
Tidal freshwater wetlands	140 ± 20	Craft (2007)
Brackish marshes	240 ± 30	Craft et al. (2009)
Salt marshes	190 ± 40	Craft et al. (2009)
Mangrove swamps, Southeast Asia	90–230	Suratman (2008)
Coastal wetlands, Southeast Australia		
Undisturbed sites	105–137	Howe et al. (2009)
Disturbed sites	64–89	Howe et al. (2009)
Tropical freshwater wetland	56 (for 24,000 years)	Page et al. (2004)
Tropical Indian mangroves	1.5 Mt C ha^{-1} $year^{-1}$	Kathiresan and Thakur (2008)
Cyperus wetland in Uganda	480	Saunders et al. (2007)
Prairie pothole wetlands, North America		
Restored (semi-permanently flooded)	305	Euliss et al. (2006)
Reference wetlands	83	Euliss et al. (2006)
Florida Everglades	86–387	Reddy et al. (1993)
Tropical flow-through wetland, Costa Rica	306	Mitsch et al. (2013)
Tropical forest wetland, Costa Rica	84	Mitsch et al. (2013)
Tropical floodplain wetland, Cost Rica	84	Mitsch et al. (2013)
Tropical seasonally flooded wetland, Botswana	42	Mitsch et al. (2013)
Boreal wetlands	15–26	Turunen et al. (2002)

13.5 Importance of Paddy Wetlands

Ironically paddy wetlands are key ecosystems identified to sequester 466–2011 Gt of carbon as well; they act as a source of carbon contributing to emissions of major GHGs (Smith et al. 2007). The processes of autotrophic and heterotrophic respiration control ecosystem carbon fluxes. The difference between plant photosynthesis and respiration is defined as net primary production (NPP), and the difference between NPP and total consumer and soil respiration is net ecosystem production that represents the net carbon flux from the atmosphere to the ecosystems. Most organic carbon entering the soil surface is rapidly consumed, and some of it is respired by heterotrophic organisms primarily occurring in the rooting zone (top 10–20 cm). This rapid mineralization quickly returns CO_2 back to the atmosphere and is controlled in part by the composition of the organic matter inputs and environmental factors. Climate change could alter the levels of carbon storage and trace gas flux from cropland soils, since changes in temperature, precipitation and atmospheric CO_2 concentration will affect NPP, C/N inputs to soil and soil carbon decomposition rates (Erickson et al. 2013).

The increasing demand by scientific community, policy makers and the public for realistic projections of agricultural emissions has rendered the issue of regional estimations of GHG critically important. For meeting the set goals, a study was carried out in a tropical paddy, a model agro-wetland ecosystem, located in Padayatti Village, Palakkad District (10°41′137 N, 76°32′839E), Kerala, India. Considering the case study, the dynamics of major GHG emissions and the major factors regulating these emissions are discussed below giving insights on global warming potential (GWP).

13.6 Case Study on Greenhouse Gas Emissions from Paddy Wetland of Kerala, India

The study was conducted in the paddy wetlands of model agro-wetland ecosystem of Padayatti, located in the southeast province of Kerala, India. Paddy ecosystem in Palakkad, known as the rice granary of Kerala, spreading over 2415 ha, almost 42.5% of Kerala (197,277 ha) in 2012–2013, is made up of several varieties of agroecosystems (ENVIS 2016). The climate of the state is typical tropical monsoonal with seasonally high rainfall, humid and hot summer. The agricultural calendar of the area may be divided into three. The period from March to the end of May is the hot season followed by southwest monsoon, which continues until the middle of October. The northeast monsoon starts in mid-October and lasts up to the end of February, although the rains from the northeast monsoon cease by December. Though the mean temperature is only 32.2 °C, it is oppressively hot in the plains in summer. Static chamber-based study for GHGs was carried out in the 400 acres of micro-watershed paddy ecosystem of Padayatti on a monthly basis for the estimation of soil GHG emission and other soil parameters during March 2013 to March 2014. CH_4, CO_2 and N_2O emission flux were measured at 0.5 h intervals. The gas sample in the headspace was injected to a gas chromatograph (PerkinElmer Clarus 580 – Greenhouse Gas Analyzer) with a duel channel plot Q column equipped with methanizer flame ionization detector (FID) and electron capture detector (ECD) (Bhattacharyya et al. 2012).

13.6.1 Carbon Dioxide Flux

The seasonal courses of net CO_2 flux from the soil/water surface throughout the year are shown in Fig. 13.1a. In the present study, cropping seasons served as a net

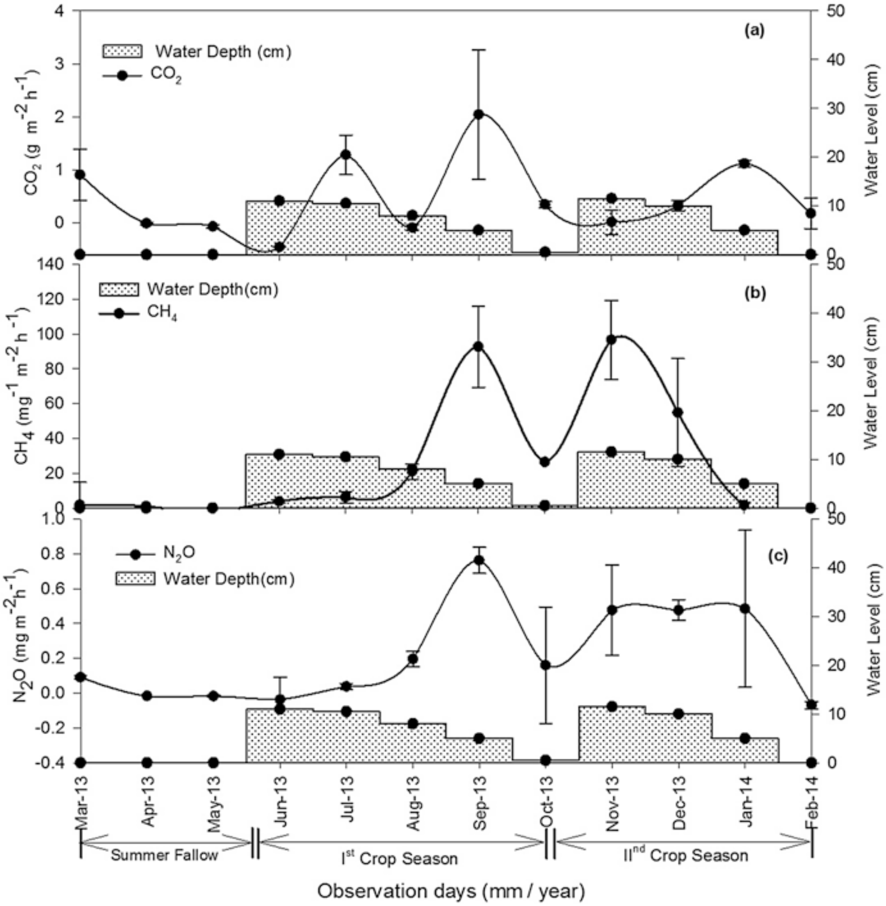


Fig. 13.1 Soil GHG fluxes from the paddy wetland during 2013–2014; (**a**) carbon dioxide (CO_2), (**b**) methane (CH_4) and (**c**) nitrous oxide (N_2O)

source of atmospheric CO_2. The soil CO_2-C uptake was high subsequent to stem elongation (−0.456 g m^{-2} h^{-1}) during periods of highest flood levels (FL~10 cm). Maximum CO_2-C emission was observed during the tillering stage. In the first crop season, the emission was 2.04 g m^{-2} h^{-1}, while in the second season it was 1.12 g m^{-2} h^{-1}. The summer fallow periods also showed increased CO_2-C emission rates of 0.09 g m^{-2} h^{-1}. However, there was increased CO_2 pulse event of 2 g m^{-2} h^{-1} during the ploughing and field preparation period followed by first crop season in September 2013 (Fig. 13.1a). A significant positive increase in soil CO_2 emissions was observed during summer fallow, panicle initiation and during field preparation. Soil CO_2 flux increased soon after transplantation in first crop season and the highest emission was during panicle initiation. While it decreased towards harvesting period subjected to mid-season drainage, no such variations were observed in the second crop season. During the paddy growth period, highest emission of CO_2 was observed during the panicle initiation stage due to the availability of the C substrates during this period and higher microbial activity (Iqbal et al. 2009; Ibrahim et al. 2013). Dynamics of CO_2 in paddy fields varies with the phase change in soil wet and dry conditions. CO_2 emissions increases with the drained summer fallow seasons, due to the aerobic decomposition of soil organic matter (Nishimura et al. 2015). However the system acts as a net sink of carbon during the crop seasons due to autotrophic fixation of carbon by the vegetation.

13.6.2 Methane Flux

Methane, evolved mostly by methanogenesis, is one of the most abundant carbon species present in the earth's atmosphere (mixing ratio ~1.8 ppm) accounting for about 20% of the global greenhouse effect. In the last several decades since pre-industrial times, atmospheric concentration of CH_4 has increased by a factor of 2.5, from 722 ppb during the year 1750 to 1803 ppb during the year 2011 (IPCC 2013). The massive increase in the number of ruminants, emissions from fossil fuel extraction and use, expansion of rice paddy agriculture and the emissions from landfills and waste are the main sources of anthropogenic CH_4. Biogenic anthropogenic sources include paddy cultivation, livestock, landfills and waste treatments, biomass burning and fossil fuel combustion, while natural sources are wetlands, oceans, forest fires, termites and geological settings. Currently, CH_4 emissions to the atmosphere, with a half-life of about 8.4 years, are about 500–600 Tg year^{-1} (Dentener et al. 2003). Presently, anthropogenic emissions of CH_4 dominate natural emissions, accounting for about 50–65% of the total emissions (Kayranli et al. 2010).

In the present study, CH_4 emission covaried with crop growth, increasing with the early crop (EC) to panicle initiation (PI), while it was low in the ripening stages (RS) (Figs. 13.1b and 13.2). Fluxes of CH_4 followed a similar seasonal pattern during both the crop seasons varying significantly between flooded crop growing season (June to February) and summer fallow (March to May) period. Generally in the tropical flooded paddy soils, CH_4 evolves as an end product of acetate cleavage by acetoclastic methanogens in the anoxic soil zones. Several physical and chemical factors (temperature, pH, redox potential, soil type and texture), water regime, fertilizer application and agricultural practices (direct seeding, transplanting) determine CH_4 from ricefields. Among these factors soil redox potential and pH are crucial in controlling the anaerobic decomposition of SOM leading to the production of methane.

In the present study, values for pH in the soil ranged from 6.0 to 7.5, which favour the growth of methanogenic bacteria (Uprety et al. 2011). In addition to pH, the soil oxidation reduction potential (Eh) plays a significant role in CH_4 production, as the obligatory anaerobic methanogenic bacteria requires Eh of about −200 mv or less to grow (Jain et al. 2004). The CH_4 emission was lowest (1.529 mg^{-1} m^{-2} h^{-1}) during the summer fallow period (March to May), having high Eh value ranging from −50.1 to −30.14 mv. Highest concentration of CH_4 was observed during the panicle initiation stage, with an average value of 352.8 mg^{-1} m^{-2} h^{-1}, at Eh

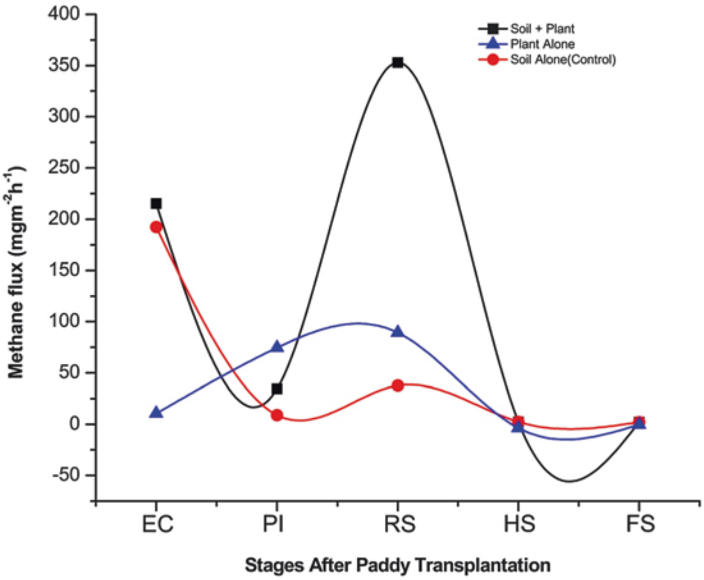


Fig. 13.2 Variations in methane emissions from paddy wetlands of Palakkad according to stages after transplantation. Where *EC* early crop, *PI* panicle initiation, *RS* ripening stage, *HS* harvest stage, *FS* fallow stage

value of −318.426 mv. Static chamber based CH_4 emission studies on paddy wetlands revealed that the emission was high during flooding to panicle initiation stages, at low Eh, while emission was low after the flowering and the ripening stages at high Eh in the paddy field with intermittent irrigation. Methane emission at the panicle initiation was mainly due to the release of root exudates and organic materials from the rice plants (Chidthaisong and Watanabe 1997). The decline in CH_4 emission from ricefields at the ripening stage was due to a decline in conductance of the rice body for CH_4. The decline in conductance was possibly due to reduced permeability of the root epidermal layer as a consequence of aging (Nouchi et al. 1994).

13.6.2.1 Factors Controlling CH_4 Emissions

In paddy fields, 15–52% of the CH_4 produced is oxidized to CO_2 by methanotrophic bacteria in the aerobic microsites present in the soil (Komiya et al. 2015). The CH_4 leftover in the soil is usually released to the atmosphere through rice plant by physical processes (molecular diffusion) and by gas bubble ebullition. Among these pathways, plant diffusional transport was found to be dominant in paddy soils (Nouchi et al. 1990). From our study, it was observed that CH_4 released through the parenchyma conduit was much higher (92% than from unplanted soil control, Fig. 13.2), possibly bypassing the microbial CH_4 oxidation (methanotrophy) at the soil oxic layers. CH_4 oxidation is the only biological sink where 80% of the produced CH_4 being consumed by methanotrophic bacteria for biological needs, for energy or building up microbial biomass (Hanson and Hanson 1996). Nouchi et al. (1990)

described the mechanism of CH_4 transport in rice plants, where the dissolved CH_4 in the soil interstitial waters diffuses into the root cortex driven by concentration gradient between the roots and lysigenous intercellular spaces. In the paddy root cortex, dissolved CH_4 is gasified and transported to the shoot via the lysigenous intercellular spaces and aerenchyma. Eventually, CH_4 is released through micropores in the leaf sheath.

13.6.3 Nitrous Oxide Flux

Agriculture contribution to the global annual N_2O emission was estimated at 62% of the anthropogenic N_2O emission (Duxbury 1994). Nitrous oxide emission from paddy soils was the result of nitrification and denitrification processes (Davidson et al. 1991). The complex processes of N_2O emission from paddy soils are regulated not only by N input and water regime but also by many other factors such as fertilizer type, temperature, soil texture, soil pH and C/N ratio (Akiyama and Tsuruta 2003). As shown in Fig. 13.1c, the variation in N_2O emission was observed between crop seasons from paddy wetlands of Palakkad. The highest emission was observed during the end of first crop season (0.76 mg m^{-2} h^{-1}), whereas the lowest was observed during summer fallow months of April (−0.017 mg m^{-2} h^{-1}). A seasonal similarity in emission was observed between the first and second crop season, which increased with the vegetative growth of the paddy and decreased by the harvest. Generally N_2O emissions from paddy fields had positive response towards N fertilizer application and are one of the main factors influencing its emission. Aerobic and anaerobic soil conditions due to the alternate wetting and drying process also increase the soil N_2O emissions, which are commonly stimulated by organic and non-organic soil amendments (Clayton et al. 1994; Hinton et al. 2015). Duel peaks of N_2O emissions occurred in both the seasons immediately after the top dressing (Fig. 13.1c). The cumulative N_2O emissions were estimated to be 76.3 ± 8.1 mg m^{-2} h^{-1}.

13.7 Global Warming Potential (GWP)

The global warming potential (GWP) is defined as the time-integrated radiative forcing (RF) due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2. It is used to compare the effectiveness of each GHG to trap heat in the atmosphere relative to CO_2. Integrated evaluation of GHG emissions expressed as GWP was computed by using the Intergovernmental Panel on Climate Change (IPCC) factors integrated over 20 years, 100 years or 500 years. The GWP of different treatments were calculated using the following equation:

$$[GWP = 34 ? CH_4 + CO_2 + 296 ? \mathrm{N_2O}\ kg\ CO_2\text{equivalent}\ ha^{?1}]$$

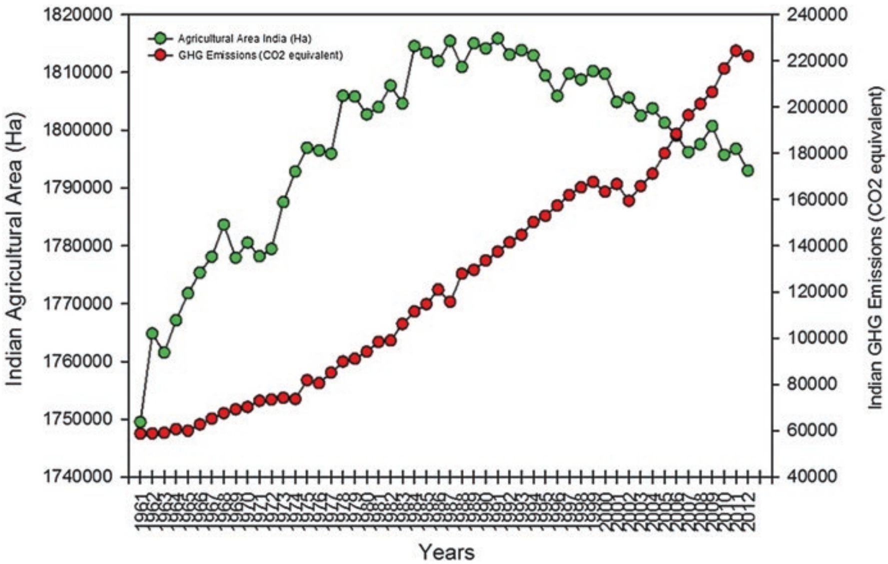


Fig. 13.3 Status of GHG emissions as CO_2 equivalent from Indian agricultural area (ha) during 1961–2012 (FAO. FAOSTAT 2015)

Based on a 100-year time frame, the GWP coefficients for CH_4 and N_2O are 34 and 298, respectively, when the GWP value for CO_2 is taken as 1 (IPCC 2013). During the study, the global warming potential determined for the paddy wetland of Palakkad was 337.16 g/m^2. Comparison of the GWP with other similar locations reveals that the GHG emission was much lower from the paddy wetlands of Palakkad. A general trend of Indian agricultural GHG emissions for the last 50 years in relation to productive total cultivable area is given in Fig. 13.3.

13.8 Conclusion

As wetlands are dynamic components of the global carbon and nitrogen cycles acting as a significant storehouse of carbon, there is a considerable potential for climate mitigation via enhancing wetland soil carbon sequestration and GHG reduction. Various natural and anthropogenic factors along with climate-driven changes disrupt the delicate balance, converting it into a major source of carbon. Globally over the next 100 years, climate models have projected temperature increase of about 1.4–4.0 °C, and significant changes in the regional precipitation pattern, while CO_2 concentration, could reach two to five times of the present day values. These climate forcing factors may affect the global land use pattern and also alter the vegetative composition and GHG fluxes affecting the carbon sequestration levels. Globally, long-term changes in crop productivity and harvest index are likely to reduce C and N inputs, thus affecting soil carbon storage and GHG fluxes in the absence of adaptive measures. Controlling and regulating the release of these gases from agricultural soils through judicious land use and appropriate management practices can mitigate the process of climate change while maintaining the crop yield. Thus, understanding the combined impact of these factors and potential synergies between land-based adaptations and mitigation strategies requires more global and regional collaborations with a holistic approach.

Acknowledgement The case study was supported by Directorate of Environment and Climate Change, Government of Kerala, India. The KSCSTE research fellowship for Akhilesh Vijay by Kerala State Council for Science Technology and Environment (KSCSTE) is greatly acknowledged.

References

Akiyama H, Tsuruta H (2003) Effect of organic matter application on N_2O, NO, and NO_2 fluxes from an Andisol field. Glob Biogeochem Cycle 17(4):1–16. doi:10.1029/2002GB002016

Baggs EM (2011) Soil microbial sources of nitrous oxide: recent advances in knowledge, emerging challenges and future direction. Curr Opin Environ Sustain 3:321–327

Bhattacharyya P, Roy KS, Neogi S, Adhya TK, Rao KS, Manna MC (2012) Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice. Soil Tillage Res 124:119–130

Callaway JC, Borgnis EL, Turner RE, Milan CS (2012) Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. Estuar Coast 35:1163–1181

Chidthaisong A, Watanabe I (1997) Methane formation and emission from flooded rice soil incorporated with 13C-labeled rice straw. Soil Biol Biochem 29:1173–1181. doi:10.1016/S0038-0717(97)00034-5

Chmura GL, Anisfeld SC, Cahoon DR, Lynch JC (2003) Global carbon sequestration in tidal, saline wetland soils. Glob Biogeochem Cycle 17(4):1111. doi:10.1029/2002GB001917

Clayton H, Arah J, Smith K (1994) Measurement of nitrous oxide emissions from fertilized grassland using closed chambers. J Geophys Res-Atmos 99:16599–16607

Craft C (2007) Freshwater input structures soil properties, vertical accretion, and nutrient accumulation of Georgia and U.S. tidal marshes. Limnol Oceanogr 52:1220–1230

Craft C, Clough J, Ehman J, Samantha J, Park R, Pennings P, Guo H, Machmuller M (2009) Forecasting the effects of sea-level rise on tidal marsh ecosystem services. Front Ecol Environ 7:73–78

Davidson EA, Vitousek PM, Matson PA, Riley R, Garcia-Mendez G, Maass JM (1991) Soil emissions of nitric oxide in a seasonally dry tropical forest of Mexico. J Geophys Res 96:15439–15445. doi:10.1029/91JD01476

Dentener F, Peters W, Krol M, VanWeele M, Bergamaschi P, Lelieveld J (2003) Interannual variability and trend of CH_4 lifetime as a measure for OH changes in the 1979–1993 time period. J Geophys Res 108:4442. doi:10.1029/2002JD002916

Dieleman CM, Branfireun BA, Mclaughlin JW, Lindo Z (2015) Climate change drives a shift in peatland ecosystem plant community: implications for ecosystem function and stability. Glob Chang Biol 21:388–395. doi:10.1111/gcb.12643

Duxbury JM (1994) The significance of agricultural sources of greenhouse gases. Fertil Res 38:151–163

ENVIS (2016) Kerala state of environment and related issues. ENVIS Centre Kerala, www.kerenvis.nic.in/. Accessed 12 Jan 2016

Erickson JE, Peresta G, Montovan KJ, Drake BG (2013) Direct and indirect effects of elevated atmospheric CO_2 on net ecosystem production in a Chesapeake Bay tidal wetland. Glob Chang Biol 19:3368–3378. doi:10.1111/gcb.12316

Euliss NH, Gleason RA, Olness A, McDougal RL, Murkin HR, Robarts RD, Bourbonniere RA, Warner BG (2006) North American prairie wetlands are important nonforested landbased carbon storage sites. Sci Total Environ 361:179–188

FAO. FAOSTAT (2015) Emissions_Agriculture_Agriculture_total_E_Asia_1. http://faostat3.fao.org/download/G1/GT/E. Accessed 1 Feb 2016

Freund P, Ormerod WG (1997) Progress towards storage of carbon dioxide. Energy Conv Manag 38:198–205. doi:10.1016/S0196-8904(96)00269-5

Gorham E (1991) Northern peatlands: role in the carbon cycle and probable responses to climate warming. Ecol Appl 1:182–195

Hanson RS, Hanson TE (1996) Methanotrophic bacteria. Microbiol Rev 60:439–471

Hanson PJ, Edwards NT, Garten CT, Andrews JA (2000) Separating root and soil microbial contributions to soil respiration: a review of methods and observations. Biogeochemistry 48:115–146 http://dx.doi.org/10.1023/A:1006244819642

Hinton NJ, Cloy JM, Bell MJ, Chadwick DR, Topp CFE, Rees RM (2015) Managing fertiliser nitrogen to reduce nitrous oxide emissions and emission intensities from a cultivated Cambisol in Scotland. Geoderma Reg 4:55–65

Howe AJ, Rodriguez JF, Saco PM (2009) Surface evolution and carbon sequestration in disturbed and undisturbed wetland soils of the Hunter Estuary, southeast Australia. Estuar Coast Shelf Sci 84:75–83

Ibrahim M, Cao CG, Zhan M, Li CF, Iqbal J (2013) Changes of CO_2 emission and labile organic carbon as influenced by rice straw and different water regimes. Int J Environ Sci Tech 12:263–274

IPCC Climate change (2013) The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, D, Qin GK, Plattner M, Tignor SK, Allen J, Boschung A, Nauels Y, Xia, V. Bex PM, Midgley]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324

Iqbal J, Hu R, Lin S, Hatano R, Feng M, Lu L, Ahamadou B, Du L (2009) CO_2 emission in a subtropical red paddy soil (Ultisol) as affected by straw and N- fertilizer applications: a case study in Southern China. Agric Ecosyst Environ 131:292–302

Jain N, Pathak H, Mitra S, Bhatia A (2004) Emission of methane from rice fields – a review. J Sci Ind Res India 63:101–115

Janzen HH (2004) Carbon cycling in earth systems – a soil science perspective. Agric Ecosyst Environ 104:399–417

Kathiresan K, Thakur S (2008) Mangroves for the future: National Strategy and Action Plan, India. Ministry of Environment, Forest and Climate Change, Govt. of India. Available via http://www.moef.nic.in/sites/default/files/NSAP.pdf. Accessed 01 Feb 2016

Kayranli B, Scholz M, Mustafa A, Hedmark Å (2010) Carbon storage and fluxes within freshwater wetlands: a critical review. Wetlands 30:111–124. doi:10.1007/s13157-009-0003-4

Kemmitt SJ, Lanyon CV, Waite IS, Wen Q, Addiscott TM, Bird NRA (2008) Mineralization of native soil organic matter is not regulated by the size, activity or composition of the soil microbial biomass – a new perspective. Soil Biol Biochem 40:61–73

Kishwan J, Pandey R, Dadhwal VK (2009) India's forest and tree cover: contribution as a carbon sink. Ministry of Environment, Forest and Climate Change, Govt. of India Available via http://www.envfor.nic.in/mef/Technical_Paper.pdf. Accessed 01 Feb 2016

Komiya S, Noborio K, Katano K, Pakoktom T, Siangliw M, Toojinda T (2015) Contribution of ebullition to methane and carbon dioxide emission from water between plant rows in a tropical rice paddy field. Int Sch Res Not 2015:1–8. doi:10.1155/2015/623901

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627

Lal R (2008) Carbon sequestration. Phil Trans R Soc B 363:815–830. doi:10.1098/rstb.2007.2185

Ma K, Liu J, Balkovič J, Skalský R, Azevedo LB, Kraxner F (2016) Changes in soil organic carbon stocks of wetlands on China's Zoige plateau from 1980 to 2010. Ecol Model 327:18–28. doi:10.1016/j.ecolmodel.2016.01

Mitra S, Wassmann R, Vlek PLG (2005) An appraisal of global wetland area and its organic carbon stock. Curr Sci 88:25–35

Mitsch WJ, Bernal B, Nahlik AM, Mander Ü, Zhang L, Anderson CJ, Jørgensen SE, Brix H (2013) Wetlands, carbon, and climate change. Landsc Ecol 28:583–597. doi:10.1007/s10980-012-9758-8

Nishimura S, Yonemura S, Minamikawa K, Yagi K (2015) Seasonal and diurnal variations in net carbon dioxide flux throughout the year from soil in paddy field. J Geophys Res Biogeosci 120(1):63–76

Nouchi I, Mariko S, Aoki K (1990) Mechanism of methane transport from the rhizosphere to the atmosphere thorough rice plants. Plant Physiol 94:59–66

Nouchi I, Hoson S, Aoki K, Minami K (1994) Seasonal variation in methane flux from rice paddies associated with methane concentration in soil water, rice biomass and temperature, and its modeling. Plant Soil 161:195–208

Page SE, Wust RAJ, Weiss D, Rieley JO, Shotyk W, Limin SH (2004) A record of late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present, and future carbon dynamics. J Quat Sci 19:625–635

Patil V, Singh A, Naik N, Seema U, Sawant B (2012) Carbon sequestration in mangroves ecosystems. J Environ Res Dev 7(1A):576–583

Patra PK, Canadell JG, Houghton RA, Piao SL, Oh N-H, Ciais P, Manjunath KR, Chhabra A, Wang T, Bhattacharya T, Bousquet P, Hartman J, Ito A, Mayorga E, Niwa Y, Raymond PA, Sarma VVSS, Lasco R (2013) The carbon budget of South Asia. Biogeosciences 10:513–527. doi:10.5194/bg-10-513-2013

Reddy KR, DeLaune RD, DeBusk WF, Koch MS (1993) Long- term nutrient accumulation rates in the Everglades. Soil Sci Soc Am J 57:1147–1155

Roulet NT, Ash R, Quinton W, Moore T (1993) Methane flux from drained northern peatlands: effect of a persistent water table lowering on flux. Global Biogeochem Cycles 7:749–769. doi:10.1029/93GB01931

Saunders MJ, Jones MB, Kansiime F (2007) Carbon and water cycles in tropical papyrus wetlands. Wetl Ecol Manag 15:489–498. doi:10.1007/s11273-007-9051-9

Saunders MJ, Kansiime F, Jones MB (2014) Reviewing the carbon cycle dynamics and carbon sequestration potential of *Cyperus papyrus* L. wetlands in tropical Africa. Wetl Ecol Manag 22:143–155. doi:10.1007/s11273-013-9314-6

Singh S, Kulshreshtha K, Agnihotri S (2000) Seasonal dynamics of methane emission from wetlands. Glob Change Sci 2:39–46

Smith P, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O (2007) Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (ed) Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 497–540

Space Applications Centre (2011) National Wetland Atlas. SAC-ISRO, Indian Space Research Organization, Ahmedabad

Suratman MH (2008) Carbon sequestration potential of mangroves in southeast Asia. In: Bravo F, LeMay V, Jandl R, von Gadow K (eds) Managing forest ecosystems. The challenge of climate change. Springer Science, The Netherlands, pp 297–315

Turunen J, Tomppo E, Tolonen K, Reinkainen E (2002) Estimating carbon accumulation rates of undrained mires in Finland: application to boreal and subarctic regions. Holocene 12:79–90

Uprety DC, Baruah KK, Borah L (2011) Methane in rice agriculture: a review. J Sci Ind Res 70:401–411

Wang SM, Xue B, Xia WL (1997) Lake record of climatic change in the past 2000 years of Ximencuo. Quat Sci 5:62–69

Part V

Wetlands; Ecosystem Goods and Services

Economic Valuation of Wetland Ecosystem Goods and Services

14

Naren Pasupalati, Megha Nath, Abhijit Sharan, Priya Narayanan, Ramachandra Bhatta, Ramesh Ramachandran, and Purvaja Ramachandran

Abstract

The degradation of wetland resources including waterbodies, marshy coastal cropland, mangroves and salt marshes due to a variety of human activities within and outside the wetlands is a major environmental concern in India. Despite their importance, these ecosystems are under severe threat of degradation due to both natural and anthropogenic factors primarily due to the lack of awareness of the link between human support systems and natural ecosystems. Unless our natural capital is systematically accounted for, coupled with the knowledge of its total economic value, the probability of unsustainable exploitation leading to loss of human well-being would be significantly high. This necessitates a thorough understanding on the tools and techniques used in economic valuation and the ecosystem goods and services of a wetland ecosystem. The present chapter provides comprehensive information on the typology of various tools used in economic valuation of wetland resources. A synthesis of available information from published literature is also included, which provides a snapshot of monetary values of this natural resource.

Keywords

Benefit transfer • Economic valuation • Ecosystem management • Ecosystem services • Total economic value

N. Pasupalati • M. Nath • A. Sharan • P. Narayanan (✉) • R. Bhatta • R. Ramachandran
P. Ramachandran
National Centre for Sustainable Coastal Management (NCSCM), Ministry of Environment Forest & Climate Change, Anna University Campus, Chennai 600 025, Tamil Nadu, India
e-mail: narenp14@gmail.com; meghanath23@gmail.com; sharan.abhijit@gmail.com; priyarika@gmail.com; rcbhat@gmail.com; rramesh_au@yahoo.com purvaja.ramachandran@gmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_14

14.1 Introduction

Coastal wetland is one of the most biologically productive ecosystems in the world (UNEP 2006). The degradation of wetland resources such as waterbodies, marshy coastal cropland, mangroves and salt marshes due to a variety of anthropogenic activities within and outside the wetlands is a major environmental concern in India (Prasad et al. 2002). The change of landscape ecology due to change in land use pattern is inevitable (Hu et al. 2014). Industrial and urban pollution, conversion of wetlands for urban expansion and development of coastal aquaculture are some of the major causes of degradation. The fact that the wetlands have multiple uses leads to competition among users where each user tries to dominate the use of this scarce resource depending on their political power. A strict ecological and economic interest will guide the policymakers as well as social planners in the decision-making process. The value attached to each of these ecological systems depends on a multitude of factors including the institutions and culture from where communities/societies evolve (Mitsch and Gosselink 2000). Despite their importance, these ecosystems are under severe threat of degradation due to both natural and anthropogenic factors primarily due to the lack of awareness of the link between human support systems and natural ecosystems (Newcome et al. 2005; Venkataraman 2007). Unless our natural capital is systematically accounted for with the knowledge of its total economic value (TEV), which we shall get into greater detail later in the chapter, the probability of unsustainable exploitation leading to loss of human well-being would be significantly high (Cosier 2011; Provins 2013). The major threats to coastal wetland ecosystems are the use of water for irrigation, domestic and industrial needs, fisheries and recreational uses. The other major threat is global climate change and its interrelated sea level rise (SLR) (WWF 2010).

India has a land mass of 328.7 million ha, a land frontier of 15,200 km and exclusive economic zone of 202 million ha. Peninsular India and the island territories comprise six states and four union territories. Coastal population in India is around 300 million (out of 1.20 billion) as per 2011–2012 Census and is growing at the rate of 2.0% that is higher than the average annual population growth rate of 1.5% during 2001–2011. The 73 coastal districts (out of 593) have a share of 20% of the national population, and nearly 300 million people live within 50 km of the coastline. In India, wetlands account for 4.7% of the geographical space and support one-fifth of the biodiversity (Bassi et al. 2014). These wetlands are under unsustainable human pressure. Even though wetlands have been better understood now, owing to advancements in science and technology, the monetary value of wetlands and their functions is still not incorporated in policymaking, planning, construction and expansion of development projects (SAC 2011). The National Environmental Policy (NEP) of 2006 recognized the importance of wetlands in providing numerous ecological services and also pointed towards the absence of any formal system of regulation in India apart from the international commitments made with respect to the Ramsar sites (MoEF 2006).

Across India, coastal states are increasingly dependent on coastal ecosystems such as estuaries, mangroves, beaches, wetlands, mudflats and open spaces. These ecosystems provide critical services to the growing urban areas and industrial settlements and many heavy industries such as oil refineries, coal-fired power plants, atomic power plants, ports and harbours, pipelines, chemicals and fertilizers. However, mainly the coastal resources are used as a source of inputs as well as a sink for pollutants. The need to value these resources will help develop a pragmatic approach to maximize the socioecological benefits and to maintain these resources for both extractive and preservation uses. Understanding the economic value of coastal resources, particularly wetlands, can ensure a fair trade-off between development and conservation needs. The absence of valuing both tangible and non-tangible benefits derived from such ecosystems will put local communities, which depend on them for livelihoods, at risk.

The Coastal Regulation Zone (CRZ) Notification 2011 (Ministry of Environment and Forests, Government of India) has identified certain ecosystems that are ecologically sensitive and whose geomorphological features play an important role in maintaining habitat stability. These areas are designated as *protected areas*, and if the services provided by these ecosystems are not measured or valued, they cannot be managed efficiently. A policy tool known as the 'payment for ecosystem services' (PES) creates a market using valuation of ecosystem services and aims at rightfully transferring property rights and incentivizing conservation and protection programmes among coastal communities (Le Quesne and McNally 2005). To get an understanding of how to value coastal wetland ecosystem, it is necessary to understand the ecosystem in general and then the different services it provides.

14.1.1 Definition of Ecosystem Services

A natural ecosystem is a biological environment that is found in nature (e.g. a forest) rather than created or altered by humans (a farm). Ecosystems can be terrestrial (coastal, forest, desert, grassland, mountain, etc.) and aquatic (freshwater, marine, etc.). They can also vary in scale – global, regional and local (Defra 2011). Naturally, ecosystems have no strict geographical boundaries, and in many cases, ecosystems overlap and interact with one another.

Ecosystem services are the beneficial outcomes that result from ecosystem functions. They form beneficial outcomes to either the environment or the dependent communities. Some examples of ecosystem services are support of the food chain, harvesting of animals or plants and the provision of clean water or scenic views (Costanza et al. 1997). The Millennium Ecosystem Assessment (MEA) was set up during 2003, to assess the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being. The MEA (2005) identifies four main categories of ecosystem services: (1) provisioning services, (2) regulating services, (3) cultural services and (4) supporting services.

14.1.1.1 Provisioning Services

These include all physical material and energy outputs from ecosystems; they are tangible things that can be exchanged or traded, as well as consumed or used directly by people (MEA 2005). For example, the coral reefs in the Gulf of Kachchh (GoK), Gujarat, constitute important breeding as well as nursery grounds for large varieties of fish, prawns and molluscs especially pearl oyster and windowpane oyster. This is an example of a productive economic sector that is purely dependent on the health of the coral ecosystem (Dixit et al. 2010).

14.1.1.2 Regulating Services

These are defined as the benefits obtained from the regulation of ecosystem processes such as climate regulation, natural hazard regulation, water purification and waste management, pollination or pest control (MEA 2005). For example, according to a recent study (DebRoy and Jayaraman 2012), the Pichavaram mangroves in India were found to be the most useful in providing regulatory services such as protection against tsunamis, floods and heavy winds. Marine algal samples found along the coast of Visakhapatnam have been found to be effective sequesters of carbon thereby curbing global warming (Kaladharan et al. 2009).

14.1.1.3 Cultural Services

These are the non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences (MEA 2005). Cultural services are tightly bound to human values and behaviour, as well as to patterns of social, economic and political organizations. For example, the state of Kerala is one of the most popular tourism destinations in India, and some of the most prominent tourism assets in its possession are the beaches, backwaters and lagoons, which generate a substantial volume of Kerala's tourism revenue. The total revenue earned by Kerala's tourism sector was over INR 220 billion in 2013 alone (www.keralatourism.org 2013).

14.1.1.4 Supporting Services

They are services necessary for the delivery of all other ecosystem services. They differ from provisioning, regulating and cultural services in that their impacts on people are either indirect or occur over a very long period of time (MEA 2005). For example, the Gulf of Mannar Marine Biosphere Reserve hosts one of the highest concentrations of seagrass in India. Of the 11 species of seagrass recorded in the area, three are endemic species. The seagrass meadows in the reserve support complex ecological communities and serve as one of the largest feeding grounds for several species of marine turtles, fish, seahorse, mollusc, crustacean and the widely endangered *Dugong dugon* in India (www.seagrasswatch.org 2013).

14.1.2 Typology of Coastal Wetland Ecosystem Services

The various coastal wetland ecosystem services, classified under provisioning, regulating, supporting and cultural services, are explained in Table 14.1.

Table 14.1 Typology of coastal wetland ecosystem services[a]

Services	Description	Examples
Provisioning services		
Food	All available fauna and flora extracted from coastal/marine environments for the purpose of direct human consumption as food	Fish, shellfish, rice, salt, minerals, honey
(Fresh)water	Marine water that is extracted for use in human industry and as supply of potable water	Transportation, industrial cooling, desalinization, irrigation
Raw materials	The extraction of any material from coastal/marine environments	Algae (non-food), sand, seaweed
Medicinal resources	Any material that is extracted from the coastal/marine environment that contains medicinal benefits	Marine-derived pharmaceuticals
Ornamental resources	Any material extracted for use in decoration, handicrafts and souvenirs	Shells, aquarium fish, pearls, coral
Regulating services		
Air purification	Ecosystems both contribute chemicals to and extract chemicals from the atmosphere, influencing air quality	Removal from the air of pollutants like fine particular matter, sulphur dioxide, carbon dioxide, etc.
Climate regulation	Coastal ecosystems influence climate both locally and globally. For example, at a local scale, changes in land cover can affect both temperature and precipitation. At the global scale, ecosystems play an important role in climate by either sequestering or emitting greenhouse gases	Production, consumption and use by marine organisms of gases such as carbon dioxide, water vapour, nitrous oxides, methane and dimethyl sulphide
Disturbance prevention	The contribution of marine ecosystem structures to the dampening of the intensity of environmental hazards such as storm floods, tsunamis and hurricanes as well as coastal erosion	Reduction in the intensity of and/or damage caused by environmental disturbances resulting directly from marine ecosystem structures like salt marshes, seagrass beds and mangroves
Water regulation	The timing and magnitude of run-off, flooding and aquifer recharge can be strongly influenced by changes in land cover, including, in particular, alterations that change the water storage potential of the system	The effect of macroalgae on localized current intensity; maintenance of deep channels by coastal currents for shipping
Waste treatment	The removal by coastal/marine ecosystems of pollutants added to coastal/marine environments by humans through processes such as storage, burial and biochemical recycling	Breaking down of chemical pollutants by marine microorganisms; filtering of coastal water by shellfish

(continued)

Table 14.1 (continued)

Services	Description	Examples
Nutrient cycling	Nutrients – essential for life – cycle through ecosystems and are maintained at different concentrations in different parts of ecosystems	Nitrogen and phosphorus – fish mineralize nitrogen and phosphorous through excretion[b]
Biological control	The contribution of marine/coastal ecosystems to the maintenance of natural healthy population dynamics to support ecosystem resilience through maintaining food web structure and flows	Support of reef ecosystems by herbivorous fish that keep algal populations in check; the role that top predators play in limiting the population sizes of opportunistic species like jellyfish and squid
Supporting services		
Life cycle maintenance	The contribution of a particular habitat to migratory species' populations through the provision of essential habitat for reproduction and juvenile maturation	Reproduction habitat for commercially valuable species that are harvested elsewhere
Pollination and seed dispersal	Movement of plant genes	Seed dispersal by aquatic animals and insects
Gene pool protection	The contribution of marine habitats to the maintenance of viable gene pools through natural selection/evolutionary processes	Inter- and intraspecific genetic diversity that is supported by marine ecosystems which enhances adaptability of species to environmental changes
Habitat	The physical place where organisms reside	Refugia for resident and migratory species; spawning and nursery grounds
Hydrological cycle	Movement and storage of water through the biosphere	Evapotranspiration; stream run-off; groundwater retention
Cultural services		
Recreation and leisure	Provision of opportunities for recreation and leisure that depend on the health of marine/coastal ecosystems	Bird/whale watching, sailing, recreational fishing, scuba diving, etc. directly depend on the state of the ecosystems
Aesthetic value	Contribution that a coastal/marine ecosystem makes to the existence of an 'attractive' surface or subsurface landscape that generates a noticeable response within the individual observer	Examples are 'seascape', like open 'blue' water, a 'reef-scape' with abundant and colourful marine life, a 'beachscape' with white sand, etc.
Cultural heritage and identity	Contribution that a coastal/marine ecosystem makes to cultural traditions and folklore. This covers the appreciation of a coastal community for local coastal/marine environments and ecosystems as well as the global importance that may be associated with a particular marine landscape	Mahabalipuram is a designated UNESCO World Heritage site

Adopted from Böhnke-Henrichs et al. (2013) and Harte Research Institute for Gulf of Mexico Studies, Texas A&M University

[a]http://www.greenfacts.org/en/ecosystems/toolboxes/box2-1-services.htm

[b]http://www.marbef.org/wiki/Nutrient_cycling

14.2 Analytical Framework for Economic Valuation

Although conventional economic appraisals such as cost-benefit analysis (CBA) and cost-effective analysis (CEA) are effective ways to gauge the trade-offs of any policy or project, they are often the cause of much debate when it comes to incorporating the implicit benefits delivered by natural ecosystems or negative externalities caused by the policy or the project (Defra 2011; Wegner and Pascual 2011). For example, a conventional CBA may not capture and quantify the benefits of improved biodiversity status of a particular area of forest cover that has been granted reserved forest status or a loss in recreational services offered by a beachfront because of port development. Therefore, incorrect determination of the true value of benefits and costs to the natural environment may cause poor distribution of funds and ultimately result in failure of the policy. Thus, the valuation of ecosystem services will contribute to a better-informed decision-making process, ensuring policy appraisals take full account of all costs and benefits to the natural environment.

Thus, understanding the economic value of ecosystem services is useful for informed decision-making. The regulatory framework governing coastal zone (CRZ 2011) and NEP (MoEF 2006) contains the directions for considering all types of benefits and costs, both market and non-market, to the extent they are quantifiable. Assessment of economic value of ecosystem services is relatively a new phenomenon. The non-market valuation research does not always address ecosystem services explicitly.

Monetization of an ecosystem requires a clear and comprehensive understanding of the interactions of both ecological and economic elements of the ecosystem. Most ecosystems, including wetland ecosystems, are highly interdependent where the health of multiple components of one ecosystem influences the survival of its own and of another. Equally, it is important to note the linkages and dependencies of changes in ecosystem services (tangible or intangible) on socio-economic welfare. The socio-economic assessment must clearly focus on not just the ecosystem services but the benefits the stakeholders derive directly or indirectly from the same. Therefore, by combining an ecological and economic perspective to valuation, the benefits accrued are valued rather than the services per se.

The most appropriate valuation technique may be adopted based on the understanding of the interactions between ecosystem services and their economic endpoints. This is illustrated in Fig. 14.1 as adopted from Rasul et al. (2011).

14.2.1 Stocks and Flows

For the purposes of economic valuation, an ecosystem is categorized by two related concepts – stocks and flows. The flow of goods and services from an ecosystem is provided by the stock of natural resources from a single or multiple habitats. For example, a standing mangrove forest is the stock of trees, while the carbon sequestered annually by the forest represents the service flow. Depending on the appraisal process and policy context, it would be necessary to acknowledge either the flow or stock value:

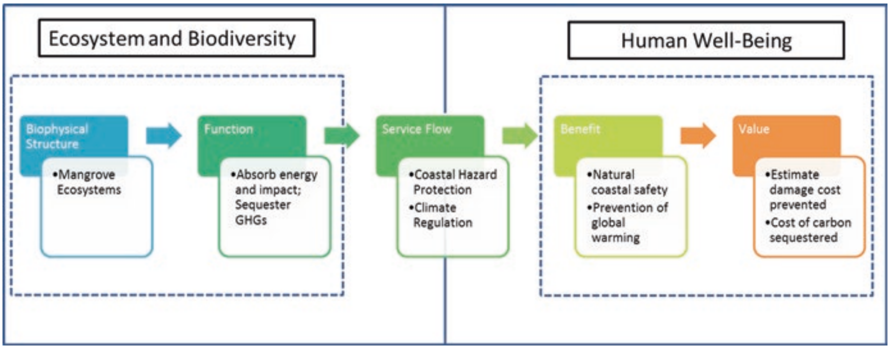


Fig. 14.1 Interactions between services and their economic endpoints – a framework

- Flow value: It is defined as the value that can be derived from a resource over a specific interval of time.
- Stock value: It is considered as the net present value sum of all flow values that could be derived from an ecosystem/resource over all future periods.

In addition, estimating economic values depends upon whether the practitioner measures the marginal changes in the flow of ecosystem goods and services or the total stock value of goods and services for a given coastal resource:

- Total value: It refers to the entire value of flow of goods or service during a defined time period or the entire value of a stock at a given point in time.
- Marginal value: It is the additional value gained or lost by an incremental change in provision of a flow or in the level of stock.

14.2.2 Total Economic Value

The value of natural resources is often considered within the framework of TEV, and this framework can be used to value ecosystem services. Generally, the term TEV refers to the aggregate value of all types of flows of services provided by a particular resource rather than the total value of the stock of that resource. Therefore, the TEV of a small change in the flow of services from the resource can be estimated and is referred to as marginal TEV. In terms of policy relevance, the assessment of marginal TEV of a particular ecosystem is more relevant because environmental management decisions are made in response to incremental changes (positive or negative) in the health of the ecosystem which in turn affects the flow of services contributing to human well-being (Defra 2011).

In general, individual preferences for ecosystem goods and services are captured with the help of the TEV framework. As illustrated in Fig. 14.2, TEV is primarily composed of 'use' and 'non-use' values. In the case of use values, individuals express their preferences through their purchasing patterns and behaviours for

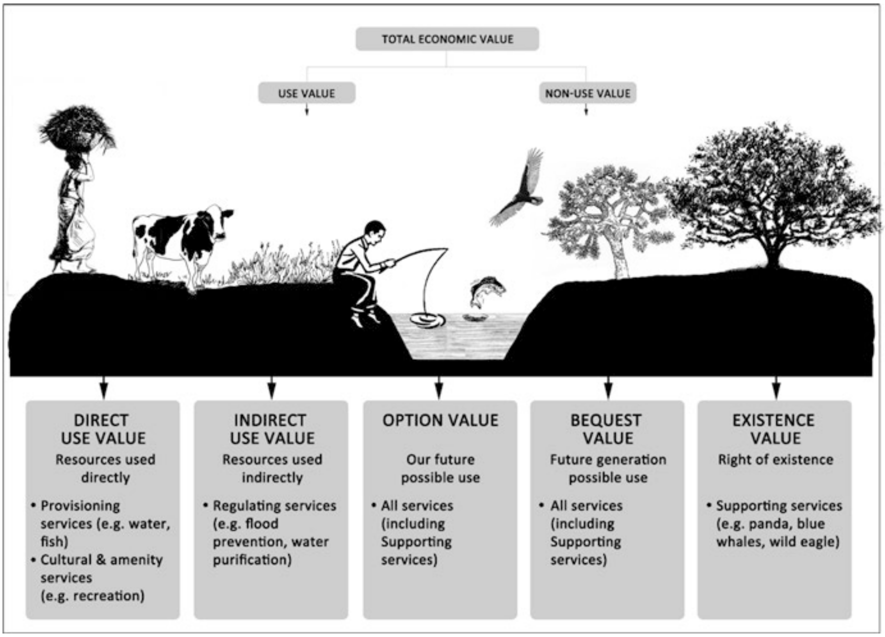


Fig. 14.2 Total economic value (TEV) and its components (Adopted from Smith et al. 2006)

goods and services that are openly traded in markets. The price of the product is an indicator of the value of the benefit derived from the consumption of that particular good or service. In the case of non-use values, values of environmental goods and services preferred by individuals are not directly observable either because they are not traded in actual markets or market data for their prices are missing. The methods of valuation discussed below capture both use and non-use values depending on the adopted approach and goods/services considered. The concept behind the components of TEV being expressed in monetary terms for a given ecosystem good or services is critical in assimilating relevant information for an informed and effective decision-making process (Newcome et al. 2005).

14.2.2.1 Components of Total Economic Value (TEV)

The components of TEV, namely, use value, non-use value and option value, and their further subcomponents are described in Table 14.2.

Several valuation techniques are there to determine the monetary value of market and non-market environmental goods and services. The valuation approach is chosen based on the good or service to be valued, the availability of data and the applicability of the value. There are essentially three broad categories of valuation approaches – market techniques, revealed preference and stated preference. Techniques that value certain environmental goods or services traded in open markets with a predetermined price are referred to as market techniques. Revealed preference techniques are those techniques whose data source is observations on

Table 14.2 Components of total economic value (TEV)

Use value: This involves some interaction with the resource either directly or indirectly	
Direct use value	Values associated with the actual use of an ecosystem resource or service. This can be in the form of consumptive use which refers to the use of resources extracted from the ecosystem (e.g. food, timber) and nonconsumptive use, which is the use of the services without extracting any elements from the ecosystem (e.g. recreation, landscape amenity). Most use values are associated with goods and services that are, in some way, traded in the open market. Such goods are known as 'market goods and services'
Indirect use value	Values associated with the benefits derived from the ecosystem services supported by a resource rather than directly using it. Benefits derived from regulating or supporting services such as soil retention and provision, nutrient cycling, waste decomposition, pollination, etc. are examples of indirect use value. It is significantly more challenging to monetize indirect use values than direct use values as changes in such regulating and supporting functions affecting human well-being are insufficiently understood, thus hard to capture. In other words, those goods and services associated with indirect use benefits and that have no ready market for its trade are known as 'non-market goods and services'
Non-use value: Although this value is not directly associated with the use of the good or service, the benefit to the individual arises from simply knowing that the ecosystem is maintained for his/her potential current and future use	
Existence value	The values derived from the existence of an ecosystem resource, even though an individual has no actual or planned use of it
Bequest value	The values individuals attach to the fact that the ecosystem resource will be passed on to future generations
Altruistic value	The values that individuals attach to the availability of the ecosystem resource to others in the current generation
Option value: It is the value that individuals place on having the option to use an ecosystem good or service in the future even if they are not presently using it. These future uses may be either in the form of direct or indirect uses	

people's choices in reality and include a variety of methods such as production function, replacement cost, travel cost and hedonic prices. If economists rely on data that is obtained from people's willingness to pay for a change in the provision of particular environmental good or service, then these methods are termed stated preference methods such as contingent valuation and choice modelling. In addition to these, a number of methods such as meta-analysis and benefit transfer rely on secondary information under similar contexts, which are then applied to areas where there is limited or no data available. Figure 14.3 illustrates the three broad categories of valuation approaches.

Appendix A.14.1 describes the different valuation techniques, their applicability and limitations. Each of the valuation techniques has its advantages and disadvantages, and the choice of one technique over the other is, as mentioned above, usually dependent on what needs to be valued (use, non-use or TEV values), the purpose and assumptions of the valuation and availability of information.

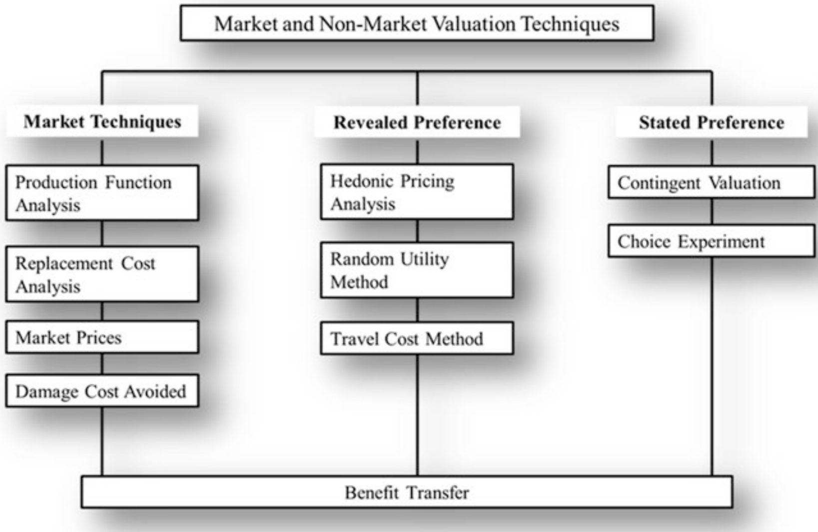


Fig. 14.3 Valuation methodologies within TEV framework

Table 14.3 Wetland ecosystem service values (US$) in South Asia – consolidated

	Regulating	Provisioning	Supporting	Cultural
Max	$47,700	$14,100	$10,700	$23,900,000
Min	$0.35	$3.45	$26	$0.07
Mean	$4624	$1,213.75	$1605	$541,365
Median	$389	$198	$342	$305

Source: Harte Research Institute (Texas A&M University)

14.2.3 Review of South Asian Ecosystem Services

Some descriptive statistics of the values of the ecosystem services from wetlands in South Asia are presented in Table 14.3. The data in Table 14.3 was filtered based on two criteria:

– The country of origin, which predominantly was South Asian owing to similarities in geography, climate and levels of economic development with India
– The two types of wetland ecosystems – freshwater and saltwater wetlands

The original database lists various services provided by these ecosystems, but for the purposes of the table above, they are classified into four main groups as per the MEA, namely, provisioning, regulating, supporting and cultural services. The definitions for these groups are discussed in detail in the previous chapters. All values in Table 14.3 and the original database have been normalized to US$ (2012) for meaningful comparisons and assessment.

14.2.3.1 Provisioning Services

Harte Research Institute (Texas) mentions 41 studies that have calculated the provisioning values of South Asian wetlands. The mean value of provisioning services from South Asian wetlands was calculated to be US$ 1213.73/ha/year with values ranging from US$ 3.45 to 14,100/ha/year.

Many species of fish, spices and herbs are abundantly available in wetlands. Salt is a major product that is extracted from coastal saltpans in the country that is used by both food and chemical manufacturing industry. Wetlands also provide favourable conditions for paddy cultivation. More than 70% of the wetland area in India is under paddy cultivation (Prasad et al. 2002). For example, a value of US$ 74.90/ha/year has been assigned to the food material from the mangroves of Bhitarkanika Conservation Area in Odisha (Hussain and Badola 2010).

Coastal wetlands are a major source of raw materials to the industry, contributing significantly to the economic growth of the country. Minerals and sands, which hold a strategic importance to the country, are mined from the sand dunes and beaches. Algae such as *Botryococcus braunii*, *Chlorella* sp., *Dunaliella tertiolecta*, *Gracilaria* and *Pleurochrysis carterae* are also extracted from coasts, which can be used for purposes such as micro-algal biofuel, a potential alternate fuel. Apart from this, mangroves and estuaries provide a range of products such as timber, fuel wood and fertilizers. Coastal wetlands, especially mangroves, are rich in resources with medicinal properties. The honey produced from mangroves is said to have medicinal properties, due to which it is priced higher than the regular honey in the market. A study employing the market price method arrived at a value of US$ 115/ha/year (2012 US$) for the medicinal resources derived from the mangroves of Tapean forests in Cambodia (Bann 2003). Coastal wetlands are also a rich source of ornamental materials such as pearls, shellfish, aquarium fish and corals. Owing to its rich biodiversity, coastal wetlands are a reservoir of genetic resources. The saltwater wetlands of Chongming Island, China, using the benefit transfer method, were valued to have US$ 4.56/ha/year (2012 US$) worth of coral reefs under their provisioning services (Zhao et al. 2004).

14.2.3.2 Regulating Services

There are two reasons for valuing regulating services. One, it enables us to assign values for those non-market services delivered by wetland ecosystems that indirectly contribute to human well-being and where policymakers could make use of these values to better-informed decision-making regarding conservation and habitat management schemes. Two, it also enables us to estimate the extent of damage to a particular wetland by valuing the loss in services delivered. For example, the East Kolkata Wetlands located on the south-eastern fringe of the Kolkata city in India have been used for discharging municipal and industrial untreated sewage since the 1930s. On the other hand, local companies have been generating income and employment by using water from this wetland for crops and fish production. However in recent years, there has been a steady decline in the profitability of rice farming in these wetlands due to increased metal and nutrient content (Mukherjee and Gupta 2013). Some of the most important regulating services of coastal wetland ecosystems are air purification, climate regulation, disturbance prevention, water regulation, waste treatment and nutrient cycling.

The highest regulating service value recorded on the database was estimated to be US$ 47,700 which was the annual unit value for disturbance protection per hectare of mangrove cover in Malaysia (Rönnbäck 1999). The lowest regulating service recorded was also for mangroves and was estimated to be US$ 0.35/ha/year for the provision of greenhouse gas regulation (Padilla 2009). Of the studies, Sri Lanka has the highest number of values (21%) associated with regulating services closely followed by the Philippines (17%) and China (15%). The relevant studies from India were by Hirway and Goswami (2007), Das and Vincent (2009) and Das (2011) that mainly observed the disturbance regulation services by mangroves in Gujarat and Odisha, respectively. There are over 400,000 ha of mangrove forests spread across the coastal states (SAC 2011) with the potential of sequestering anywhere between 17 and 24 tons CO_2-e/ha/year depending on the density and species of mangroves (Ray et al. 2011). Assuming each ton of CO_2-e is valued at US$ 10 (Nordhaus 2011; Verma et al. 2013), the value of climate regulation/air purification by mangrove ecosystems would be around US$ 170–$ 240/ha/year.

14.2.3.3 Cultural Services

These are services providing benefits of non-material nature. These benefits can be recreational, leisure, aesthetic, educational and spiritual values. These services also include benefits that have a heritage or an identity value attached to them. The mean value of cultural services from South Asian wetlands was estimated to be US$ 541,365.10/ha/year with the values ranging from US$0.07 to 23,900,000/ha/year (Table 14.3) based on the synthesis of 45 studies on valuing the cultural services by Harte Research Institute. Cultural services are purely dependent on how much value human institutions attach to them, and they may vary from individual to individual. For example, recreation and leisure values are positively related to the health of the given ecosystem. People attach a heritage and cultural value to ecosystems that have been supporting them since centuries.

Using the travel cost method, a value of US$ 213/ha/year (2012 US$) has been attached to the saltwater wetland of Olango Island, Philippines, for its recreational value (White et al. 2000). In Malaysia, using the benefit transfer and expenditure method, a value of US$ 137/ha/year (2012 US$) has been assigned to the coral reefs for their science and educational services (Chua and Nancy 1999).

14.2.3.4 Supporting Services

Coastal wetlands provide several important supporting services such as life cycle maintenance, biological control of the ecosystem and gene pool protection that mostly affect humans indirectly and mainly promote conservation of the ecosystem. The mean value of supporting services from South Asian wetlands was computed to be US$ 1605.22/ha/year with the values ranging from $25.60 to 10,700/ha/year (Table 14.3) from the 36 studies that have estimated the supporting values for South Asia.

Life cycle maintenance means the provision of essential habitat for reproduction and juvenile maturation of certain species, especially the migratory ones. Biological control is the contribution of marine/coastal ecosystems to the maintenance of natural healthy population dynamics to support ecosystem resilience through maintaining food web structure and flows. The support of reef ecosystems by herbivorous fish that keep algal populations in check and the role that top predators play in limiting the population of opportunistic species like jellyfish and squid are some examples of the biological control in coastal wetland ecosystems. The service of gene pool protection deals with the contribution of marine habitats to the maintenance of viable gene pools through natural selection/evolutionary processes. Inter- and intra-specific genetic diversity that is supported by marine ecosystems enhances adaptability of species to environmental changes.

In terms of disturbance/hazard protection, coastal wetlands such as beaches, dunes, estuaries and mangroves are naturally adept for protecting against the full effects of climate change which includes the increased frequency of storms, changing rainfall patterns, rising sea levels and coastal erosion (Barbier 2007). For example, Das (2011) has systematically estimated the value of storm/hazard protection provided by mangroves in Kendrapara District in the event of the supercyclone that hit the Eastern Indian state of Orissa in the year 1999. In this case, the value was estimated using a regression analysis incorporating the number of human lives and livestock saved and damages to buildings avoided by mangroves. Further, Das (2011) estimated that a hectare of mangrove forest mitigated damages worth US$ 43,352 (INR 1.8 million) in the district during the supercyclone. Using the former value along with the probability of occurrence of very severe storms in Orissa over the last three decades, it was estimated that US$ 8670/ha/year (1999 US$) was the annual protection value of a hectare of intact mangrove forests. Coastal and inland wetlands also play a significant role in purifying water. Nutrients such as phosphorous and nitrogen seen in high levels in agricultural and municipal run-offs are effectively removed by wetlands. Because of this, eutrophication is effectively prevented further downstream, which in turn curbs the rapid plant and algal growth that affects other species. Acting as waste recycling system, it can prevent high concentrations of nutrients reaching groundwater aquifers and other potable water sources. In this regard, a study (Emerton and Kekulandala 2003) estimated the value of the wetlands' domestic and industrial sewage treatment potential to be INR 4.3 million/year and INR162 million/year based on costs avoided to build improved latrines for households and two major joint industrial treatment plants.

The break-up of evaluation studies conducted on coastal wetlands in South Asia on the basis of the four ecosystem services is depicted in Fig. 14.4.

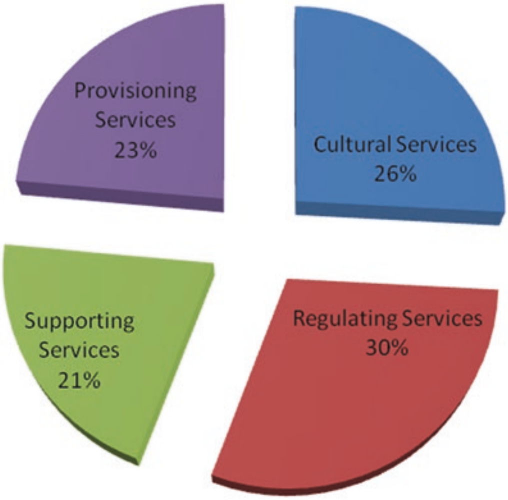


Fig. 14.4 Distribution of economic valuation studies on coastal wetlands in South Asia

14.3 Challenges and Issues with Environmental Valuation

Environmental valuation, like any science, is not without its fair share of challenges and uncertainties. Many ecologists and conservationists strongly believe that the commoditization of nature through market instruments as discussed in earlier sections ignore the intrinsic value that our environment provides whether or not we derive tangible benefits from it (Chiesura and de Groot 2003; Braat and de Groot 2012; Schröter et al. 2014).

14.3.1 Uncertainty

Valuing environmental services (both market and non-market) is often argued to be difficult, if not impossible, considering its infinite intrinsic value to human well-being. Ecologists and conservationists believe that science alone should guide policymaking. Thus, in a bid to integrate biophysical and economic parameters, ecological economists are constantly evolving and improving tools to effectively capture nature's monetary value. One of the most fundamental issues for both ecologists and economists in environmental management and, in particular, valuation is uncertainty. Although current knowledge on ecological processes and economic theory is well documented, understanding causal links among parameters such as changes in biophysical processes, ecosystem health, demographic conditions and policy reforms is not fully known (Waite et al. 2014). Effective ecosystem service valuation can better inform environmental policy, but valuation as such has become increasingly difficult and uncertain because modelling the flow of ecosystem services depends on data that are often vague and inaccurate and, in some cases, direct monitoring data on ecosystem services are missing altogether (Johnson et al. 2012).

In terms of the valuation methodology used, most contingent valuation techniques assume all individuals and groups as rational entities and have full knowledge of their preferences when assessing their willingness to pay/accept for a change in the flow of an environmental service; but in reality it is not always the case (Bingham et al. 1995). The choice of valuation tool, which comes with its own set of technical challenges, is subject to the researcher's expertise and conceptual clarity of the issue. Thus, the value of a particular ecosystem service/good could be substantially different based on the method used.

14.3.2 Double Counting

The risk of double counting occurs when an 'intermediate' ecosystem service is first separately valued and its corresponding final benefit (e.g. provisioning service) is valued subsequently. The final benefit value of an ecosystem services/good is the aggregation of the values of 'intermediate' services. For example, timber from mangrove forests, which is directly consumed by households, is dependent on a range of intermediate ecological services. If, in an appraisal process, the values of such intermediate supporting services are considered separately in addition to the value of timber, it may result in double counting. Hence, it is often desirable to identify and differentiate intermediate ecosystem services from final ecosystem goods and services so that overestimation of an ecosystem service may be avoided (Boyd and Banzhaf 2007). Inconsistent classification of ecosystem services, poor understanding of ecosystem functions and interlinkages and spatiotemporal dependence are just some of the reasons why double counting occurs (Fu et al. 2011).

14.3.3 Valuation at Environmental Thresholds

When a particular ecosystem is deteriorated upon use, the services delivered by that ecosystem will diminish either rapidly or gradually depending on the level of supply and demand, conservation efforts and socio-economic conditions. Every environmental resource has a certain ecological threshold limit or a critical level below which the health of the ecosystem must not be permitted to fall. If, due to some unsustainable use, the resource falls below the ecological threshold limit, it could lead to catastrophic effects and irreversible damages, and the ecosystem in that region could be lost forever. Estimating marginal values of ecosystem services is considered most appropriate for appraisal purposes. It may be meaningless to estimate marginal values at such threshold points; because resources are severely exploited, their existence itself is of utmost importance. Thus, it makes their intrinsic value and benefits to people immeasurably high or infinite (Daily et al. 1997).

14.3.4 Spatial and Temporal Variability of Values

An important limitation of ecosystem service valuation (benefit transfer) is the variability in spatial and temporal impacts of any particular service. Values of a particular ecosystem service in different locations may vary owing to differences in ecological processes, economic conditions, infrastructure conditions and behavioural patterns and cultural norms of local people who depend on that service. In addition, spatial variations in the supply of a particular service may alter values accordingly. For example, values for coastal protection services of mangroves in Asia may be different from those in North America. Hence, while applying benefit transfer method, validation of the study is essential. Comparing certain studies assessing a particular service could exhibit significant variations in value and errors to the tune of 30% (for routine coastal and flood defence projects) to as much as 7028% (for meta-analysis) (Spash and Vatn 2006).

Some valuation techniques may try and value future benefits accrued by relevant stakeholders over a specific period. Besides the location, the value of an ecosystem service also depends on at which point in time the service is assessed. There are a couple of reasons why ecosystem services and their values change over time (Fisher et al. 2011). First, ecological conditions of wetland ecosystems are dynamic in nature. In addition to changing land use patterns and human interventions, there are inherent natural drivers that affect the topography and the ecological succession[1] of the habitat over time. This, in turn, affects the goods and services delivered from the respective ecosystem, and the value associated with quantum of service/good provided will not necessarily remain static over a period. For example, the value of regulating services associated with an estuary will increase over time if effective conservation programmes are implemented on site. Alternatively, if mangrove forests either are highly degraded due to human exploitation or increased occurrences of storms and other natural hazards, the value of same regulating services tend to decline over time. Second, social and individual preferences and utilities vary across time and space. A rupee or dollar is worth more today than it would in the future. In such cases, irrespective of the flow of ecosystem services, its value will either appreciate or decline depending on current social and financial conditions. The social rate of time preference would be used to value future benefits at current price levels. The social rate of time preference, also known as the discount rate, is a rate used to convert future benefits and costs of environmental services to 'present value' so that relevant and accurate comparisons can be made (Khan and Greene 2013). Apart from being a point of considerable debate, the choice of discount rate plays a very

[1] Ecological succession: Many ecosystems experience a phenomenon known as ecological succession, a slow process in which the species inhabiting an ecosystem fluctuate or change completely. Some species increase in population, while others decrease or even disappear altogether. These shifts can be due to new species entering the ecosystem, current species impacting the ecosystem, or evolutionary changes within a certain species allowing them to better adapt to the ecosystem.

important role in determining unit values for particular ecosystem services. Low discount rates reflect higher emphasis on future costs and benefits and normally encourage conservation strategies that enable sustainable and constant flow of ecosystem services. On the other hand, higher discount rates reflect greater emphasis on short-term costs and benefits and, in general, discourage conservation efforts.

14.4 Conclusion

The importance of coastal wetlands in providing provisioning, cultural or recreational, supporting and regulating services was known to ecologists for many decades. However, the studies by social scientists particularly related to economic valuations are very few. Thus, appropriate policies to address the issue of wetland degradation are negligible. The review of studies on the valuation of coastal wetland services reveals that there are very few comprehensive assessments of value of coastal wetlands especially in the South Asian context. The literature search from international database on valuation especially The Economics of Ecosystems and Biodiversity (TEEB), Harte Research Institute, etc. shows that there are limited studies which quantify the different provisioning, regulating and cultural services from coastal wetlands. Further, there is wide variation between the studies ranging from a minimum of US$ 3.00 to 14,100 for provisioning services, from US$ 0.35 to 47,700 for regulating services, from US$ 0.07 to 23,900,000 for cultural services and from US$ 26 to 10,700 for supporting services. Thus, the valuation of the provisioning services varies substantially making it difficult for using benefit transfer method to value the coastal wetlands.

In this chapter, an attempt is made to address these issues related to the value of different services provided by coastal wetlands. By presenting the estimates made by researchers in the South Asian context, the importance of valuing the ecosystem services is highlighted for the policymakers as well as the producers to aid them in decision-making.

In order to address threats to wetlands, many developed countries adopt a combination of command and control and market-based (charges/subsidies) methods. In India, there are only regulatory controls to protect wetlands, and there is no scope for market-based approach within the existing legal framework, as there is no foundation for valuing an ecosystem service. A pricing mechanism where we give value to the ecosystem as an entity so that we can bring a holistic system of evaluation of services with a bottom-up approach needs to be considered.

Appendices

Appendix A.14.1: Valuation Methodologies within TEV Framework

Valuation technique	Applicability to Indian wetland ecosystems	Examples of wetland ecosystem application	Limitations
Revealed preference techniques			
Hedonic pricing method (HPM): The value of an environmental amenity (such as a view) is obtained from readily available property or labour markets. The basic assumption is that the observed property value (or wage) reflects a stream of benefits (or working conditions) and that it is possible to isolate the value of the relevant environmental amenity or attribute	Hedonic pricing has potential for valuing certain wetland functions (e.g. aesthetic beauty, landscapes and open spaces from sandy beaches) in terms of their impact on land values, assuming that they are fully reflected in land prices	Landry and Hindsley (2011) conducted a study to explore the influence of beach quality on coastal property values. It was estimated that property values within 300 m of HTL are positively impacted by the width of the beach and dune field	Application of this approach to value wetland services requires these values to be reflected in proxy markets. The approach may be limited by unstable real estate markets, choices constrained by income and unequal distribution of information about environmental conditions
Travel cost approach (TC): The travel cost approach derives willingness to pay for environmental benefits at a specific location by using information on the amount of money and time that people spend to visit the location	Widely used to estimate the value of recreational, religious and cultural sites in coastal and wetland areas. It could also be used to estimate willingness to pay for ecotourism	Raybould et al. (2011) estimated the value of recreational benefits (AU$365 million to AU$1.7 billion) to Gold Coast residents depending on their travel costs including time and fuel costs	The approach is data intensive; it is restrictive on the assumptions about consumer behaviour (e.g. multifunctional trips); its results are highly sensitive to statistical methods used to specify the demand relationship

(continued)

Valuation technique	Applicability to Indian wetland ecosystems	Examples of wetland ecosystem application	Limitations
Random utility method (RUM): This is an extension of the travel cost method and is used to test the effect of changing the quality or quantity of an environmental characteristic at a particular site	The travel cost RUM analyses a person's discrete choice of one recreation site over other sites. The site choice is assumed to depend on the features of the site and to reveal the person's preferences for those features	Parsons et al. (2000) estimated a (TC) random utility model of recreation demand. The model evaluates the loss in mean welfare value per trip per person if select beaches were too close to its residents	The random utility model is an extremely complicated and expensive (in terms of man-hours required) approach to value ecosystem service benefits
Stated preference techniques			
Contingent valuation method (CVM): constructs a hypothetical market to elicit respondents' willingness to pay for a particular environmental service. It can be used to estimate use and more importantly non-use values	It is the only method that can measure existence values and provide a true measure of total economic value. Most regulating and cultural services of wetland ecosystems are estimated using CVM. E.g. protection from extreme weather events by estuaries and recreational benefits from coral reefs	Bann (1999) estimated the willingness to pay values (US$7512/Ha) of protecting mangroves for its nursery and biodiversity services in Malaysia	The results of this approach are sensitive to numerous sources of bias in survey design and implementation
Choice experiments: estimate implicit values of different use and non-use environmental services. Since it is based on the trade-off between options with different specified characteristics, it is best suited to better-informed policy decisions	CE method, just like the CVM, attempts to measure all use and non-use values including biodiversity and cultural values of wetland ecosystems	Birol and Cox (2007) used the choice experiment approach to investigate whether the communities living around the Severn wetland derived positive economic values if the wetlands were sustainably managed	Some of the critical issues for choice experiments are the technical and behavioural uncertainties in monetizing the actual value of responses taken on a particular good or service. It may cause biases in responses or decision-making

(continued)

Valuation technique	Applicability to Indian wetland ecosystems	Examples of wetland ecosystem application	Limitations
Market-based techniques			
Production function approach (PFA): estimates the value of a non-marketed resource or ecological function in terms of changes in economic activity by modelling the physical contribution of the resource or function to economic output	Widely used to estimate the impact of wetlands and reef destruction, deforestation, water pollution, etc. on productive activities such as fishing, hunting and farming	The study utilized the production function method to value the mangrove forests to a local community. The method was particularly used for the value of fisheries (~US$50) supported by local mangroves in the Gulf of Thailand region (Sathirathai and Barbier 2001)	Requires explicit modelling of the 'dose-response' relationship between the resources and some economic output. Application of the approach is most straightforward in the case of single-use systems but becomes more complicated with multiple-use systems. Problems may arise from multi-specification of the ecological-economic relationship or double counting
Replacement cost (RPC): this method uses cost of artificial substitutes for environmental goods or services	RPC: useful in estimating indirect use benefits when ecological data are not available for estimating damage functions with first-best methods	McAllister (1991) estimated the value of coastal protection provided by the coral reefs in the Philippines using the replacement cost method. The study estimated US$22 billion, based on construction costs of concrete tetrapod breakwaters to replace 22,000 km^2 of reef protection	RPC: difficult to ensure that net benefits of the replacement do not exceed those of the original function. May overstate willingness to pay if only physical indicators of benefits are available

(continued)

Valuation technique	Applicability to Indian wetland ecosystems	Examples of wetland ecosystem application	Limitations
Market prices (MP): are those that capture the value of goods and services that are traded in the open market. Market prices can act as proxies for direct and indirect use values	Market prices reflect the private willingness to pay for several use values. For example, the value of fish nurseries provided by mangroves is measured by the market price of all fish harvested from that area	Emerton and Kekulandala (2003) used market price to value the economic benefits associated with fishing, agriculture and handicraft production activities in Muthurajawela wetland. The market value of firewood obtained from Muthurajawela was INR 7.96 million/year	Market imperfections and/or policy failures may distort market prices, which will therefore fail to reflect the economic value of goods or services to society as a whole. Seasonal variations and other effects on prices need to be considered when market prices are used in economic analysis
Benefit transfer			
Benefit transfer (Rosenberger and Loomis 2003): the process by which the economic value of an environmental good or service generated in one context – the 'study site' – is applied to another context known as benefit transfer or value transfer. In principle, a value from any economic valuation methodology may be used as long as the contexts of both sites are the same	This technique is used when primary valuation studies are not feasible in terms of timelines and budgets. Also policy and conservation schemes predominantly use macro-level monetary estimates, and benefit transfer offers an effective solution to include environmental values to the appraisal process	Gujarat Ecology Commission (Dixit et al. 2010) estimated the values of coastal protection (INR 2.89 million/km^2/year) and biodiversity maintenance (INR 0.32 million/ km^2/ year) of coral systems in the Gulf of Kachchh region in India using benefit transfer methodology	One of the critical issues with the use of benefit transfer is the validity and accuracy of secondary data

Appendix A.14.2: Online Databases on Valuation

Institute	Particulars
Marine Ecosystem Services Partnership (MESP)	MESP is a virtual centre for information and communication on the human uses of marine ecosystems around the world, including an extensive database of marine and coastal valuation studies with nearly 2000 value estimates
Harte Research Institute – Texas A&M University-Corpus Christi	The two main goals of the GecoServ database are to allow for the distribution and sharing of information about ES valuation studies and to identify current gaps in the ES literature. The studies summarized here are for habitats that are relevant to the Gulf of Mexico region even though they may have been conducted elsewhere
National Ocean Economics Program (NOEP)	NOEP provides economic and socio-economic information on changes and trends along the US coast and will soon expand its scope internationally. NOEP includes databases on market and non-market values of coastal and marine resources
Environmental Valuation Reference Inventory (EVRI)	EVRI is a searchable storehouse of more than 2000 empirical studies on the economic value of environmental benefits and human health effects. It has been developed as a tool to help policy analysts use the benefit transfer approach
The Economics of Ecosystems and Biodiversity (TEEB)	Ecosystem Service Valuation Database (ESVD), initially developed for TEEB initiative, contains more than 1300 data points from more than 300 case studies on both marine and terrestrial ecosystem services
Lincoln University, New Zealand	This database provides users with a large (850+) bibliography of valuation studies. The economic value of many of these studies is also analysed and reported. These values have been standardized temporally and spatially so the application of the values is adequately robust
Beijer Institute of Ecological Economics	The Valuation Study Database for Environmental Change in Sweden (ValueBaseSWE) was developed at the Beijer Institute of Ecological Economics within a project funded by the Swedish Environmental Protection Agency. The database is the result of a survey of empirical economic valuation studies on environmental change in Sweden

References

Bann C (1999) A contingent valuation of the mangroves of Benut, Johor State, Malaysia. Johor State Forestry Department/DANCED/Darudec, Johor

Bann C (2003) An economic analysis of alternative mangrove management strategies in Koh Kong Province, Cambodia, Penang

Barbier EB (2007) Valuing ecosystem services as productive inputs. Econ Policy 22(49):178–229

Bassi N, Kumar MD, Sharma A, Pardha-Saradhi P (2014) Status of wetlands in India: a review of extent, ecosystem benefits, threats and management strategies. J Hydrol: Reg Stud 2:1–19

Bingham G, Bishop R, Brody M, Bromley D, Clark E, Cooper W, Costanza R, Hale T, Hayden G, Kellert S, Norgaard R, Norton B, Payne J, Russell C, Suter G (1995) Issues in ecosystem valuation: improving information for decision making. Ecol Econ 14:73–90

Birol E, Cox V (2007) Using choice experiments to design wetland management programmes: the case of Severn Estuary Wetland, UK. J Environ Plan Manag 50(3):363–380. doi:10.1080/09640560701261661

Böhnke-Henrichs A, Baulcomb C, Koss R, Hussain SS, de Groot RS (2013) Typology and indicators of ecosystem services for marine spatial planning and management. J Environ Manag 130:135–145

Boyd J, Banzhaf S (2007) What are ecosystem services? The need for standardized environmental accounting units. Ecol Econ 63(2–3):616–626

Braat LC, de Groot R (2012) The ecosystem services agenda:bridging the worlds of natural science and economics, conservation and development, and public and private policy. Ecosyst Serv 1(1):4–15

Chiesura A, de Groot R (2003) Critical natural capital: a socio-cultural perspective. Ecol Econ 44(2–3):219–231

Chua T, Nancy B (1999) Challenges and opportunities in managing pollution in the East Asian seas: proceedings of the International Conference, Metro Manila, Philippines, 22–24 March 1999. GEF, Quezon City

Cosier P (2011) Accounting for the condition of environmental assets, Wentworth Group of Concerned Scientists, UN Committee of Experts on Environmental Accounting Technical Meeting on Ecosystem Accounts, London, no. December (2011), pp 5–7

Costanza R, d'Arge R, de Groot R, Farberk S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Suttonkk P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387(6630):253–260

Daily GC, Alexander S, Ehrlich PR, Goulder L, Lubchenco J, Matson PA, Mooney HA, Postel S, Schneider SH, Tilman D, Woodwell GM (1997) Ecosystem services: benefits supplied to human societies by natural ecosystems. Issues Ecol 2:16

Das S (2011) Examining the storm protection services of mangroves of Orissa during the 1999 cyclone. Econ Polit Wkly 46(24):60–68

Das S, Vincent JR (2009) Mangroves protected villages and reduced death toll during Indian super cyclone. Proc Natl Acad Sci U S A 106:7357–7360

DebRoy P, Jayaraman R (2012) Economic valuation of mangroves for assessing the livelihood of fisherfolk: a case study in India. Proceedings of the Sixteenth Biennial Conference of the International Institute of Fisheries Economics and Trade, Dares Salaam, Tanzania 2012.

Defra (2011) An introductory guide to valuing ecosystem services. Department of Environment, Food and Rural Affairs, Crown Copyright, London, pp 8–32

Dixit AM, Kumar P, Kumar L, Pathak KD, Patel MI (2010) Economic valuation of coral reef systems in Gulf of Kachchh. Final Report. World Bank aided Integrated Coastal Zone Management (ICZM) Project. Submitted to Gujarat Ecology Commission, Gandhinagar, India, p 158

Emerton L, Kekulandala LDCB (2003) Assessment of the economic value of Muthurajawela Wetland. Occ. Pap. IUCN, Sri Lanka., p 4:iv + 28

Fisher B, Bateman I, Turner RK (2011) Valuing ecosystem services: benefits, values, space and time. In: Kumar P, Thiaw I (eds) Values, payments and institutions for ecosystem management. Edward Elgar, London, pp 58–69

Fu B, Su C, Wei Y (2011) Double counting in ecosystem services valuation: causes and countermeasures. Ecol Res 26(1):1–14

Hirway I, Goswami S (2007) Valuation of coastland resources: the case of mangroves in Gujarat. Academic Foundation, New Delhi

Hu J, Zhang M, Huang X (2014) Research on the ecological conflict between coastal wetland and port construction – A case study of the Meizhou Gulf. Low Carbon Econ 5:57–64. http://dx.doi.org/10.4236/lce.2014.52007

Hussain SA, Badola R (2010) Valuing mangrove benefits: contribution of mangrove forests to local livelihoods in Bhitarkanika Conservation Area, east coast of India. Wetl Ecol Manag 18(3):321–331. doi:10.1007/s11273-009-9173-3

Johnson G, Snapp R, Villa F, Bagstad K (2012) Modelling ecosystem service flows under uncertainty with stochastic SPAN. http://www.iemss.org/sites/iemss2012//proceedings/D1_2_0900_Johnson_et_al.pdf. Accessed 2 Mar 2015

Kaladharan P, Veena S, Vivekanandan E (2009) Carbon sequestration by a few marine algae: observation and projection. J Mar Biol Assoc India 51(1):107–110

Khan J, Greene P (2013) Selecting discount rates for natural capital accounting. http://webarchive.nationalarchives.gov.uk/20160105160709/http:/www.ons.gov.uk/ons/about-ons/get-involved/events/events/valuation-for-natural-capital-accounting-seminar/index.html. Accessed 11 Mar 2015

Landry CE, Hindsley P (2011) Valuing beach quality with hedonic property models. Land Econ 87(1):92–108

Le Quesne T, McNally R (2005) The green buck: using economic tools to deliver conservation goals. A WWF field guide. https://www.cbd.int/doc/books/2005/B-02617.pdf. Accessed 7 Mar 2015.

McAllister DE (1991) What is a coral reef worth? Sea Wind 5(1):21–24

MEA (2005) Millennium ecosystem assessment, ecosystems and human well-being: synthesis. Island Press, Washington, DC

Mitsch WJ, Gosselink JG (2000) The value of wetlands: importance of scale and landscape setting. Ecol Econ 35(200):25–33

MoEF (2006) National environment policy. Ministry of Environment and Forests, Government of India, New Delhi, pp 33–34

Mukherjee V, Gupta G (2013) Toxicity and profitability of rice cultivation under wastewater irrigation: the case of the East Calcutta wetlands. Ecol Econ 93:292–300

Newcome J, Provins A, Johns H, Ozdemiroglu E, Ghazoul J, Burgess D, Turner K (2005) The economic, social and ecological value of ecosystem services. https://www.cbd.int/financial/values/unitedkingdom-valueliterature.pdf. Accessed 1 Mar 2015

Nordhaus W (2011) Estimates of the social cost of carbon: background and results from the RICE-2011 model. National Bureau of Economic Research, p 48

Padilla J (2009) Analysis of coastal and marine resources: a contribution to the Philippines country environmental analysis. World Bank, p 158

Parsons GR, Massey DM, Tomasi T (2000) Familiar and favorite sites in a random utility model of beach recreation. Mar Resour Econ 14:299–315. doi:10.2307/42629275

Prasad SN, Ramachandra TV, Ahalya N, Sengupta T, Kumar A, Tiwari AK, Vijayan VS, Vijayan L (2002) Conservation of wetlands – a review. Trop Ecol 43:173–186

Provins A (2013) Accounting for the value of wetland services. Paper presented at the seminar on the valuation for natural capital accounting, Office of National Statistics London, 13 December 2013.

Rasul G, Chettri N, Sharma E (2011) Framework for valuing ecosystem services in the Himalayas. http://lib.icimod.org/record/8115/files/attachment_745.pdf. Accessed 22 Mar 2015

Ray R, Ganguly D, Chowdhury C, Dey M, Das S, Dutta MK, Mandal SK, Majumder N, De TK, Mukhopadhyay SK, Jana TK (2011) Carbon sequestration and annual increase of carbon stock in a mangrove forest. Atmos Environ 45(28):5016–5024

Raybould M, Lazarow N, Anning D, Ware D, Blackwell B (2011). A travel cost model of local resident's beach recreation values on the Gold Coast. Paper presented at the 20th NSW Coastal Conference, Coffs Harbour City Council, Coffs Harbour 8–11 November 2011

Rönnbäck P (1999) The ecological basis for economic value of seafood production supported by mangrove ecosystems. Ecol Econ 29:235–252

Rosenberger RS, Loomis JB (2003) Benefit transfer. In: Champ PA, Boyle KJ, Brown TC (eds) A primer on non-market valuation. Kluwer, Dordrecht, pp 445–482

Sathirathai S, Barbier E (2001) Valuing mangrove conservation in Southern Thailand. Contemp Econ Policy 19:109–122. doi:10.1111/j.1465-7287.2001.tb00054.x

Schroter M, van der Zanden EH, van Oudenhoven APE, Remme RP, Serna-Chavez HM, de Groot RS, Opdam P (2014) Ecosystem services as a contested concept: a synthesis of critique and counter-arguments. Conserv Lett 7(6):514–523

Smith M, de Groot D, Perrot-Maîte D, Bergkamp G (2006) Pay – establishing payments for watershed services. Gland, Switzerland: IUCN. Reprint, Gland, Switzerland: IUCN, 2008

Spash CL, Vatn A (2006) Transferring environmental value estimates: issues and alternatives. Ecol Econ 60(2):379–388

UNEP (2006) Marine and coastal ecosystems and human wellbeing: a synthesis report based on the findings of the millennium ecosystem assessment. United Nations Environment Programme, p 76

Venkataraman K (2007) Coastal and marine wetlands in India. http://www.moef.nic.in/sites/default/files/nlcp/C-%20Biodiversity/C-2.pdf. Accessed 29 Mar 2015

Verma M, Negandhi D, Wahal AK, Kumar R (2013) Revision of rates of NPV applicable for different class/category of forest. http://envfor.nic.in/sites/default/files/report.pdf. Accessed 15 Mar 2015

Waite R, Burke L, Gray E (2014) Coastal capital ecosystem valuation for decision making in the Caribbean. http://www.wri.org/sites/default/files/coastal_capital_ecosystem_valuation_caribbean_guidebook_online.pdf. Accessed 1 Apr 2015

Wegner G, Pascual U (2011) Cost-benefit analysis in the context of ecosystem services for human well-being: a multidisciplinary critique. Glob Environ Chang 21:492–504

White A, Ross M, Flores M (2000) Collected essays on the economics of coral reefs. In: Cesar H (ed) Collected essays on the economics of coral reefs. CORDIO, Department for Biology and Environmental Sciences, Kalmar University, Sweden, pp 215–227

WWF (2010) www.worldwildlife.org/press-releases/climate-change-threatens-to-wipe-out-one-of-world-s-largest-tiger-populations-this-century (2010). World Wildlife Fund

www.keralatourism.org (2013) Kerala Tourist Statistics – 2013

www.seagrasswatch.org (2013) India seagrass

Zhao B, Kreuter U, Li B, Ma Z, Chen J, Nakagoshi N (2004) An ecosystem service value assessment of land-use change on Chongming Island, China. Land Use Policy 21:139–148

Understanding the Social-ecological System of Wetlands

15

Md Sarwar Hossain and Sylvia Szabo

Abstract

The concept of social-ecological system is receiving increasing recognition from the scientific community as a tool for analysing complex phenomena. The wetlands' social-ecological systems provide valuable economic, social and environmental benefits to society. However, disturbances in wetland system due to human intervention have already led some of the wetlands' social-ecological system towards the tipping point. Furthermore, in the context of the projected impacts of environmental and climate change, organisms inhabiting and dependent on wetlands, which are at the centre of the social-ecological system, are likely to require greater resilience and innovative coping strategies. The present chapter introduces the concepts of the social-ecological system using real-world case studies from the coastal Ganges-Brahmaputra Delta in Bangladesh in order to facilitate understanding of social-ecological system as well as interactions between ecological factors and human wellbeing. The chapter also discusses the critical issues of managing social-ecological system in order to support sustainable ecosystem management.

Keywords

Climate change • Ecosystem management • Resilience • Social-ecological system

Md Sarwar Hossain, Ph.D. (✉)
Geography and Environment, University of Southampton, Southampton, UK
e-mail: Koushikadd@yahoo.com; Sarwar.Sohel@soton.ac.uk

S. Szabo, Ph.D.
Social Statistics and Demography, University of Southampton, Southampton, UK
e-mail: sylviaszabo.dev@gmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_15

15.1 Introduction

The concept of social-ecological system (SES) is receiving increasing recognition from the scientific community as a tool for analysing complex phenomena. This is despite a previous reluctance to use the concept (Halliday and Glaser 2011) because of the complexities and difficulties in parsing the components of the system (Walker et al. 2006), lack of theoretical framework (Cumming 2014) and data unavailability. The integration of this scientific discourse for management and sustainability of environmentally vulnerable regions, particularly in the context of wetlands, is important. This is because of the social, economic and environmental values of wetlands, which cover more than 12.8 million km^2 of the earth and provide a wide range of ecosystem services, including food, water, human security and spiritual and cultural benefits worth approximately US$ 70 billion per year (Brander and Schuyt 2010). Moreover, the growing threats of environmental changes are likely to increase the vulnerability of wetlands and thus aggravate the living conditions of wetland-dependent people. Similarly, feedbacks from society towards ecosystems are likely to increase because of the increasing exploitation of resources to accommodate continuously growing populations (Nicholls 2004; MA 2005; Kirwan and Megonigal 2013; Hossain et al. 2016).

A system can be self-perpetual because of the feedbacks in the SES, which may experience tipping points from the continuous ecological degradation and increasing pressure from the social system. For example, water scarcity in dry season in wetlands can be triggered by rising temperature, which in turn reduces water in wetlands. This water scarcity reaches a critical stage possibly by drying out the wetlands when the social system invokes pressure in the system by extracting water for irrigation and household uses. In such a case, the wetland may experience tipping points by turning into dry land because of feedbacks between ecological and social systems.

Apart from the economic, social and environmental values of wetlands, environmental disasters constitute another reason why wetland ecosystems are so important. Environmental disasters are often linked to misconceived development (Deb 1998; Hossain 2010) as a result of ignoring the nexus between social and ecological systems. The present chapter aims to introduce the concepts of the SES (feedbacks, tipping points), using real-world case studies to facilitate our understanding on the interactions between ecological factors and human wellbeing.

15.2 The Concept of Social-ecological System

An ecological system refers to the interactions between biotic (e.g. living organisms) and abiotic (e.g. temperature, rainfall) components of nature. A social system, on the other hand, incorporates human life, in which interactions take place amongst individuals, groups and institutions. The concept of socio-economic systems incorporates two independent systems (social and ecological) and the interaction between them. Olsson et al. (2004) described SES as complex systems in which ecological components invoke feedbacks and social systems respond to those feedbacks. Further, the interactions between these two systems create a compound adaptive system that requires an integrated approach for sustainable management. Ecosystem services, defined as the “benefits” that people receive from ecosystems (Bennett et al. 2009), constitute critical links between ecosystem processes and human wellbeing.

Both ecosystem services and integrated SES can be conceptualized as adaptive cycles, as they are subject to constant evolution on both temporal and spatial scales. While this change can at times have negative impacts, disturbances are necessary as they allow a system’s rigour and diversity to evolve in the long term (Burkhard et al. 2011). The adaptive cycle of the SES is even more complex, as it entails changes and adaptation in all components of the social and ecological systems as well as in the interactions between the different elements (Hossain et al. 2016). The adaptive management approach was developed in response to the changing nature of ecosystems (Folke 2006). It recognizes future uncertainties and thus encourages learning and revision of management practices in order to enable optimal prevention and coping strategies. Adaptive governance is a broader concept and encompasses aspects such as understanding the dynamics of ecosystems, establishing relevant management practices, generating adaptive capacity and focusing on social networks and versatile institutions as part of multi-governance systems (Folke 2006).

Resilience is another key concept relating to SES and their adaptive capacity. Resilience can be defined as the capacity of SES to cope with instabilities while at the same time ensuring that the functions and configurations of the systems are preserved (Burkhard et al. 2011). In other words, resilience measures the degree to which the systems are able to self-organize and develop a continuing capacity for learning and adjustment (Adger et al. 2005). The concept of resilience as a return to a state of equilibrium after a period of change, or disturbance, has been dominant in ecological science and is often referred to as engineering resilience (Folke 2006). In SES, different equilibrium levels or departures from the state of equilibrium are influenced by both “fast” and “slow” variables. The former are the key features of ecosystems, including fresh water, crop production and other provisioning services, while the latter are factors that affect the functioning and type of ecosystem, such as soil or sediments. All elements of SES are interlinked and influence livelihoods and human wellbeing both directly and indirectly (Hossain et al. 2016).

15.3 Operationalizing Social-ecological System

The key linkages between ecosystem services and human wellbeing are illustrated in Fig. 15.1. The conceptualization of these relationships is drawn from the Millennium Ecosystem Assessment (MEA) framework, wherein human wellbeing is considered as an integral part of ecosystems and thereby directly influencing the structure and functioning of ecosystem services (MEA 2005). Each type of ecosystem service affects human wellbeing, albeit in different ways. For example, provisioning services can have a direct impact on human health through food security.

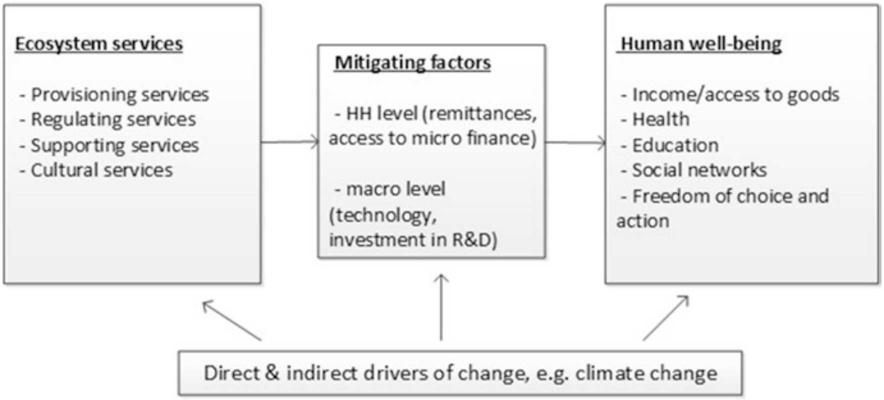


Fig. 15.1 Inter-linkages between ecosystem services and human wellbeing (Adapted from MA 2005)

Crop yields translate into availability of food, thereby influencing all aspects of food security including access to food and food stability. This link can however be mitigated by household level factors, such as the volume of migrants' remittances, which can have a positive moderating effect on human wellbeing through their contribution to overall household income (Szabo et al. 2015). External or contextual factors (climate change or construction of dams) can further affect the overall SES.

According to the MEA (2005), SES is affected by both direct and indirect drivers of change. These tend to be macro-level phenomena. Direct drivers may include factors such as, changes in land use, climate change and appearance of new faunal species. Indirect drivers, on the other hand, comprise demographic, socio-economic and cultural factors. All these drivers can operate at different levels, e.g. at local, national and global level. Thus, for example, a change in international trading regulations can have a direct effect on the livelihoods of households in wetland areas. Similarly, environmentally induced large-scale migration from a district can translate into reduced production, thus negatively affecting the overall export volume of a country.

The way in which SES operate in the local context can be best understood by looking at two case studies. Here, we focus on the way in which the SES operates in the wetlands of the Narail District and mangrove wetlands in Southwestern Bangladesh.

15.4 Case Study 1: Value of Wetland Social-ecological System

Provisioning services (e.g. food, fish) support household livelihoods and are the source of income for approximately 134,000 farmers and 16,000 fishermen in the wetlands of Narail District in Bangladesh (Fig. 15.2). They also export fish and other goods to national and international markets and thus contribute directly to

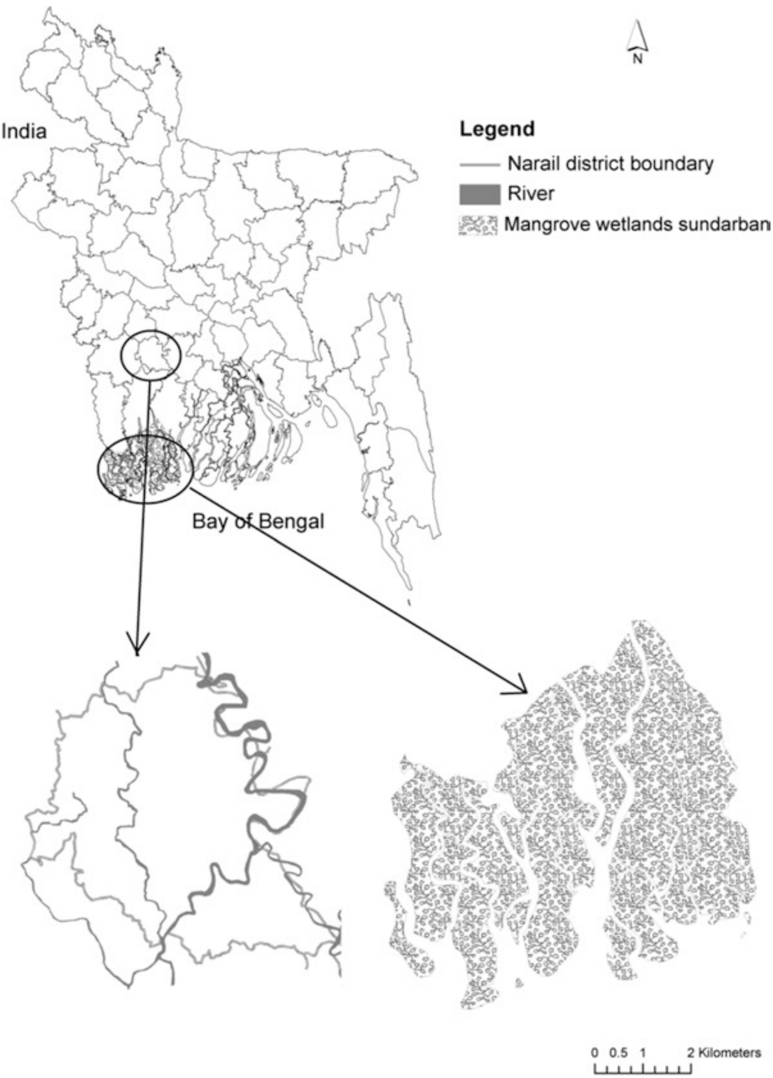


Fig. 15.2 Map of Bangladesh showing location of Narail District (Case study 1) and mangrove wetland Sundarabans (Case study 2)

local, national and global food security. We have calculated the economic value of provisioning services using direct market valuation that takes into account the total production of the products across years collected from official statistics (e.g. Bangladesh Bureau of Statistics) and the market value of that product in the respective years. This market value has been collected during the field survey in 2011.

The total yearly market output of provisioning services in the area amounts to around US$ 173 million. Annual fish production is estimated at US$ 8.8 million, while the value of yearly shrimp production is approximately US$ 10.8 million. The Narail wetland ecosystem supports the production of 235,000 t of rice per year with a local market price of US$ 57 million. Finally, the annual market price of the golden fibre “jute” has been estimated at US$ 78 million. The details of the market output of the provisioning services are given in Table 15.1. These economic outputs are the sources of people’s livelihoods (Fig. 15.3) and thus contribute to the national economy of Bangladesh. In addition to the direct contribution of provisioning services to human development, regulating services (e.g. air quality purification, erosion protection) underpin the production of provisioning services. Hossain et al. (2013) estimated that wetlands in this area accumulate 1800 t CO_2 e km^{-2} $year^{-1}$ to 3600 t CO_2 e km^{-2} $year^{-1}$. The economic values of other services (e.g. cultural, regulating services) were not estimated due to lack of data. The economic valuation of provisioning services gives insight to the role of wetlands on social system. However, the SES of the wetlands is affected by direct drivers such as climate change, dams and relatively rapid population growth (Hossain et al. 2015). People residing near wetlands are coping with environmental change through macro- (e.g. agricultural subsidy, changing crop varieties) and micro-scale (e.g. increase in production cost, occupational migration) mitigation factors (Moni and Hossain 2010; Hossain et al. 2015).

15.5 Case Study 2: Value of Mangrove Social-ecological System

The coastal mangrove wetlands of the Sundarbans, a UNESCO (United Nations Educational, Scientific and Cultural Organization) world heritage site located in Bangladesh (60% area) (Fig. 15.2) and India (40% area), are direct as well as indirect source of livelihood for ten million people in coastal Bangladesh. Uddin et al. (2013) estimated a total of US$ 744,000 per year and US$ 42,000 per year for provisioning services (e.g. forest products) and cultural services (tourism), respectively. Both these services contribute to the livelihood of people engaged in fishery, forest product collection, tourism, shrimp farming and crop production. However, revenue from these wetlands has declined since 1995 (Fig. 15.4a), mainly because of river and soil salinization, water diversion and shrimp farming (Hossain et al. 2015). On the contrary, revenue from fish catches (Fig. 15.4b) in these wetlands shows a fluctuating pattern between 2000 and 2011. The total number of tourists visiting (Fig. 15.4c) the mangrove wetlands has increased by 25,000 between 2004 and 2011. Similar to the wetlands in the Narail District, sea level rise (SLR), the rapidly growing shrimp industry and water scarcity are threatening the SES of the coastal mangrove wetlands (Mirza 1998; Swapan and Gavin 2011; Hossain et al. 2015). However, economic migration and remittances constitute household-level mitigating factors, thus improving human wellbeing (Kartiki 2011; Paul 2014; Hossain et al. 2015; Szabo et al. 2015).

Table 15.1 Economic valuation of provisioning services in the wetlands of Narail District in Bangladesh

Goods and services	Ecosystem services			Market output	
Food	Food item	Monetary value M.T-1 BDT	Production (direct use) year^{-1} (M.T)	BDT/year	US$/year
	Rice				
	Ropa amon	17,500	71,000	1242,500,000	17,750,000
	Boro	17,000	141,000	2,397,000,000	34,242,800
	AUS	17,500	7,000	122,500,000	1,750,000
	Bona amon	17,500	15,000	262,500,000	3,750,000
	Wheat	17,000	7,000	119,000,000	1,700,000
	Corn	20,000	9	180,000	2,570
	Grass pea	17,500	9,000	157,500,000	2,250,000
	Lentil	60,000	2,200	120,000,000	1,714,280
	Pea	30,000	350	105,00,000	150,000
	Chick pea	55,000	37	2,035,000	29,070
	Mung beans	65,000	180	11,700,000	167,140
	Black gram	16,000	38	608,000	8,685
	Mustard	40,000	2,100	84,000,000	1,200,000
	Linseed	35,000	305	10,675,000	152,500
	Peanuts	50,000	741	35,000,000	500,000
	Chili	50,000	1,300	65,000,000	928,570
	Potato	6,000	2,200	132,00,000	188,570
	Sweet potato	10,000	1,400	14,000,000	200,000
	Vegetable			374,205,000	5,345,700
	Til	45,000	1,100	49,500,000	707,100
	Sugar cane		26,000	4,655,000	66,500
	Betel			269,500	3,800
	Fish	150,000	4000	613,200,000	8,760,000
	Shrimp	600,000	1000	756,600,000	10,808,000
Raw material	Spices				
	Onion	20,000	3000	75,560,000	1,079,400
	Garlic	60,000	530	31,980,000	456,800
	Ginger	80,000	72	5,760,000	82,200
	Turmeric	240,000	240	57,600,000	822,800
	Coriander	60,000	350	21,000,000	300,000
	Jute			5,469,380,200	78,134,000
Total				12,103,907,700	173,250,400

Fig. 15.3 *Top* row (from *left* to *right*): wetlands in Narail District produce large quantities of rice and raw materials (e.g. wood, fuel made of cow dung). *Bottom* row (from *left* to *right*): jute (golden fibre), fish from wetlands and fuel from jute (Source: Field survey 2011)

15.6 Tipping Points in the Social-ecological System

Tipping points can be defined as a situation in which the ecosystem goes through a relatively rapid change from one state to another. This change is often irreversible posing significant challenges to both the ecosystem and the society (CBD 2010). In the case of the highly resilient SES of wetlands, external drivers must apply a large force to the system for it to cross the threshold for rapid change, which, in turn, leads to another state for the system. However, a system can also experience tipping point when it gradually changes to a different state over a long period (Lenton et al. 2008; Brook et al. 2013; Hughes et al. 2013). The SES can adapt in response to the changes in stressors. However, during the adaptation phase, low-resilience systems can pass through a tipping point even when external drivers are relatively weak (Renaud et al. 2013).

According to CBD (2010), we can identify a tipping point, if any of the following characteristics are observed in wetland SES: (i) self-perpetuating change through positive feedbacks, (ii) passing the threshold of a system, (iii) irreversible change and (iv) significant delay between the drivers impacting on the system and the system response towards the drivers. Tipping points are not scale dependent and can happen on regional and global scales. Reduction in water discharges may lead from a natural state of wetland to desertification, which, for example, could cause a 50% loss of fish production in the Chalan Beel wetlands of Bangladesh (Hossain et al. 2013). On a global scale, the earth's climate system has already passed multiple tipping points (Lenton et al. 2008).

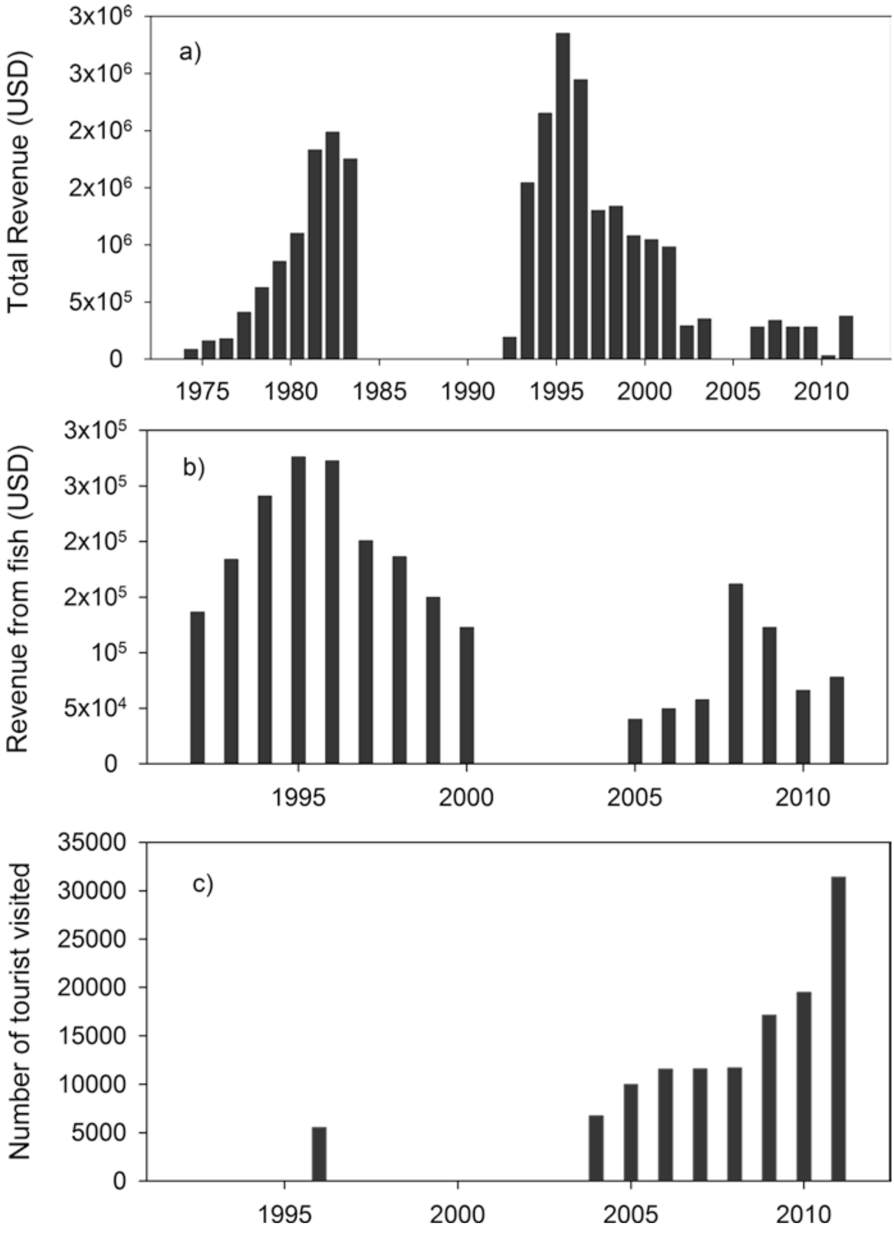


Fig. 15.4 (**a**) Total revenue from products (e.g. wood, honey, wax, fish) from the mangrove wetlands during 1975–2010; (**b**) From 1990 to 2011, total revenue from fish catch from the wetlands has been fluctuating; (**c**) From 1996 to 2011, the total number of tourists has increased four to five times - Data source: Forest department, Khulna, Bangladesh)

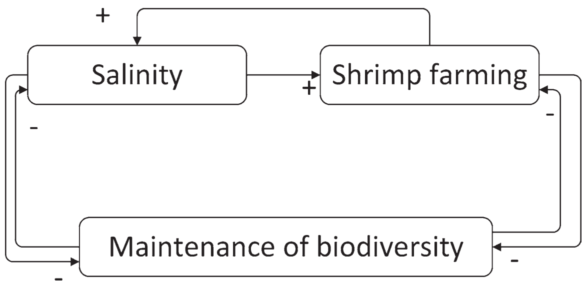


Fig. 15.5 Positive feedback in the ecosystem leads towards tipping points in the mangrove wetlands (Hossain et al. 2015)

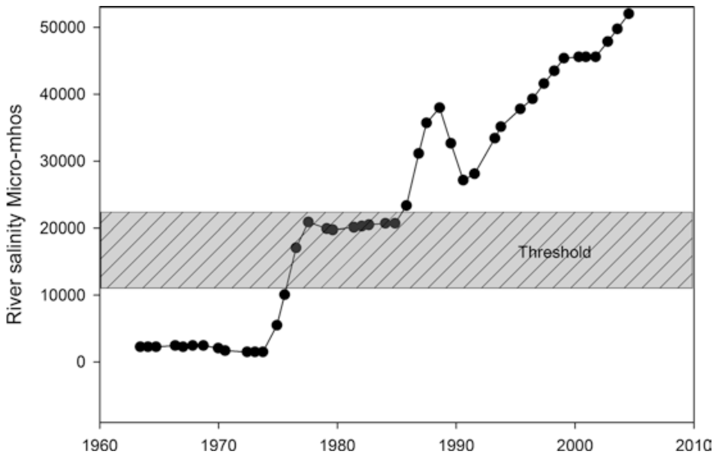


Fig. 15.6 The mangrove wetlands of Bangladesh have already experienced the threshold range (Data source: Islam 2008)

A system can pass a tipping point when it experiences a change that becomes self-perpetual because of the positive feedback within the system. For example, the southwest coastal part of the Ganges Delta in Bangladesh has passed a tipping point for biodiversity, water quality and shrimp industry. In this delta (Fig. 15.5), the explosion of the shrimp industry has increased salinity, which has deteriorated the mangrove diversity. In turn, reduction in mangrove diversity is accelerating the salinity rise and favouring shrimp farming in this region (Hossain et al. 2015).

A system can also pass a tipping point if it experiences a threshold, which leads the system towards another state. Mangrove wetlands in Bangladesh are a good example for the second characteristic of a tipping point. Figure 15.6 shows that river salinity in the wetland mangrove system has already crossed the threshold because of multiple stressors (e.g. water scarcity, sea level rise, shrimp industry). The mangrove wetlands maintain the balance of seawater and fresh water exchange required for sustaining the biodiversity. Because of the rapid salinity rise beyond the threshold (Islam 2008), tree density has halved within the last 60 years (Hossain et al. 2015). Besides a possible regime shift in the salinity of this wetland, the area of the mangrove wetlands and biodiversity are also good examples of an irreversible

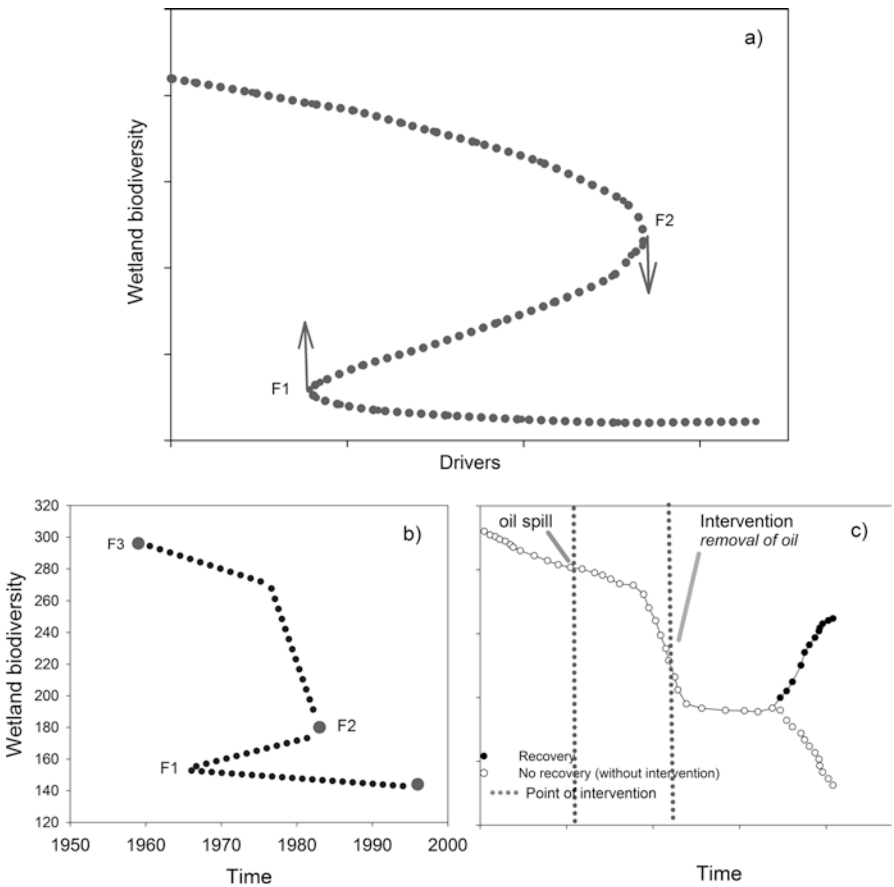


Fig. 15.7 Conceptualization of the irreversible change in the social-ecological system (SES) (**a**) (Adopted from Kinzig et al. 2006, Hughes et al. 2013). We also conceptualize in this study (1) irreversible change of the mangrove density (tree per hectare) between 1950 and 2000 (**b**). (2) Delay between the impacts and time to respond by a system can slow down the restoration of wetlands (**c**). Here, F1, F2 and F3 denote the different ecological stages at different time points (Data source: MoEF 2010; Hossain et al. 2015)

change that is hard to restore; this is known as the hysteric effect (Kinzig et al. 2006). When the threshold for wetland biodiversity has reached (Fig. 15.7a), slight changes (beyond F2) in the drivers lead to regime shift and a state of low biodiversity. In such a case, if an attempt is made to restore the wetland biodiversity to its original state, then it would have to be achieved at the value of F1 (Fig. 15.7a). Around 200 years ago, the size of the mangrove wetland was double (~12,000 km^2) of its current size (~6000 km^2). The wetland was reduced to 7500 km^2 in 1873 and then to 6000 km^2 in 1933 because of human settlement (Curtis 1933; Blasco 1977). The mangrove area further decreased from 6000 to 4000 km^2 between 1933 and 1985. Of 2000 km^2 of mangrove area, ~100 km^2 has been chopped to make space

Fig. 15.8 Oil spill in the mangroves has changed the colour of the water and soil and is likely to have negative impacts on the social-ecological system of the region (Photo courtesy: Shakir Ahmed)

for the shrimp revolution in the Ganges Delta (Azad et al. 2009; Hossain et al. 2015). The mangrove forest is difficult to restore, even to the state it was 40 years ago. The available data (Fig. 15.7b) show that wetland biodiversity (number of trees per hectare) has been reduced by half during the last 50 years. Therefore, to restore the biodiversity to its 1950s state, it must be decreased to F1 and F2 value before the wetland is restored to F3 value (Fig. 15.7b).

A fourth characteristic of tipping points is significant delay between the impacts of drivers and the system response, which is often difficult to identify in a SES because this type of system response is usually recognized only after an event has occurred. A recent example of this delayed driver-impact response could be the oil spillage in the Sundarbans mangrove wetlands (Fig. 15.8), where 94,000 gallons of oil was spilled over the 350 km^2 wetlands (Alexander 2015). Figure 15.7c shows the conceptualization of the delayed impacts and recovery of the system. Although it has shown some impacts (e.g. degradation of water quality), the SES is likely to experience delayed effects, such as biodiversity loss, degradation of habitat and displacement of some parts of the wetlands. Furthermore, the ecological system could possibly show a delayed response towards intervention to clean up the wetlands and removal of oil from soil and water. However, in cases of delayed intervention, no intervention, or other mismanagement, wetland biodiversity may experience another alternative state (very low biodiversity) because of the increasing stress of other drivers (e.g. climate change, SLR, rapidly growing shrimp industry). Although most of the tipping point examples are directly related to the ecological system,

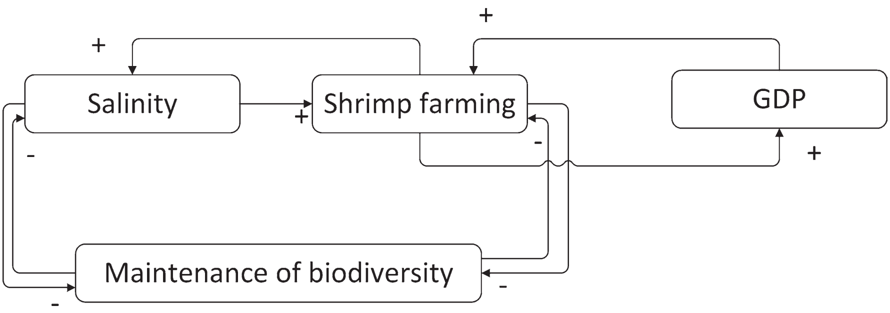


Fig. 15.9 Feedbacks from social system into the ecological system can magnify the environmental degradation and lead towards rapid change in the social-ecological system (SES) of wetlands (Modified from Hossain et al. 2015)

most of the drivers, as well as the ultimate response, are driven and experienced by the social system. In the above case study, because of the high profit from the shrimp firms, people started to produce more shrimps, thus further degrading water quality and reduction of biodiversity. Moreover, loss of biodiversity is likely to have a negative effect on the livelihoods of wetland-dependent people. This could result in migration of household members and may increase poverty in the society (Swapan and Gavin 2011; Hossain et al. 2015). Thus, the interactions and feedbacks within the ecological system are sometimes accelerated and directly driven by the social system (Fig. 15.9). However, because of the resilience shown by the mangrove wetlands, the social system has not experienced any regime shift yet, though it is likely to undergo drastic change if the multiple stressors continue in future (Mirza 1998).

15.7 Managing the Social-ecological System and Implications for Research

Management of the SES of the wetlands is a major challenge to their ability to remain in the safe operating space (the point beyond which is dangerous to humanity) (Rockström et al. 2009) and contribute to regional and global sustainability. This is why understanding the SES and incorporating these concepts into development planning is key for wetland management.

Biggs et al. (2012) have reviewed and suggested seven principles (e.g. managing connectivity, maintaining diversity, fostering the understanding, etc.) for managing the SES. Similar principles, including maintenance of diversity, can be adopted for managing the SES of wetlands. Increasing the diversity of wetland resources, together with modularization of the system by ensuring greater spatial heterogeneity, could enhance the resilience of the SES. In our case study, maintaining the diversity of mangrove wetlands and modularity, such as shrimp farming, could be effective without increasing the conflicts between shrimp farming and crop production in high saline areas; integrated management that takes ecosystems and all types of livelihood into consideration could support this overall management process. Management of slow variables (e.g. climate, water quality, biodiversity) that shape fast variables (e.g. food production, forest product) could be a viable alternative. For example, government interventions to manage the diversity of mangrove wetlands in Southwestern Bangladesh after the significant damage by the super cyclone Sidr in 2007 supported restoration of those wetlands (Iftekhar 2008). Encouragement of learning, participation and decentralization of governance through polycentricism could constitute useful further approaches to manage SES.

As shown above, it is crucial to understand the dynamics of the SES and take into consideration the interactions, feedbacks, thresholds and delayed responses of the system when managing wetlands. As such, research aimed at unravelling long-term socio-ecological dynamics and creating a wide range of data for the wetlands in South Asia is an essential step, not only because of the current data scarcity but also in order to gain greater understanding of the concept of tipping points pertaining to the SES of the wetlands. System dynamic modelling could be a useful tool for analysing the complexities and developing management options, while conceptual tools such as DPSIR (Driver-Pressure-State-Impact-Response) could be applied (Hossain et al. 2015) in order to tackle the environmental challenges of the wetlands while managing their SES.

15.8 Conclusion

This chapter provided an overview of the concept of SES, suggested ways to operationalize SES, analysed the concept of tipping points related to SES and discussed the integrated management of SES. A conceptual framework linking ecosystem services and human wellbeing showed that provisioning services contribute substantially to human wellbeing in the two wetlands of Southwestern Bangladesh. Although the pressure of drivers on human wellbeing has been increasing, the social system has been mitigating the impacts of these drivers through micro- and macroscale factors. The concept of tipping points, along with the case studies, showed that mangrove wetlands may have passed a tipping point in the ecological system in Bangladesh and there is a risk that the system may transgress the safe operating space due to the growing complexities in the region. Therefore, managing the SES involves concerns about long-term changes, interactions and feedbacks. In this context, system dynamic modelling can be a useful tool for capturing the relationships and dynamics of the SES.

Acknowledgement Authors would like to acknowledge Dr. Chris Hackney from the University of Southampton for critically reviewing and commenting on the chapter. Md. Sarwar Hossain acknowledges financial support provided by a joint NERC/ESRC interdisciplinary Ph.D. studentship award and the University of Southampton.

References

Adger WN, Hughes TP, Folke C et al (2005) Social-ecological resilience to coastal disasters. Science 309(5737):1036–1039. doi:10.1126/science.1112122

Alexander C (2015) After oil spill, unique mangrove forest faces more threats. National Geographic. Available via http://news.nationalgeographic.com/2015/05/150507-sundarbans-india-bangladesh-oil-spill-royal-bengal-tiger-irrawaddy-dolphin-bay-of-bengal/. Accessed 14 Apr 2016

Azad A, Jensen K, Lin C (2009) Coastal aquaculture development in Bangladesh: unsustainable and sustainable experiences. Environ Manag 44:800–809. doi:10.1007/s00267-009-9356-y

Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple ecosystem services. Ecol Lett 12(12):1394–1404. doi:10.1111/j.1461-0248.2009.01387.x

Biggs R, Schlüter M, Biggs D et al (2012) Toward principles for enhancing the resilience of ecosystem services. Annu Rev Environ Resour 37:421–448. doi:10.1146/annurev-environ-051211-123836

Blasco F (1977) Outlines of ecology, botany and forestry of the mangals of the Indian subcontinent. In: Chapman VJ (ed) Wet coastal ecosystems, ecosystems of the world, vol 1. Elsevier, Amsterdam, pp 241–260

Brander L, Schuyt K (2010) The economic value of the world's wetlands. TEEB case. Available via: http://www.teebweb.org/wp-content/uploads/2013/01/The-economic-value-of-the-worlds-wetlands.pdf. Accessed 21 Dec 2014

Brook BW, Ellis EC, Perring et al. (2013) Does the terrestrial biosphere have planetary tipping points? Trends Ecol Evol 28(7): 396–401. doi:http://dx.doi.org/10.1016/j.tree.2013.01.016

Burkhard B, Fath BD, Muller F (2011) Adapting the adaptive cycle: hypotheses on the development of ecosystem properties and services. Ecol Model 222(16):2878–2890. doi:10.1016/j.ecolmodel.2011.05.016

CBD (2010) Global biodiversity outlook 3. Convention on Biological Diversity (CBD), Montreal 94

Cumming GS (2014) Theoretical frameworks for the analysis of social–ecological systems. In: Sakai S, Umetsu C (eds) Social–ecological systems in transition. Springer, Global Environmental Studies, pp 3–24. doi:10.1007/978-4-431-54910-9_1

Curtis SJ (1933) Working plan for the forests of the Sundarbans division for the period from 1st April 1931 to 31st March 1951, volume III part of appendix III description of the compartments and their histories. Government of Bengal

Deb AK (1998) Fake blue revolution: environmental and socio-economic impacts of shrimp culture in the coastal areas of Bangladesh. Ocean Coast Manag 41(1):63–88

Folke C (2006) Resilience: the emergence of a perspective for social-ecological systems analyses. Glob Environ Chang 16(3):253–267. doi:10.1016/j.gloenvcha.2006.04.002

Halliday A, Glaser M (2011) A management perspective on social ecological systems: a generic system model and its application to a case study from Peru. Hum Ecol Rev 18(1):1–18

Hossain MS (2010) Climate error: misconceiving the development issue: a hardline view of the water resource management project of ADB in Bangladesh. Quezon City, PH, NGO Forum on ADB, 3 pp. Available via http://www.forum-adb.org/docs/Climate-Error_Misconceiving-the-Development-Issue-A-Hardline-View-of-the-WRMP-ADB-in-Bangladesh-Md-Sarwar-Hossain.pdf. Accessed 21 Dec 2014

Hossain MS, Hein L, Rip F, Dearing J (2013) Integrating ecosystem services and climate change responses in coastal wetlands developments plans for Bangladesh. Mitig Adapt Strateg Glob Chang 20(2):241–261. doi:10.1007/s11027-013-9489-4

Hossain MS, Dearing JA, Rahman MM et al (2015) Recent changes in ecosystem services and human well-being in the Bangladesh coastal zone. Reg Environ Chang. doi:10.1007/s10113-014-0748-z

Hossain MS, Eigenbrod F, Johnson FA, Dearing JA (2016) Unravelling the interrelationships between ecosystem services and human wellbeing in the Bangladesh delta. Int J Sust Dev World. doi:http://dx.doi.org/10.1080/13504509.2016.1182087

Hughes TP, Carpenter S, Rockström et al. (2013) Multiscale regime shifts and planetary boundaries. Trends Ecol Evol 28 (7): 389–395. doi:http://dx.doi.org/10.1016/j.tree.2013.05.019
Iftekhar MS (2008) An overview of mangrove management strategies in three south Asian countries: Bangladesh, India and Sri Lanka. Int For Rev 10(1):38–51
Islam MSN (2008) Cultural landscape changing due to anthropogenic influences on surface water and threats to mangrove wetland ecosystems: a case study on the Sundarbans, Bangladesh. PhD Dissertation, Brandenburg University of Technology, Cottbus, Germany
Kartiki K (2011) Climate change and migration: a case study from rural Bangladesh. Gend Dev 19(1):23–38. doi:10.1080/13552074.2011.554017
Kinzig AP, Ryan P, Etienne M et al (2006) Resilience and regime shifts: assessing cascading effects. Ecol Soc 11(1):20
Kirwan ML, Megonigal JP (2013) Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504:53–60. doi:10.1038/nature12856
Lenton TM, Held H, Kriegler E et al (2008) Tipping elements in the Earth's climate system. Proc Natl Acad Sci 105(5):1786–1793. doi:10.1073/pnas.0705414105
MA (2005) Ecosystems and human well-being: synthesis. Millennium ecosystem assessment. Island Press, Washington, DC
MEA (2005) Ecosystems and human well-being: a framework for assessment. Millennium ecosystem assessment. Island Press, Washington, DC
Mirza MM (1998) Diversion of the Ganges water at Farakka and its effects on salinity in Bangladesh. Environ Manag 22(5):711–722
MoEF (2010) Fourth national report to the convention on biological diversity: biodiversity national assessment and programme of action 2020. Ministry of Environment and Forests (MoEF), Dhaka
Moni AH, Hossain MS (2010) Response of environmental changes (Climate) in wetlands. Proceedings 3rd International Conference on Bangladesh Environment 2010 by BEN and BAPA, Dhaka
Nicholls RJ (2004) Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. Glob Environ Chang 14:69–86
Olsson P, Folke C, Berkes F (2004) Adaptive co-management for building resilience in social–ecological systems. Environ Manag 34(1):75–90
Paul S (2014) Post-cyclone livelihood status and strategies in coastal Bangladesh. Rajshahi Univ J Life Earth Agr Sci 06(40–41):1–20
Renaud FG, Syvitski JPM, Sebesvari Z et al (2013) Tipping from the Holocene to the anthropocene: how threatened are major world deltas? Curr Opin Environ Sustain 5:644–654
Rockström J, Steffen W, Noone K et al (2009) A safe operating space for humanity. Nature 46: 472–475
Swapan MSH, Gavin M (2011) A desert in the delta: participatory assessment of changing livelihoods induced by commercial shrimp farming in Southwest Bangladesh. Ocean Coast Manag 54:45–54. doi:10.1016/j.ocecoaman.2010.10.011
Szabo S, Hossain MS, Matthews Z et al (2015) Soil salinity, household wealth and food insecurity in agriculture-dominated delta. Sustain Sci:1–11 10.1007/s11625-015-0337-1
Uddin MS, de Ruyter vanSteveninck E, Stuip M et al (2013) Economic valuation of provisioning and cultural services of a protected mangrove ecosystem: a case study on Sundarbans reserve forest, Bangladesh. Ecosyst Serv 5:88–93
Walker B, Gunderson L, Kinzig A, Folke et al (2006) A handful of heuristics and some propositions for understanding resilience in social-ecological systems. Ecol Soc 11(1):13

Community Dependency on the Ecosystem Services from the Sundarbans Mangrove Wetland in Bangladesh

16

Mohammad Mahmudul Islam
and Mohammad Mosarof Hossain

Abstract

The Sundarbans is the largest salt-tolerant tropical mangrove forest in the world occupying complex networks of wetlands situated in the Bengal deltaic plain that shares territories with Bangladesh and India. This chapter explores the goods and services, collectively known as ecosystem services that the Sundarbans deliver to the populations living in the impact zone and to the wider landscape of Bangladesh. Similiar to other wetlands, four types of ecosystem services are derived from the Sundarbans mangrove ecosystem. These are provisioning services (e.g. fish and shellfish, woods, and honey), cultural services (e.g. mangrove tourism, religious value), regulatory services (e.g. carbon sequestration), and other supporting services (e.g. soil formation). Particularly, provisioning services from the Sundarbans help to ensure employment, income, and food security and constitute a last resort activity when all other livelihood options are lost. However, a number of threats and stressors, both of natural and anthropogenic origin, continue to affect the flow and quality of the ecosystem services due to overuse and degradation. This chapter submits that for sustainable delivery of ecosystem services, urgent research and policy attention is required to manage the wetland in a manner that is socially equitable and ecologically sound.

Keywords

Ecosystem services • Mangrove • The Sundarbans

M.M. Islam (✉) • M.M. Hossain
Department of Coastal and Marine Fisheries, Sylhet Agricultural University, Sylhet 3100, Bangladesh
e-mail: mahmud2512@googlemail.com; mosarofmh.cmf@sau.ac.bd

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_16

16.1 Introduction

Situated strategically at the confluence of land and sea boundaries, mangroves are among the most productive wetland ecosystems on earth (Alongi 2009). As halophytic and salt-tolerant species, mangroves flourish along the estuaries and shorelines of tropics and subtropics latitudes (Brander et al. 2012). Mangrove forests are distributed in 123 countries of tropical and sub-tropical regions with a large dependent human population (MEA 2005; Spalding et al. 2010). The term "ecosystem services" encompass both the tangible and the intangible benefits humans obtain from mangrove ecosystems, which are sometimes distinguished into "goods" (e.g. food) and "services" (e.g. erosion protection), respectively (MEA 2005). The services also include timber (Uddin et al. 2013), shelter, breeding, and nursery ground for aquatic and nonaquatic animal species (Hussain and Badola 2010; Brander et al. 2012), carbon sequestration and storage (Donato et al. 2011; Lee et al. 2014), protection from natural hazards and erosion (Alongi 2008; Lee et al. 2014), land building (Lee et al. 2014), and recreational services (MEA 2005; UNEP 2014).

Dependency on mangrove goods and services is likely to further rise, as the estimated 100 million people living within 10 km of significant mangrove presence at the beginning of this century are predicted to increase to 120 million by 2015 (UNEP 2014). The majority of these people, who rely on mangrove ecosystems for food, income, and overall well-being, live in developing countries of Asia and Africa (MEA 2005; Duke et al. 2007; UNEP 2014). In the changing world, the instrumental role of mangrove wetlands in delivering critical ecosystem services is well recognized (Lee et al. 2014). However, destruction and degradation of mangroves continue at an alarming rate, driven by a number of factors, for instance, over-exploitation and clear-felling for development purposes such as urbanization, constructions of housing, ports, and aquaculture ponds that raise huge concern regarding the capacity of mangroves in meeting the increased demand (Spalding et al. 2010). The Food and Agriculture Organization (FAO 2010) estimated that around the world, mangrove areas have decreased from 16.1 million ha in 1990 to 15.6 million ha in 2010. Another study found that the disappearance of mangrove is faster than most other biomes on earth, such as tropical forests and coral reefs (Balmford et al. 2002; Duke et al. 2007; FAO 2010). Such rapid loss and degradation of mangroves may seriously undermine their ability to provide critical ecosystem services for present and future generations (Spalding et al. 2010).

In many parts of the world, mangroves are often perceived negatively as muddy wastelands promoting the spread of diseases (Horowitz et al. 2012). Many stakeholders are not aware of the real value of mangroves as valuing the mangrove ecosystem services are difficult (Vo et al. 2015). The evaluation of ecosystem services is a complex process and not all the services can be quantified in tangible monetary terms (Mukherjee et al. 2014). This makes the contribution of mangroves less visible in markets; consequently, mangroves are generally undervalued in both private and public decision-making relating to their use, conservation, and restoration (Brander et al. 2012). As a remedy, scientists believe that valuation of goods and services might help decision-makers to apprehend the actual value to society and the cost of their loss (Clavel et al. 2011; Ruckelshaus et al. 2013). Thus, understanding the value of mangrove ecosystems and the services has become increasingly important for policy and decision-makers (Mukherjee et al. 2014; Vo et al. 2015). In a turn of the tide, over the past few decades, wetland forests received greater attention, and research on mangrove has increased exponentially (Lee et al. 2014). Though surprisingly, in Bangladesh, until recently the Sundarbans has been less researched in terms of ecosystem services despite the fact that they provide essential services for human well-being in terms of food security, income, and livelihoods. In this chapter, different ecosystem services that the Sundarbans provide are discussed. Then we delve into different threats and stressors that caused a shift in the quality of the mangrove ecosystem.

16.2 The Sundarbans Mangrove Wetland

The Sundarbans mangrove forest (SMF) is the largest coastal wetland, with an area of 10,000 km^2 spanning across the territory of Bangladesh (60%) and India (40%). In the Bangladesh part, the Sundarbans has 115 km^2 tidal marshes within a network of 450 rivers. The rivers constitute about 12,000 km of watercourses in addition to canals, mudflats, and creeks (DoF 2010; Aziz and Paul 2015). The Sundarbans occupies 4.2% of the total area of Bangladesh and constitutes 44% of the forest cover in the country (DoF 2010, Fig. 16.1) situated in the ancient delta of the Ganges River in the southwest coastal part of Bangladesh. The Sundarbans in Bangladesh spreads across Satkhira, Khulna, and Bagerhat districts. Among the globally reported 80 mangrove/associated species, 65 species belonging to 37 families (10 species of large trees, 20 species of small trees, 25 species of shrubs, and 10 herbs

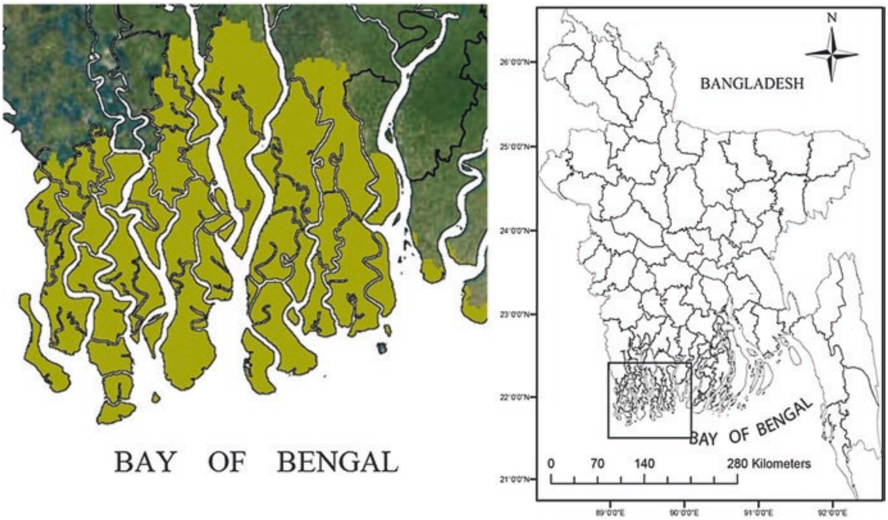


Fig. 16.1 Location of the Sundarbans Mangrove Forest (SMF)

Table 16.1 Floral and faunal composition in the Sundarbans wetland ecosystem, Bangladesh

Type of species	Total number	Source
Mangrove - large tree species	10	Chaffey et al. (1985)
Mangrove - small tree species	20	
Shrubs	25	
Herbs (including 2 fern species)	10	
Birds (including 84 migratory)	315	DoF (2010)
Terrestrial fauna	289	
Aquatic fauna	678	
Cetaceans	11	
Amphibians	8	
Molluscs	16	
Fishes	210	

species including two ferns) were found from the Bangladesh Sundarbans (Chaffey et al. 1985). There are 315 species of birds (84 migratory), 289 terrestrial animal species [49 species of mammals, including the great Royal Bengal tiger, *Panthera tigris* (Linnaeus 1758), estimated to be 440 in number and considered as endangered by IUCN (2015)], and 678 aquatic species (11 cetaceans, 59 reptiles, eight amphibians, 210 fishes, and 16 molluscs). That in total constitutes 35% of the fauna of Bangladesh (Table 16.1, DoF 2010).

Given its global significance, the Sundarbans was declared as a “Ramsar Site” in 1992, and the UNESCO has enlisted three wildlife sanctuaries of the forest as “World Heritage Site” in 1997. More than 3.5 million people living around the Bangladesh Sundarbans are directly or indirectly dependent on the goods and services of the forest (Giri et al. 2007). Particularly, the rural communities living within 20 km zone outside the forest boundary, referred to as the impact zone, are largely dependent on the mangrove forest for their livelihoods and survival (Rouf and Jensen 2001; Islam and Chuenpagdee 2013).

16.3 Ecosystem Services from the Sundarbans Wetland

Similiar to other wetlands, four types of ecosystem services are derived from the Sundarbans mangrove ecosystem in Bangladesh. These include provisioning services (mangrove products, such as fish), cultural services (nonmaterial benefits, e.g. mangrove tourism), regulatory services (benefits obtained from regulation of ecosystem processes, for instance, carbon sequestration), and supporting services (services necessary for the production of all other ecosystem services, such as nutrient recycling). Of the four services, provisioning, regulating, and cultural services of the Sundarbans are discussed here.

16.3.1 Provisioning Services

16.3.1.1 Fishery Production (Fish, Shrimp, Crab, Oyster, Dry Fish)

The Sundarbans mangrove fishery resources consist of fish, prawn, shrimp, crab, molluscs, and other crustaceans. The Sundarbans harbors several commercially important fish species that inhabit the wetland during all or part of their lives, with the mangrove providing critical food, reproduction, and shelter and refuge functions (Table 16.2). It is noted that 90% of commercial fishes and 35% of all fishes in the Bay of Bengal rely on the Sundarbans wetland as breeding and nursery ground (Kamal 1999 cited in Rouf and Jensen 2001). A total stock here has been estimated to be 90 kg/ha, which contributes 1.7% of the total inland fisheries production in Bangladesh (FRSS 2014). In 2004–2015, on an average about 10.37 metric ton (MT) of fish was harvested every day from the Sundarbans. The revenue from fish products was US$ 158,368 in 2014–2015 (DoF 2015).

Inshore, estuarine, and coastal fisheries of the Sundarbans provide a major source of livelihood for nearly 200,000 fishers operating daily in the area (Hoq 2007). The Sundarbans fishery also provides cheaper and accessible sources of protein and thus helps to ensure food security of people living in its impact zone and beyond. When other sources of income and food provision fail, mangroves offer an emergency food provision function to many poor fishers. This role was made particularly evident after the onslaught of the cyclone Aila (2009) in the region: when a majority of income sources were lost, the collection of shrimp and prawn post-larvae (PL) was the first economic activity for the affected people. Particularly, 70–75% of the family members who live along the rivers of the Sundarbans are known to engage in collection of PL of shrimp and prawn for stocking in commercial shrimp farms (Rouf and Jensen 2001; Islam and Chuenpagdee 2013). On an average, about 2.6 millions of shrimp PL are collected per year from the Sundarbans (Uddin et al. 2013). In 2014–2015, about 1,123 MT Mud Crab, *Scylla serrata* (Forsskål 1775), were harvested from the Sundarbans, generating revenue of US$ 52,026 (DoF 2015). It was estimated that more than 50,000 people are directly involved in the harvesting, trading, transportation, and export of the mud crab (Uddin et al. 2013). Bivalves are underexploited in the forest due to insufficient consumer demand. In 2013–2014, about 10.50 MT of oyster was extracted from the wetlands and the Department of Forest earned US$ 2,300 as revenue. Each year during winter, people from other parts of the coast, particularly from Chittagong, migrate to the inshore islands of the Sundarbans to engage in fish drying activities. In 2014–2015, about 2,773 MT of dry fish was produced in the region and US$ 179,761 was collected as revenue.

16.3.1.2 Forest Production (Timber, Nipa Palm, Woods, Wax, etc.)

Commercial harvesting of timbers such as *Sundri* (*Heritiera fomes* Buch.-Ham.), *Goran* (*Ceriops decandra* Griff. Ding Hou), and *Baen* (*Avicennia officinalis* L.) was the main economic activity in the Sundarbans until the late 1980s. Reduction in growing stock due to overexploitation forced the government to impose a sweeping moratorium on timber harvesting in 1989. Eventually, all types of timber harvesting including the collection of fuel wood were banned in 1995. Yet, about 26,930 ft^3

wood (for use as fuel wood) were collected during 2014–2015, mainly from timbers confiscated from encroachers as well as trees fallen during a cyclone or other natural calamities (DoF 2015).

The Sundarbans also supply affordable thatching materials for poor communities. The main species used are *golpatta* (Nipa Palm – *Nypa fruticans* Wurmb) and *malia grass* (*Phragmites karka* Retz. Trin. ex Steud.), which are used for light construction, boat roofing and weaving and to build walls for cottages or houses. Around 16,868 MT of *golpatta* was collected during 2014–2015 (DoF 2015). An estimated 67 MT of honey and 63 MT of wax were harvested from the Sundarbans in 2014–2015 (Table 16.3). Among other non-wood products, some plant products such as *keora* fruits (*Sonneratia apetala* Buch.-Ham.) and nectar from *N. fruticans* are also collected for food and drink by the Sundarbans communities.

16.3.2 Cultural Services

Although the cultural and spiritual values of mangroves remain very difficult to be converted into monetary values (UNEP 2014), the Sundarbans is culturally very important habitat for the local communities and beyond. Each year Hindu pilgrims from different corners of the country travel to the region to participate in a religious festival named "*Rush Mela*" taking place in the forests of the Sundarbans. In recent years, the Sundarbans became an excursion attraction for students. It has also become a site of researches and experiments, particularly to study patterns of global environmental changes as many mangrove species serve as indicator species of environmental fluctuations. The economic benefits of the cultural services of the Sundarbans come mainly from tourism revenues. The scenic beauty, river cruise, wildlife watching, and trekking activities in the Sundarbans attract a large score of tourists each year. In 2014–2015, a total of 96,949 native and 3,868 foreign tourists visited the Bangladesh Sundarbans, generating around US$ 144,832 as revenue (Table 16.3). This is indicative of the high potential, to reap economic benefits from tourism, of the Sundarbans. Tourism also creates employment opportunities for local communities, through an introduction of widespread ecotourism in the Sundarbans region. However, such opportunities remain rather untapped now.

The sociocultural context and the ecological environment of the Sundarbans also strengthen the religious beliefs of the forest goers. Before going to the forest, local Hindu communities perform various rituals to worship the goddess *Bon Bibi* (The Lady of Forest) in a way that is different from the mainstream Hindu beliefs. Statues of the forest goddess *Bon Bibi* are erected throughout the forest for worship. It is a belief that *Bon Bibi* is always vigilant in the forest and has the power to protect and save lives of all those who seek protection. This ritual and associated beliefs, they feel, provide them with spiritual services and mental strength to engage in risky professions in the forest (Uddin 2011; Islam and Chuenpagdee 2013). In the cultural landscape of the Sundarbans, specialized professional livelihood segments such as *bawali* (timber collector), *mowali* (honey collector) and *chunar* (oyster and snail collector) have evolved which are not seen elsewhere in Bangladesh.

Table 16.2 Major fishery species in the Sundarbans wetland, Bangladesh

Scientific name	English name	Local name	IUCN (2015) global status[a]
Lates calcarifer (Bloch 1790)	White Sea Bass, Asian Sea Bass, *Barramundi*	Coral, Vetki	NE
Congresox talabonoides (Bleeker 1853)	Indian Pike Conger	Kamila/conger-pike eel	NE
Drepane longimana (Bloch & Schneider 1801)	Sickle fish, banded sickle fish, concertina fish	Bishtara	NE
Mystus gulio (Hamilton 1822)	Long whiskers catfish	Nuna tengra	LC
Rhinomugil corsula (Hamilton 1822)	Corsula, corsula mullet	Bata/Khorsula/Khalla	LC
Liza parsia (Hamilton 1822)	Gold-spot mullet	Bata, Parshe bata, Parse	NE
Plotosus canius (Hamilton 1822)	Gray eel catfish, striped catfish eel	Kain magur	NE
Pangasius pangasius (Hamilton 1822)	Fatty catfish	Pungus/desi pungus	LC
Raconda russeliana (Gray 1831)	Smooth back herring, Russell's smooth-back herring	Fatra/Phansha	LC
Tenualosa ilisha (Hamilton 1822)	Hilsa shad, hilsa	*Ilish*	LC
Tenualosa toil (Valenciennes 1847)	Toli shad or Chinese herring	Chandana ilish	NE
Hilsa kelee (Cuvier 1829)	Kelee shad	Gurta ilish	NE
Cynoglossus cynoglossus (Hamilton 1822)	Bengal tongue sole/ tonguefish	Kukurjeeb	NE
Cynoglossus arel (Bloch & Schneider 1801)	Large scale tonguesole	Kukurjeeb	NE
Dasyatis zugei (Müller & Henle 1841)	Pale-edged stingray/ sharp-nose stingray	Saplapata	NT
Dussumieria acuta (Valenciennes 1847)	Rainbow sardine/common sprat	Goru mash	NE
Coilia dussumieri (Valenciennes 1848)	Gold spotted grenadier anchovy	Boiragi/Olua	NE

(continued)

Table 16.2 (continued)

Scientific name	English name	Local name	IUCN (2015) global status[a]
Coilia neglecta (Whitehead 1967)	Whitehead's/neglected grenadier anchovy	Boiragi/Olua	LC
Setipinna phasa (Hamilton 1822)	Scaly hairfin anchovy	Phasa/Moduphasa	LC
Stolephorus indicus (Van Hasselt 1823)	Indian/Hardenberg's anchovy	Sea mola	NE
Acentrogobius cyanomos (Bleeker 1849)	Gobi	Nuna baila	NE
Apocryptes bato (Hamilton 1822)	Gobi mudskipper	Baila, Chewa bele	NE
Boleophthalmus boddarti (Pallas 1770)	Blue-spotted mudskipper, Boddart's goggle-eyed goby	Dahuk	LC
Odontamblyopus rubicundus (Hamilton 1822)	Red eel goby	Raja chewa	NE
Trypauchen vagina (Bloch & Schneider 1801)	Burrowing goby	Chewa	NE
Pisodonophis boro (Hamilton 1822)	Rice-paddy eel	Kharu/Bamos/Kecho baim	LC
Platycephalus indicus (Linnaeus 1758)	Bartail flathead, Indian flathead, Indo-Pacific flathead	Char bele/Mur baila	DD
Lutjanus johnii (Bloch 1792)	John's snapper, golden snapper	Ranga choukka	NE
Eleutheronema tetradactylum (Shaw 1804)	Four finger threadfin, Indian salmon, blunt-nosed salmon	Lakkha/Rawas	NE
Polynemus indicus (Shaw 1804)	Indian threadfin, Indian salmon	Lakkha, Lakhua	NE
Polynemus paradiseus (Linnaeus 1758)	Paradise threadfin, Indian salmon	Taposi, Tapasi	NE
Dendrophysa russelii (Cuvier 1829)	Goatee croaker	Poa	NE
Johnius belangerii (Cuvier 1830)	Belanger's croaker/jewfish	Poa	NE
Johnius dussumieri (Cuvier 1830)	Sin croaker	Poa	NE
Pennahia argentata (Houttuyn 1782)	Silver jaw fish	Lalpoa/Vola fish	NE
Johnius macropterus (Bleeker 1853)	Big-snout croaker/large-fined croaker	Poa, large fin poa	NE

(continued)

Table 16.2 (continued)

Scientific name	English name	Local name	IUCN (2015) global status[a]
Panna microdon (Bleeker 1849)	Panna croaker	Poa, jewfish	NE
Johnius carutta (Bloch 1793)	Karut croaker	Karut poa	NE
Lutjanus erythropterus (Bloch 1790)	Crimson snapper	Photo poa	NE
Scomberomorus guttatus (Bloch & Schneider 1801)	Indo-Pacific king mackerel, Indian Spanish mackerel	Maittya	DD
Rastrelliger kanagurta (Cuvier 1816)	Indian mackerel	Champa	DD
Thunnus albacares (Bonnaterre 1788)	Yellowfin tuna, yellow-finned albacore	Surma	NT
Sillaginopsis panijus (Hamilton 1822)	Flathead/gangetic sillago	Tulardandi/Hundra	NE
Pampus argenteus (Euphrasen 1788)	Silver or white pomfret	Folichanda	NE
Pampus chinensis (Euphrasen 1788)	Chinese silver pomfret	Rupchanda	NE
Harpadon nehereus (Hamilton 1822)	Bombay duck or bummalo	Loitta	NE
Netuma thalassina (Rüppell 1837)	Sea catfish	Guizza	NE
Arius arius (Hamilton 1822)	Threadfin sea catfish	Mad/Kata	NE
Terapon jarbua (Forsskål 1775)	Jarbua terapon, tiger perch, crescent grunter	Gogo/Barguni	LC
Lobotes surinamensis (Bloch 1790)	Tripletail	Somudra koi	NE
Lepturacanthus savala (Cuvier 1829)	Savalai hairtail/spiny hairtail	Churi	NE
Trichiurus lepturus (Linnaeus 1758)	Large-headed hairtail, large-head ribbonfish, Cutlass fish, gray ribbon fish	Churi/cutlass fish	LC
Pomadasys argenteus (Forsskål 1775)	White grunter, lined silver grunter, silver javelin	Karkara	LC
Dussumieria acuta (Valenciennes 1847)	Sharp-nosed sprat, rainbow sardine	Nailla	NE
Sardinella gibbosa (Bleeker 1849)	Goldstripe sardinella	Khoira	NE

Source: Field observation during 2005–2015

[a]IUCN (2015) Global status of the species according to the IUCN Red List of Threatened Species. Version 2015-4. Not evaluated (*NE*) (taxon has not yet been assessed for the IUCN Red List), data deficient (*DD*), least concern (*LC*), near threatened (*NT*)

16.3.3 Regulatory Services

Though there are lots of erosion and accretion in the Sundarbans region, some evidence suggests that the Sundarbans, in general, is currently growing in landmass through sediment accumulation (Inman 2009). Conversely, some other studies (Aziz and Paul 2015) suggest a net loss of land in the Sundarbans. Nevertheless, it is an undisputable fact that mangrove forest serves as a bio-shield against storm surges; the Sundarbans thus protect coastal habitats from tropical cyclones that otherwise could be more devastating. The Sundarbans protect approximately ten million people of Bangladesh from any cyclonic storms (CEGIS 2007). During cyclones Sidr (2007) and Aila (2009), the Sundarbans mangrove forest acted as a shield that helped to minimize the calamitous impacts of these events by reducing storm surge velocity and stabilizing sedimentation (Barbier 2006; CEGIS 2007; Shamsuddoha et al. 2013). Past cyclone events, such as the devastating 1991 cyclone Gurky that struck the Southeastern district of Chittagong, proved that the absence of mangrove forests could have resulted in a greater number of deaths, and more extensive losses and damages (Barua et al. 2010). The SMF is also important in terms of carbon sequestration. In 2010, the total carbon estimated in the Sundarbans was about 56 million MT. Bangladesh is a signatory to the Copenhagen Accord, UN Framework Convention on Climate Change, and thus can sell the Sundarbans carbon at US$ 05–15 per ton that would be about US$ 280–840 million per year (Aziz and Paul 2015).

16.4 Threats and Stressors

The Sundarbans is situated in one of the most populated and largest deltas in the world, which is also a major locus of global poverty. People depend on the Sundarbans for a wide range of services (Table 16.3), which inevitably result in some degradation of the wetland ecosystem, further compounded by the global environmental changes. Several threats and stressors are identified that caused downward shift in the quality of the ecosystem and adversely affect ecosystem services. Such factors include overexploitation of resources, pollution, and other anthropogenic disturbances and severe environmental changes including disturbances from tropical cyclones and globalization of market.

Nearshore fisheries areas of the Sundarbans ecosystem are believed to be overexploited. Among the commercial fish species, *Tenualosa ilisha* (Hamilton 1822), *Lates calcarifer* (Bloch 1790), *Pangasius pangasius* (Hamilton 1822), *Plotosus canius* (Hamilton 1822), and mud crab *S. serrata* are considered overexploited (Rouf and Jensen 2001). In the peripheral areas the mangrove forest, many agricultural lands were converted to shrimp farms that bought massive socio-ecological changes to the region. In the absence of labor-intensive agriculture, many people became dependent upon the Sundarbans to earn a living, which exacerbated overexploitation of the resources. Particularly, the use of fine-meshed bag nets and mosquito nets for extensive shrimp PL collection has been blamed for a massive loss of

Table 16.3 Forest products and revenue (in US$) collected during 2001–2002 and 2014–2015 from the Bangladesh Sundarbans

Types of ecosystem services		2001–2002		2014–2015	
Provisioning	Produces (unit)	Amount	Revenue	Amount	Revenue
	Excoecaria agallocha (ft^3)	84,630	33,187	6,026	3,894
	Ceriops decandra (no.)	15,865 (MT)	47,742	118,451 (no)	7,520
	Thatching material *Nypa fruticans* (MT)	17,525	33,123	16,868	57,338
	Thatching material grass (MT)	3,621	790	668	225
	Phoenix paludosa	543 (MT)	348	19,761 (no)	1,044
	Fuel wood (ft^3)	69,370	47,523	14,455	10,190
	Honey (MT)	84	7,970	67	24,048
	Wax (MT)	23	1,665	63	8,108
	Fish (MT)	2,061	58,374	3432	158,368
	Crab (MT)	123	2,148	1,123	52,026
	Dry fish (MT)	1,095	18,998	2,773	179,761
Cultural	Tourist (no.)	59,169	14,588	100,817	144,832

Source: DoF (2015)

biodiversity of other nontarget aquatic species that are discarded after collection. Rising demand of shrimp and live crabs also contributes to overexploitation of those species. At present, live crabs are exported to approximately 23 countries (such as Malaysia, Singapore, Taiwan, China, Japan, Korea, and Thailand) with high consumer demand (Table 16.4, Ferdoushi et al. 2010).

Overexploitation also seems to result from noncompliance with regulations and rent dissipation due to corrupt practices in the Sundarbans. Forest goers have to pay a certain fee for obtaining permits to collect forest products. This management rule allegedly promotes corruption, as they need to pay 10–15 times the amount of the actual fees for the permit. Khoda (2008) estimates that forest officials in the Sundarbans extort around 2.3 million BDT (about US$ 28,400) per year from the fishers. To recover these additional expenses, harvesters usually resort to illegal activities such as illegal logging and fishing with poison, creating thus a vicious circle of over exploitation and corruption that negatively affects the long-term sustainability of ecosystem services. This eventually reinforces impoverishment of forest dependent communities.

A number of local development and economic activities pose an immediate concern for the Sundarbans wetlands. Various cargo vessels use riverways of the Sundarbans to reach the second largest seaport of the Bangladesh, Mongla, situated near the forest. Discharge of oil and other pollutants to the Sundarbans waterway is a regular phenomenon. During December 2014, a tanker carrying 75,000 gallons of

Table 16.4 Ecosystem services from the Sundarbans and their usage pattern

Extracted resources	Usage pattern	Harvesting season/peak season	Countries involved in utilization
Fish *(Tenualosa ilisha, Lates calcarifer, Pangasius pangasius, Plotosus canius)*	Fresh and dried food	All the year round	Bangladesh, Middle East (dried fish) India (hilsa shad)
Crab (*Scylla serrata)*	Live food	All the year round	Southeast Asia
Shrimp (adult and fingerlings)	Frozen food, input in aquaculture pond for rearing	All the year	EU and USA (frozen seafood)
Timber	Pole, furniture, housing	December to March	Bangladesh
Other non-wood products	*N. fruticans* (nipa palm) for thatching, malia grass for thatching matting, reed for fencing, keora fruits as food and culinary, nipa nectar as drink	Mid November to Mid March	Bangladesh
Honey, wax	Honey as food, medicine, wax for commercial uses	March to June	Bangladesh
Molluscs (oyster, gastropods)	Food and lime	All the year round	Bangladesh
Aesthetic	Tourism	All the year round with peak season in winter	Bangladesh, EU, Japan, USA

oil sank in the Shela River in the Sundarbans (GoB 2014; Aziz and Paul 2015). Within 1 day, the oil spread at least 20 km upstream and 20 km downstream. The oil was deposited on the soil, plants leaves, roots, pneumatophores, stems, and floating fruits (Chowdhury et al. 2014; GoB 2014). Only 18 species of phytoplankton (primary producer of the food chain) were recorded in the oil-contaminated areas, and their abundance was very poor (24–67 units/l), while 47 phytoplankton species were recorded in the Sundarbans earlier, and their abundance was 226–456 units/l (Chowdhury et al. 2014). Industrial pollutants, heavy metals, pesticides, insecticides, drugs, antibiotics, and effluents from Khulna city and adjacent shrimp farms may also compromise the capacity of the forest in delivering ecosystem services. The proposed coal-fired power plant at Rampal is another potential threat to the forest habitat as it will release approximately 8 million tons of CO_2, 0.75 million tons of fly ash and 0.2 million tons of bottom ash annually to the Sundarbans wetlands (Aziz and Paul 2015).

Globally, wetland ecosystems are vulnerable to changes in the quantity and quality of their water supply, and anticipated climate change will likely alter further the hydrological regimes of wetlands (Erwin 2009). The high-elevation Himalayan glaciers, which provide up to half of the dry season flow in the Ganges and Brahmaputra Rivers, are gradually thinning and threatening the supply of freshwater to the region

(Inman 2009). The Ganges flow has been drastically reduced in Bangladesh after the construction of the Farakka Barrage on the Ganges River in India. The reductions of water flows already have caused dramatic ecological changes in the forest and trailing active ecosystems functions. The soil and water salinity has exceeded upper thresholds (20 ppt) in most parts of the Sundarbans wetlands. The siltation in the Sundarbans has increased, and sediment trapping has been aided by pneumatophores and dense roots of mangroves. Increased salinity and sedimentation caused shifting in fish habitat by destroying or reducing the quality of the ground. The dominant species of sundri (*H. fomes*) and goran (*C. decandra*) are affected by top-dying diseases (Islam and Gnauck 2008).

In view of the future projection, the effects of climatic pressures are expected to continue and probably intensify in mangrove wetlands. At least 70 major cyclones reached the coastal region of Bangladesh over the past two centuries, and the Sundarbans mangroves have acted as the first physical barrier, therefore reducing the loss and damage to a great extent. As a consequence, the forest itself was also exposed to loss and damage, as observed, for instance, from the effects of the cyclone Sidr in 2007, when 36% of the mangrove area was severely damaged (CEGIS 2007). Cyclonic storms and other natural events such as flood, tidal surges, and erosion affect the Sundarbans by uprooting plants, damaging branches and stems, eroding soils, human settlements, and lives. A study shows that in the aftermath of cyclone Aila, almost 80% of regional (local) workers lost their jobs, among which 40% are bound to change their profession (Mallick et al. 2011). A majority of the people living in the impact zone turned to shrimp PL collection as their first survival strategy. Climate change-related risk is set to increase for the Sundarbans. With 1 m rise in sea level, the Sundarbans are likely to disappear, which may cause the demise of the tiger and other wildlife (Inman 2009), together with the ecosystem goods and services it provides to the numerous riparian communities.

16.5 Conclusions and Recommendations

The wetlands in Asia are increasingly vulnerable to global environmental changes. Warmer climate together with droughts and declining precipitation in most of the river delta regions, for instance, Bangladesh, have led to the shrinking and drying up of wetlands as well as degradation of ecosystems. Moreover, different anthropogenic disturbances such as habitat destruction, loss of biodiversity, and pollution with ever-increasing population pressure have further compounded the climate-related risks that hamper their capacity to deliver ecosystem services. Consequently, the unique Sundarbans wetland, which is instrumental in providing a wealth of goods and services to the communities of its impact zone, is already under serious threat. Given that frequency and intensity of extreme climatic events like cyclones are anticipated to increase, the future bio-shield role of the Sundarbans is of paramount importance. The Sundarbans also acts as a buffer against livelihood crises in the impoverished areas. When all other gainful livelihood options are lost, affected people largely depend on the wetland services as a "last resort" for immediate needs, survival, and income, as evident in the aftermath of the cyclone Aila in 2009. Unfortunately, policy makers are unaware of real-world values of ecological goods and services.

In view of the above, the Sundarbans requires a transformation in governance structure, one that will focus on restoring ecological diversity and fostering economic diversity in line with rapidly changing socio-ecological context. For each commercially exploitable species, the optimum harvest limits (e.g., maximum economic yield and maximum sustainable yield) need to be determined to control the level of effort. Interventions are required to create alternative economic opportunities in the region in order to release the pressure on mangrove resources. To this end, this study calls for the attention of policy makers to manage the Sundarbans ecosystem sustainably that is economically viable, socially equitable, and ecologically sound.

Acknowledgments We thank the anonymous reviewers of this chapter and the book editor B. Anjan Kumar Prusty for their help and suggestions. The manuscript has benefited from language editing and useful comments from Andrew M Song, Svein Jentoft, and SM Sharifuzzaman. We also thank Subrata Sarker for his help to draw the map.

References

Alongi DM (2008) Mangrove forests: resilience, protection from tsunamis and responses to global climate change. Estuar Coast Shelf Sci 76:1–13. doi:10.1016/j.ecss.2007.08.024

Alongi DM (2009) Paradigm shifts in mangrove biology. In: Perillo GME, Wolanski E, Cahoon DR, Brinson MM (eds) Coastal wetlands: an integrated ecosystem approach. Elsevier, Amsterdam, pp 615–640

Aziz A, Paul AR (2015) Bangladesh Sundarbans: present status of the environment and biota. Diversity 7:242–269. doi:10.3390/d7030242

Balmford A, Bruner A, Cooper P, Costanza R, Farber S et al (2002) Economic reasons for conserving wild nature. Science 297:950–953. doi:10.1126/science.1073947

Barbier EB (2006) Natural barriers to natural disasters: replanting mangroves after the tsunami. Front Ecol Environ 4(3):124–131

Barua P, Chowdhury MSN, Sarker S (2010) Climate change and its risk reduction by mangrove ecosystem of Bangladesh. Bangladesh Res Pub J 4(3):218–225

Brander LJ, Wagtendonk AS, Hussain S, McVittie A, Verburg PH, de Groot RS, vanderPloeg S (2012) Ecosystem service values for mangroves in Southeast Asia: a meta-analysis and value transfer application. Ecosyst Serv 1:62–69

CEGIS (2007) Effect of cyclone Sidr on the Sundarbans a preliminary assessment. Center for Environmental and Geographic Information Services (CEGIS), Dhaka, pp 1–8

Chaffey DR, Miller FR, Sandom KH (1985) A forest inventory of the Sundarbans, Bangladesh. Project report 140, Overseas Development Administration, Land Resources Development Centre, Tolworth Tower, Surbiton, Surrey, England, UK.KT6 7DY, p 196

Chowdhury AH, Mannan MA, Gosh PK, Akbar MA (2014) Draft report of the research impact of oil spillage on the environment of Sundarbans (world largest mangrove forest) in Bangladesh, pp 1–16. http://ncbd.org/wp-content/uploads/2014/12/Impact-of-oil-spills-on-the-Sundarbans_AHC.pdf. Accessed 12 Feb 2016

Clavel J, Julliard R, Devictor V (2011) Worldwide decline of specialist species: toward a global functional homogenization. Front Ecol Environ 9:222–228

DoF (2010) Integrated resources management plans for the Sundarbans. Department of Forest, Ministry of Environment and Forests, Dhaka, p 325 http://pdf.usaid.gov/pdf_docs/pnaec417.pdf. Accessed 12 Feb 2016

DoF (2015) Forest production and revenue generation from the Sundarbans from 2001–02 to 2014–15. Department of Forest, Ministry of Environment and Forests, Dhaka (unpublished).

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M (2011) Mangroves among the most carbon-rich forests in the tropics. Nat Geosci 4:1–5

Duke NC, Meynecke JO, Dittmann S, Ellison AM, Anger K, Berger U, Cannicci S, Diele K, Ewel KC, Field CD, Koedam N, Lee SY, Marchand C, Nordhaus I, Dahdouh-Guebas F (2007) A world without mangroves? Science 317:41–42

Erwin KL (2009) Wetlands and global climate change: the role of wetland restoration in a changing world. Wetl Ecol Manag 17(1):71–84

FAO (2010) Global forest resources assessment. FAO Forestry Paper 163. Food and Agriculture Organization of the United Nations Rome, Italy, p 378. http://www.fao.org/docrep/013/i1757e/i1757e.pdf. Accessed 12 Feb 2016

Ferdoushi Z, Xiang- guo Z, Hasan MR (2010) Mud crab (*Scylla* sp.) marketing system in Bangladesh. As J Food Ag-Ind 3(02):248–265

FRSS (2014) Fisheries statistical yearbook of Bangladesh. Fisheries Resources Survey System (FRSS), Department of Fisheries, Bangladesh. Vol 30, p 52

Giri C, Pengra B, Zhu Z, Singh A, Tieszen LL (2007) Monitoring mangrove forest dynamics of the Sundarbans in Bangladesh and India using multi-temporal satellite data from 1973 to 2000. Estuar Coast Shelf Sci 73:91–100

GoB (2014) Sundarbans oil spill assessment: joint United Nations – Government of Bangladesh Mission. Joint UNEP/OCHA Environment Unit: Geneva, Switzerland. p 106. http://reliefweb.int/sites/reliefweb.int/files/resources/Sundarbans_Report_18Feb2015_FINAL_01.pdf. Accessed 12 Feb 2016

Hoq ME (2007) An analysis of fisheries exploitation and management practices in Sundarbans mangrove ecosystem. Ocean Coast Manag 50:411–427

Horowitz P, Finlason C, Weinstein P (2012) Healthy wetlands, healthy people: a review of wetlands and human health interactions. Ramsar Technical Report No. 6. Secretariat of the Ramsar Convention on Wetlands, Gland, Switzerland, & The World Health Organization, Geneva, Switzerland, p 114. http://www.ramsar.org/sites/default/files/documents/pdf/lib/rtr6-health.pdf. Accessed 12 Feb 2016

Hussain SA, Badola R (2010) Valuing mangrove benefits: contribution of mangrove forests to local livelihoods in Bhitarkanika conservation area east coast of India. Wetl Ecol Manag 18:321–331

Inman M (2009) Where warming hits hard. Nature 3:18–21

Islam MM, Chuenpagdee R (2013) Negotiating risk and poverty in mangrove fishing communities of the Bangladesh Sundarbans. Mar Stud 12(7):1–20

Islam SN, Gnauck A (2008) Mangrove wetland ecosystems in Ganges-Brahmaputra delta in Bangladesh. Front Earth Sci China 2(4):439–448. doi:10.1007/s11707-008-0049-2

IUCN (2015) The IUCN red list of threatened species. Version 2015–4. <www.iucnredlist.org>. Accessed 02 Jun 2016

Kamal D (1999) Biodiversity conservation in the coastal zone of Bangladesh. M.Sc Thesis. Dalhousie University Halifax, Novascotia, Canada

Khoda ME (2008) Transparency and accountability in forest conservation and management: problems and way out. Transparency Int Bangladesh, Dhaka, p 11. http://www.ti-bangladesh.org/beta3/images/max_file/rp_es_forest_08.pdf. Accessed 13 Feb 2016

Lee SY, Primavera JH, Dahdouh-Guebas F, McKee K, Bosire JO, Cannicci S, Diele K, Fromard F, Koedam N, Marchand C, Mendelssohn I, Mukherjee N, Record S (2014) Ecological role and services of tropical mangrove ecosystems: a reassessment. Glob Ecol Biogeogr 23:726–743

Mallick B, Rahaman KB, Vogt J (2011) Coastal livelihood and physical infrastructure in Bangladesh after cyclone Aila. Mitig Adapt Strateg Glob Chang 16(6):629–648

MEA (2005) Ecosystems and human well-being: current state and trends. The millennium ecosystem assessment series xxi. Island Press, Wahington, DC p 47. http://www.unep.org/maweb/documents/document.766.aspx.pdf. Accessed 12 Feb 2016

Mukherjee N, Sutherland WJ, Dicks L, Huge J, Koedam N et al (2014) Ecosystem service valuations of mangrove ecosystems to inform decision making and future valuation exercises. PLoS One 9(9):1–9. doi:10.1371/journal.pone.0107706

Rouf MA, Jensen KR (2001) Coastal fisheries management and community livelihood: possible strategy for the Sundarbans, Bangladesh. ITCZM monograph series, no 04. Asian Institute of Technology, Pathumthani, p 24

Ruckelshaus M, Doney SC, Galindo HM, Barry JP, Chan F, Duffy JE, English CA, Gaines SD, Grebmeier JM, Hollowed AB, Knowlton N (2013) Securing ocean benefits for society in the face of climate change. Mar Policy 40:154–159

Shamsuddoha M, Islam M, Haque MA, Rahman MF, Roberts E, Hasemann A, Roddick S (2013) Local perspective on loss and damage in the context of extreme events: insights from cyclone-affected communities in coastal Bangladesh. Center for Participatory Research and Development (CRPD), Dhaka, p 26

Spalding M, Kainuma M, Collins L (eds) (2010) World atlas of mangroves. Earthscan, London, pp xvi–+319

Uddin S (2011) Beyond national borders and religious boundaries: Muslim and Hindu veneration of Bonbibi. In: Schmalz MN, Gottschalk P (eds) Engaging South Asian religions: boundaries, appropriations, and resistances. State University of New York Press, Albany, pp 61–81

Uddin MS, de Ruyter van Steveninck E, Stuip M, Shah MAR (2013) Economic valuation of provisioning and cultural services of a protected mangrove ecosystem: a case study on Sundarbans reserve forest. Bangladesh Ecol Ser 5:88–93

UNEP (2014) In: Bochove J, Sullivan E, Nakamura T (eds) The importance of mangroves to people: a call to action. United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, p 128

Vo TQ, Kuenzer C, Oppelt N (2015) How remote sensing supports mangrove ecosystem service valuation: a case study in Ca Mau province, Vietnam. Ecosyst Serv 14:67–75

Wetlands: Biodiversity and Livelihood Values and Significance with Special Context to Bangladesh

17

A.K. Yousuf Haroon and Golam Kibria

Abstract

Wetlands provide various ecosystem goods and services to humans. Rice, the staple food of about 50% of global population and consumed at the rate of one-fifth of the total global calorie count, is grown in wetland systems. The total area of wetlands in Bangladesh is about 7–8 million ha, which constitutes about 50% of the land surface of the country. Wetlands of Bangladesh encompass *haors* (freshwater marshes of bowl or saucer-shaped shallow depression), *baors* (oxbow lakes – dead arms of a river), *beels* (saucer-shaped deeper part of the floodplain landscape), fishponds and *dighi* (large ponds), flooded rice lands and floodplains, natural lakes, man-made reservoirs (Kaptai Lake), and coastal (Sundarbans) and marine (St. Martin's Coral Island) areas. Wetlands are rich in flora and fauna (300 plant species, 400 vertebrate species, and 260 freshwater fish species are dependent on wetlands of Bangladesh). Some wetlands of Bangladesh are of national and international significance such as Tanguar *haor* (Ramsar and an Ecologically Critical Area), Hakaluki *haor* (Ecologically Critical Area), Sundarbans (Ramsar and UNESCO World Heritage Site and Ecologically Critical Area), and St. Martin's Coral Island (Ecologically Critical Area). About two-thirds of people in Bangladesh depend on wetlands for a variety of purposes including water (drinking, irrigation), food production (agriculture, aquaculture), fishing, livestock grazing, bird hunting, fire-/fuelwoods, medicinal plants, wild food, honey, waterway transportation, harvesting grasses and seaweeds, and tourism/recreational business. Some poorest of the poor in the vicinity depend

A.K. Yousuf Haroon (✉)
Food and Agriculture Organization (FAO) of the UN, Dhaka, Bangladesh
e-mail: dharoon@ymail.com; akyousuf.haroon@fao.org

G. Kibria
School of Applied Sciences, Royal Melbourne Institute of Technology (RMIT) University, Melbourne, Australia
e-mail: kibriagolam0@gmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_17

totally on the goods and services of the wetland for livelihood. Apart from biodiversity and livelihood support, wetlands have additional significances as a source and sink for greenhouse gases and in mitigation of disasters in Bangladesh. Livelihood diversification, awareness, and education of local communities on preservation and conservation of wetlands would be needed to reduce pressure on wetland resources.

Keywords
Bangladesh • Biodiversity • Ecosystem goods and services • Wetlands

17.1 Introduction

The Ramsar classification of wetland types include 42 types of wetlands, which belong to one of the three broad categories: inland wetlands (e.g., rivers, lakes, creeks), marine/coastal wetlands (e.g., shallow marine waters, estuaries, coral reefs), and human-made wetlands (aquaculture ponds and permanently or temporarily inundated agricultural lands such as rice paddies, salt pans, reservoirs, gravel pits, sewage farms, and canals). There is also a range of other wetland classifications used for different purposes, based on hydro-geomorphology and/or vegetation characteristics, such as:

- Marine (coastal wetlands, including coastal lagoons, rocky shores, and coral reefs)
- Estuarine (including deltas, tidal marshes, and mangrove swamps)
- Lacustrine (wetlands associated with lakes)
- Riverine (rivers and wetlands along rivers and streams)
- Palustrine (marshes, swamps, and bogs)

17.1.1 Importance and Role of Wetlands

Rice, the staple food of about 50% of global population and consumed at the rate of one-fifth of the total global calorie intake, is grown in wetlands. Wetlands, among the most productive and biodiversity-rich areas, filter pollutants and sequester carbon, whereas rivers transport water and nutrients from the catchment downstream. Lakes serve as sediment and carbon sinks (Fischlin et al. 2007). In addition, food (fish and aquatic plants), medicine, and building materials are available from wetlands because of the rich living aquatic resources. Living aquatic resources, as common property natural resources (Nishat 1993), from wetlands play an essential role in people's livelihood in rural areas in many parts of the world including Bangladesh. The most significant of these are fishes, prawns, crabs, molluscs, and clams that have all or part of their life cycle within a wetland system. Fresh and saltwater fishes are the main source of protein for about 3 billion people globally (at least 20% of their animal protein intake) and an important source of essential vitamins and omega-3-polyunsaturated fatty acids (Kibria et al. 2010). In addition, fish generates a fishing industry that provides 80% of income and employment in developing countries. In countries like Bangladesh, Myanmar, Thailand, Cambodia, and Vietnam, where rice paddies are predominant, rice consumption reaches up to 70%. From wetlands such as mangroves, fuelwood, salt (produced by evaporating seawater), animal fodder, traditional medicines (e.g., from mangrove bark), fibers for textiles, and dyes and tannins are extensively sourced. Various studies also reveal that such wetlands have tremendous potentials for integrated concurrent rice-fish culture and fish nursery operations (Haroon et al. 1992; Haroon and Pittman 1997).

Production cycles in wetlands are closely linked with seasonal changes in temperature and precipitation and therefore are affected by seasonal climate variability or long-term climate changes. Climate change will have significant impacts on wetland ecology, biodiversity, and livelihoods of people connected with it. Wetlands in a natural state are crucial for humans mainly because of their capacity for storing large quantities of freshwater, mitigating the impact of floods and droughts for a whole area and for their enormous biological productivity that can be harvested in the forms of fish, wood, reed, etc. Some wetland types like peat swamps are inaccessible and unproductive. Wetlands, in general, provide the following ecosystem goods and services.

Goods: wetland nonfood products, freshwater, food for humans, genetic materials, biomass production, biodiversity, support for food chains, storage of floodwater, and production of logs, fuelwoods, peat, fodder, etc.

Cultural services: recreation and tourism, natural heritage values, scientific and educational, and spiritual and inspirational

Regulating services: groundwater recharge, shoreline stabilization and reduction of erosion, sediment trapping, nutrient retention/removal, habitat for wildlife, hazard reduction (flood control, storm protection), maintenance of hydrological regimes, water transport, pollution control and detoxification, microclimate stabilization (IWRB 1992), climate regulation, and carbon source and sinks

17.2 Wetlands of Bangladesh

Wetlands of Bangladesh encompass a wide variety of dynamic ecosystems, *viz.*, mangrove forest (about 577,100 ha), natural lakes, man-made reservoir (Kaptai Lake), freshwater marshes, estuaries, and seasonal inundated floodplains and paddy fields. The freshwater marshes include 114,161 ha of saucer-shaped natural depressions locally called as *beels*/*haors*, about 5,488 ha of oxbow lakes locally called as *baors*, and 371,309 ha of fishponds and *dighi* (large ponds). The total area of wetlands, both inland freshwater and tidal saltwater wetlands, in Bangladesh, comes to about 50% of the land surface of the country (Table 17.1 and Fig. 17.1). Considering the major rivers (700 rivers), their tributaries and streams, the major wetlands in Bangladesh constitute the fluvial or floodplains, *viz.*, Sundarbans mangroves

Table 17.1 Wetlands of Bangladesh based on their land types as well as hydrological and ecological functions

Wetlands	Types	Characteristics
Saltwater	Marine	Shallow waters at low tide, e.g., bay, coral reefs like St. Martin's Island
	Estuarine	Intertidal sand, mud or salt basins with specific vegetation, like newly accreted intertidal land, marshes, forests, and mangroves, e.g., the Sundarbans
	Lagoonal	Brackish to saline lagoons with narrow connection with the sea
Freshwater	Riverine	Rivers and streams with their tributaries including the *Chars*
	Lacustrine	Lakes, *beels*, or *jheels* of different sizes and shapes distributed all over the country, especially in the districts of Noakhali, Comilla, Brahmanbaria, Sylhet, Faridpur, Pabna, Rajshahi, Jessore, and Khulna
	Palustrine	Marshes and swamps with emergent vegetation or swamp forest of *Barringtonia acutangula* (Hijal), *Pongamia pinnata* (Koroch), *Crataeva nurvala* (Barun), *Trewia nudiflora* (Gotagamar), and *Salix tetrasperma* (Indian willow, Panijam). Associated with these at the edges of the water bodies are thick spiny bushes of wild rose, *Rosa clinophylla* (Jongli golap), and scrub - *Lippia javanica* (fever bush/lemon bush); *Ficus heterophylla* (Ludi sarbua in Chakma); and *Phyllanthus disticha* in the hoars of northeast region
Man-made		Aquaculture ponds (brackish and freshwater), irrigated lands and irrigation channels, saltpans or hydro-dam, e.g., the Kaptai Lake in Rangamati, brackish water shrimp farms (*ghers*) in the southwest coastal area (Satkhira)

(140,000 ha), Kaptai Lake (68,800 ha), Chalan *beel* (36,800 ha), Hakaluki *haor* (20,400 ha), Chakaria mangroves (20,000 ha), the Naaf river estuary (16,000 ha), Arial beel (14,400 ha), Hail *haor* (3,643 ha), Tanguar *haor* (2,802 ha), St. Martin's Coral Island and reef (800 ha), Kawadighi *haor* (414 ha), Dekhar *haor* (325 ha), Erail *beel* (320 ha), Dubriar *beel/haor* (150 ha), Meda *beel* (122 ha), Aila *beel* (106 ha), Ramsagar *dighi* (102 ha), Atadanga *haor* (102 ha), Kuri *beel* (73 ha), Bogakine Lake (60 ha), Baikka *beel*, Gopalganj-Khulna *beel*, *Beel* bhatia, Atrai basin, lower Punarbhaba floodplains, and Surma-Kushiara floodplains (Islam 2010). These wetlands form a unique mosaic of habitats, extremely rich in biodiversity. Wetlands are critically important in Bangladesh for water resources (rivers, *haors*), human settlements, biodiversity, agriculture/land resources, navigation and communication, and ecotourism. These wetlands have a wide range of ecological, socio-cultural, economic, and commercial importance and values in Bangladesh.

17.2.1 Inland Freshwater Wetlands

Floodplains, *beels* (low-lying depressions in the floodplain), *haors*, and *baors* (oxbow lakes) represent the inland freshwater wetlands. Some important wetlands

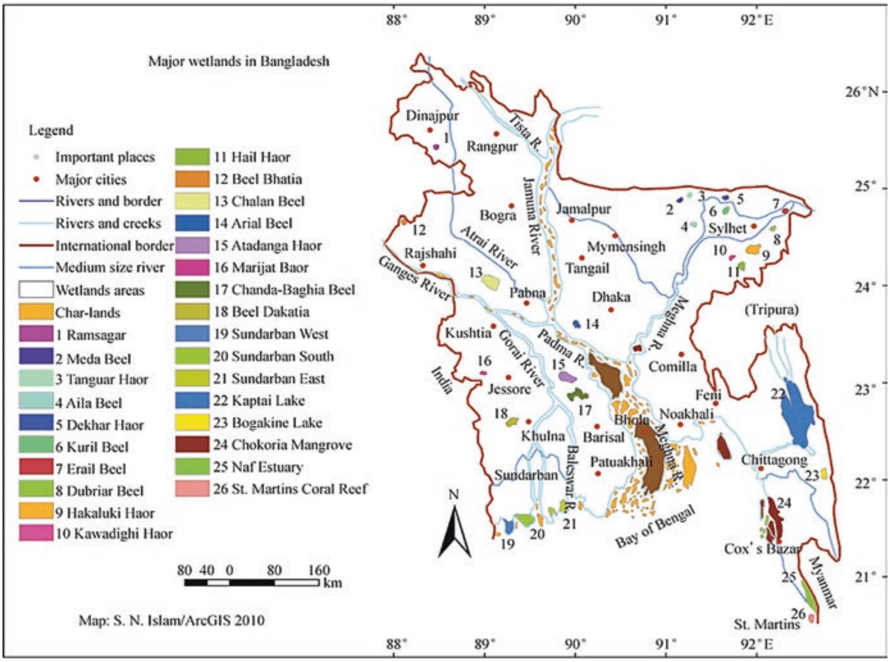


Fig. 17.1 The major wetlands in Bangladesh (Islam 2010); the Ecologically Critical Areas (ECAs)/Ramsar wetlands are *3*, Tanguar haor (Ramsar); *9*, Hakaluki haor (ECA); *19–21*, Sundarbans (west, south, and east (Ramsar and UNESCO World Heritage Site)); and *26*, St. Martin's Coral Island (ECA)

of the country are Chalan *beel*, lower Atrai basin, lower Punarbhaba floodplain, Gopalganj-Khulna *beels*, Arial *beel*, Akhaura terrace, Tanguar *haor*, and Hakaluki *haor* (Fig. 17.1) and Baikka *beel* of Surma-Kushiyara floodplain. Due to overexploitation of its natural resources and considering its critical conditions, the Government of Bangladesh declared Tanguar *haor* as an Ecologically Critical Area (ECA) in 1999. In 2000, the Tanguar *haor* was declared a Ramsar site of international importance. Hakaluki *haor*, with an area of 181.15 km^2, is one of the large marsh wetland systems of northeastern Bangladesh. It is spread over Barolekha, Kulaura, and Juri Upazila (subdistrict) of Moulvibazar district and Golapganj, Fenchuganj Upazila of Sylhet district. Ramsagar dighi (102 ha) is a man-made lake situated about 8 km south of the Dinajpur town. It was created by Raja Ram Nath in the mid-1750s. The lake is about 1,079 m wide from north to south and 192.6 m long from east to west. The Kaptai Lake (68,800 ha) is a man-made lake that was formed due to the Kaptai dam for hydroelectricity generation in the late 1960s in Rangamati, Chittagong.

Haors The *haors* are bowl-shaped natural depressions comprising of many individual *beels* formed during the monsoon, while the *beels* are low-lying depressions of the *haor* system retaining water even during the dry months of the year. The *haor*

Table 17.2 Major *haors* of Bangladesh

Basins/systems	Major *haors*
Eastern and lower Mymensingh basin	Baram *haor*, Banka *haor*, Habibpur *haor*, Maker *haor*, Makalkandi *haor*, Ghulduba *haor*
Foot of Meghalaya hills (Sylhet)	Tanguar *haor*, Shanir *haor*, Matian *haor*
East of the Tanguar haor system (Sylhet)	Dekhar *haor*, Pathar Chanli *haor*, Jhilkar *haor*, Jhinkar *haor*
Eastern rim of the basin	Jamaikata *haor*, Mahai *haor*, Nalua haor, Parua *haor*
Central Sylhet lowlands	Hakaluki *haor*, Chatal Bar *haor*, Haila *haor*, Kawadighi *haor*, Paglar *haor*
Southeastern hill ranges	Hail *haor*
South of the basin	Dingapota *haor*, Ganesher *haor*, Tolar *haor*, Anganer *haor*, Bara *haor*, Humaipur *haor*
Kishorganj district	Etna *haor*, Sania *haor*
Eastern Mymensingh	Khaliajuri *haor*
Southeast Mymensingh	Oail *haor*
Uncategorized	Dubriar *haor*, Chayer *haor*, Kangaler *haor*, Maijeil *haor*, Damrir *haor*, Panger *haor*, Kanamaiya *haor*, Ubdakhali *haor*, Balai *haor*, Bara *haor*, Gurmar *haor*

system is a complex of both lacustrine (lake) and palustrine (marsh) wetlands depending on the hydraulic behavior in different seasons. There are altogether 411 *haors* spread over 8,000 km^2 in the districts of Sunamganj, Sylhet, Moulvibazar, Habiganj, Netrokona, and Kishoreganj (Table 17.2 and Fig. 17.1). To protect the crops in the *haor* areas, the erstwhile landlords with the participation of the locals constructed dwarf dykes and appurtenant structures for early flood protection and irrigation. Since 1966, Bangladesh Water Development Board (BWDB), adopting " a better technology, has executed 46 Flood Control Drainage and Irrigation (FCDI) projects in the Sunamganj, Sylhet, Moulvibazar, Habiganj, Netrokona, and Kishoreganj districts. A total of about 0.29 million ha cultivable land has been made free from flash floods by implementing about 2,000 km submersible embankment and ancillary structures *[note: the main objectives of the FCDI are (a) to protect from crop losses*, *loss of life*, *and property damage due to floods and (b) to improve the physical environment to allow farmers to adopt improved agricultural practices and greater security for crop production].*

Oxbows Oxbow lakes are loops of meanders cut-off at times from rivers and gradually plugged with sediment. Locally, these are also known as *baor*, *jheel*, and commonly as *jalmohal*. Oxbows are quite common in Jessore, Faridpur, and Kushtia districts. Oxbows support a large variety of aquatic flora and fauna. During the monsoon season, oxbow lakes act as local water reservoirs and help to control the local flood level. In some areas, these lakes serve as valuable sources of irrigation during the dry season.

Fig. 17.2 A flooded haor wetland – during the lean season, most of the area of a haor may be dry (Photo courtesy: Md. Wahiduzzaman Sarker)

Floodplains Floodplain areas are the most hazard-prone areas of Bangladesh (Fig. 17.2). Elevation of the tidal floodplains from sea level is less than 1–3 m on the main rivers and estuarine floodplains. The floodplains of Bangladesh can be divided into four main regions: (i) the northwest region (in Dinajpur, Rangpur, Bogra, Rajshahi, and Pabna) between the Ganges and the Brahmaputra; (ii) the central region in Tangail, Dhaka, Comilla, and Noakhali, east of the Brahmaputra, Padma, and Lower Meghna; (iii) the main delta west of the Ganges-Padma and south to the coastal zone, in Kushtia, Jessore, Faridpur, Khulna, Barisal, and Patuakhali; and (iv) the northeast wetland regions of Sylhet, Sunamganj, Kishoreganj, Netrokona, and parts of Mymensingh.

Ponds, Dighis The man-made wetlands including ponds, *dighis* (about 147,000 ha), and lakes are distributed all over the country. These are predominantly used for bathing, washing, livestock, and fish culture and in some cases for drinking water.

17.2.1.1 Biodiversity of Inland Wetlands

The flora and fauna reported from the wetlands in Bangladesh are presented in Table 17.3a–f.

Vegetation Among the estimated 5,000 species of flowering plants and 1,500 of vertebrates of the country, up to 300 plant species and 400 vertebrate species are dependent on wetlands for all or part of their life. Flora of inland wetlands varies from place to place; but the major species are *Barringtonia acutangula, Pongamia pinnata, Rosa clinophylla, Eichhornia crassipes, Utricularia* spp., *Hydrilla verticillata, Myriophyllum spicatum, Ceratophyllum demersum, Elodea* sp., *Potamogeton* sp., *Ipomea aquatica*, *Colocasia esculenta, Monochoria vaginalis, Sagittaria sagittifolia, Cyperus papyrus, Typha* sp., *Scirpus* sp., *Salvinia* sp., *Pistia stratiotes, Lemna minor, Wolffia arrhiza, Azolla pinnata, Spirodela polyrhiza, Nymphaea nouchali* and

Table 17.3 Selected flora and fauna from the wetlands of Bangladesh

Common name – *scientific name*	Common name – *scientific name*
(A). Plants[a]	
After Islam (2010) and Islam and Kitazawa (2013)	
Amur (Pacific Maple) – *Aglaia cucullata* (NT)	**Keora** (Sonneratia mangrove) – *Sonneratia apetala* (LC); *S. caseolaris* (LC); *S. griffithii* (CR)
Arrow arum – *Peltandra virginica*	**Keya**/kewda (Thatch screw pine) – *Pandanus odoratissimus*
Baen/bain – *Avicennia officinalis* (LC)	**Khulshi** – *Aegiceras corniculatum* (LC)
Bhat, *Clerodendrum inerme*; bhat/ghetu, *C. viscosum*	**Koroch** (Indian beech) – *Millettia pinnata/ Pongamia pinnata* (LC)
Bhola – *Hibiscus tiliaceus*	**Kulekhana** – *Hygrophila auriculata* (LC)
Bijtarak – *Argyreia nervosa*	**Lotus** and water lilies, *Nymphaea* spp., *Nymphoides* spp.; **Indian lotus**/sacred lotus, *Nelumbo nucifera* (NE)
Boroi (Indian plum) – *Ziziphus mauritiana*; *Z. jujuba*	**Makhna**/makna (gorgon, prickly water lily) – *Euryale ferox* (LC)
Budding – *Clerodendrum viscosum*	**Maloncha** – *Alternanthera philoxeroides*
Casia – *Cassia tora*	**Narichha** – *Cynodon* spp.
Cattail – *Typha* spp.	**Neel nishinda** – *Vitex trifolia*
Chagal-kuri – *Ipomoea pes-caprae*; *Ipomoea* spp.	**Nal khagra/reed** – *Phragmites karka* (LC)
Dhoincha – *Sesbania* spp.	**Padma**, *Nelumbo nucifera* (VU)
Duckweed, *Lemna* spp.; common duckweed, *L. minor* (LC); rootless duckweed, *Wolffia arrhiza* (LC)	**Palms**, *Poresia coaractata*; grass, *Myriostachya wightiana*
Dumur – *Ficus hispida* (EN)	**Pan seuli** – *Phyllanthus reticulatus*
Durba ghash, *Cynodon dactylon*; Millet rampant, *Panicum repens* (LC)	**Pani fal** – *Trapa bispinosa*; *T. maxitnowizii*
Falashi paddy – *Oryza minuta*	**Passur** – *Xylocarpus granatum* (LC); *X. mekongensis*; *X. moluccensis* (LC)
Garzan – *Rhizophora apiculata* (LC)	**Ram karola** (duck lettuce) – *Ottelia alismoides* (LC)
	Shatamull, *Asparagus racemosus*
Gewa – *Excoecaria agallocha* (LC)	**Shrub** – *Lippia javanica*, *Ficus heterophylla*, and *Phyllanthus disticha*
Ghechu – *Aponogeton* spp.	**Sheora/shaora** – *Streblus asper*
Goal pata (Nypa/mangrove palm) – *Nypa fruticans* (LC)	**Sedges** – *Cyperus* spp., *Fimbristylis* spp.
Goda – *Vitex pubescens*	**Shapla** (national flower of Bangladesh) (blue lotus/ blue star water lily) – *Nymphaea nouchali/N. stellata* (LC)
Goicha (kodo millet), *Paspalum scrobiculatum* (LC); seashore paspalum, *P. vaginatum* (LC)	**Shetodron/thumbai** – *Leucas aspera*
Goran, *Ceriops decandra* (NT); Indian/ spurred mangrove, *Ceriops tagal* (LC)	**Spear grass** – *Imperata cylindrica*

(continued)

Table 17.3 (continued)

Common name – *scientific name*	Common name – *scientific name*
Gorjan (red mangrove/Asiatic mangrove) – *Rhizophora mucronata* (LC)	**Singara** (water chestnut/water caltrop) – *Trapa bispinosa*
Hantal palm (mangrove date palm) – *Phoenix paludosa* (NT)	**Sundari** – *Heritiera fomes* (EN)
Helencha (buffalo spinach/marsh herb) – *Enhydra fluctuans* (EN)	**Tamal/ebony** – *Diospyros cordifolia*
Hijol (Indian oak/*Barringtonia*) – *Barringtonia acutangula*	**Water fern/**mosquito fern – *Azolla pinnata* (LC)
Hogla (elephant grass/Indian reed mace) – *Typha elephantina* (LC)	**Water hyacinth** – *Eichhornia crassipes*
Jhau – *Casuarina equisetifolia*	**Wild rice** – *Oryza sativa* var. *fatua*; *O. coarctata* (*Porteresia coarctata*) and *O. minuta*
Jhora dhan – *Oryza rufipogon*	**Wild rose** – *Rosa clinophylla*
Kankra (oriental mangrove) – *Bruguiera gymnorrhiza* (LC); *B. conjugata*	
(B). Fish/prawn/shrimp[b,c]	
After Siddiqui et al. (2007a) and Islam et al. (2015)	
Aeir/bagha aeir (Gangetic goonch), *Bagarius bagarius* (EN); Aeir, *Aorichthys/Sperata aor* (LC); *A. seenghala* (LC)	**Kaikka** – *Xenentodon cancila* (LC)
Angrot – *Labeo angra* (LC)	**Kalabata** (Gangetic latia) – *Crossocheilus latius* (LC)
Anju (zebra fish) – *Danio rerio* (LC)	**Kajoli** (Gangetic ailia), *Ailia coilia*; Kajuli/baspata (Jamuna ailia), *A. punctata* (VU)
Ayre/aor (long whiskered catfish) – *Mystus/Sperata aor* (LC)	**Kalibaush** (black labeo) – *Labeo calbasu* (LC)
Bacha (Batchwa bacha) – *Eutropiichthys vacha* (LC)	**Kash khirra/**laubuca (Indian glass barb) – *Chela laubuca* (EN)
Baim/eel: Guchi baim (Indian striped spiny eel), *Macrognathus pancalus* (LC); tara baim (lesser spiny eel), *M. aculeatus* (NE/LC); baim (lesser spiny eel), *Mastacembelus armatus* (LC); Banehara (Indian mottled eel), *Anguilla bengalensis* (NT)	**Khalisha** Baro khalisa (striped gourami), *Colisa fasciata*; Lal khalisha (dwarf gourami), *C. lalia*; Choto khalisha, *C. chuna* (NT)
Bata: (mirror carp/boga labeo/bata labeo), *Labeo bata* (LC); Bata/Tatkani (Reba carp), *Cirrhinus reba* (LC); Bhangan, *Labeo boga* (LC)	**Khorsula** – *Rhinomugil corsula* (LC)
Batashi (Indian potasi) – *Pseudeutropius atherinoides/Neotropius atherinoides* (LC)	**Koi** (climbing perch) – *Anabas testudineus*
Behtki (barramundi, giant perch, Asian sea bass) – *Lates calcarifer* (NT)	**Kuchia** (Gangetic mud eel) – *Monopterus cuchia* (LC)

(continued)

Table 17.3 (continued)

Common name – *scientific name*	Common name – *scientific name*
Bele/baila (bar-eyed goby) – *Glossogobius giuris* (LC)	**Koksa/Khaksa/Joia/Baril** (Hamilton's barila), *Barilius bendelisis* (LC); Koksa (Vagra baril), *B. vagra* (EN)
Bheda/meni (mud perch) – *Nandus nandus* (LC)	**Kumirer khil** (Deocata pipefish) – *Microphis deocata* (NT)
Bhol/bol (Indian trout) – *Barilius bola* (EN)	**Lakha** – *Polynemus indicus*
Bistara/chitra (spotted scat) – *Scatophagus argus* (LC)	**Loytta** (Bombay duck) – *Harpadon nehereus*
Boal (freshwater shark) – *Wallago attu* (NT)	**Magur** (walking catfish), *Clarias batrachus* (LC); **Gang magur** (canine catfish eel), *Plotosus canius* (VU)
Bou/bou rani (Bengal loach) – *Botia dario* (EN)	Meni/bheda (mud perch) – *Nandus nandus* (LC)
Bujuri – *Mystus tengara* (NT)	
Catla (Gangetic major carp) – *Catla catla* (LC)	**Mahashoal/mahseer** (tor mahseer) – *Tor tor* (NT) – *T. putitora* (EN)
Cheka (squarehead catfish) – *Chaca chaca* (EN)	**Mola** (Carplet) – *Amblypharyngodon mola* (LC)
Chanda (Ranga Chanda) (Indian glass fish), *Parambassis ranga* (LC); Lamba/nama chanda (elongated glass perchlet) – *Chanda nama* (LC); Choto Chanda/Lal Chanda (highfin glassy perchlet) – *Parambassis lala* (NT)	**Mrigal** (Gangetic major carp) – *Cirrhinus cirrhosus/Cirrhinus mrigala* (VU)
Chang/cheng: Cheng/telo taki/raga (Asiatic snakehead), *Channa orientalis* (VU); Chang, *C. gachua* (LC)	**Pabda:** Kani pabda (Indian butter catfish), *Ompok bimaculatus* (NT); Madhu pabda (Butter catfish), *O. pabda* (NT); Pabda (Pabda catfish), *O. pabo* (NT)
Chapila (Indian river shad) – *Gudusia chapra* (LC)	**Mullet**/flathead mullet – *Mugil cephalus* (LC)
Chela/flkchela (finescale razorbelly minnow) – *Chela phulo/Salmophasia phulo* (LC)	**Nandi**l (Nandi labeo) – *Labeo nandina* (NT)
Chep chela/laubucha (Indian glass barb) – *Chela laubuca* (EN)	**Napit**/kio bandi (Badis) – *Badis badis* (LC)
Chiring/chewa bele (mudskipper) – *Apocryptes bato* (NE)	**Neftani** (Frail gourami) – *Ctenops nobilis* (EN)
Chital (clown knifefish) (humped featherback) – *Chitala chitala* (NT)	**Pangus** – *Pangasius pangasius* (LC)
Crab/mud crab – *Scylla serrata/Scylla olivacea* (NE)	**Potka** (ocellated puffer fish) – *Tetraodon cutcutia* (LC); *Tetraodon fluviatilis* (LC)
Cuchia (Gangetic mud eel) – *Monopterus cuchia* (EN)	**Golda chingri** (giant freshwater prawn) – *Macrobrachium rosenbergii* (LC)

(continued)

Table 17.3 (continued)

Common name – *scientific name*	Common name – *scientific name*
Darkina (flying barb), *Esomus danricus* (DD); darkina/leuzza darkina (Gangetic scissortail rasbora), *Rasbora rasbora* (EN)	Neftani – *Ctenops nobilis* (NT)
Datina – *Pomadasys hasta* (LC)	**Prawns**/minor freshwater prawns: Chotka icha (monsoon river prawn), *Macrobrachium malcolmsonii* (LC); Dimua icha, *M. villosimanus* (LC); Pata chingri, *M. rude*; Gura icha/chingri (Kuncho river prawn), *M. lamarrei* (LC); Gara icha, *Palemon styleferus*
Dhela (Cotio) – *Osteobrama cotio* (EN)	**Puti/punti:** Shar punti (Olive barb), *Puntius sarana* (CR/EN); Tit punti/two-spot barb (ticto barb), *P. ticto* (VU); Teri punti (one-spot barb), *P. terio* (LC); Bhadi punti/Jat punti (spot fin swamp barb), *P. sophore* (LC)
Ek thota (wrestling halfbeak) – *Dermogenys pussilus* (EN)	**Rani:** Bou/bou rani (Bengal loach), Botia dario (EN); Rani/putul/beti (Y-loach), *B. lohachata* (EN)
Ekthute (Congaturi halfbeak) – *Hyporhamphus limbatus* (LC)	**Rita** (Rita) – *Rita rita* (LC)
Foli/chital (bronze featherback) – *Notopterus notopterus* (VU)	**Rui/Rohu** (Gangetic major carp) – *Labeo rohita* (LC)
Gagla (Menoda catfish) – *Hemibagrus menoda* (LC)	**Rup Chanda** – *Stromateus/Pampus chinensis*
Gharua/ghaura (Gharua bacha) – *Clupisoma garua* (LC)	**Sephatia/along** (Bengal barb) – *Bengala elanga* (EN)
Ghora muikha/longu (Pangusia labeo) – *Labeo pangusia* (NT)	**Shilong** (Silond catfish) – *Silonia silondia (*LC)
Glass fish/chanda – *Ambassis ranga*/*Pseudambassis ranga* (LC), *A. nama*	**Shing/singhi** (stinging catfish) – *Heteropneustes fossilis* (LC)
Goni/gonya (Kuria labeo) – *Labeo gonius* (EN)	**Shoal** (snakehead murrel), *Channa striata* (LC); Pipla shol/tila shol (Barca snakehead), *C. barca* (EN)
Goza/gazar (giant snakehead) – *Channa marulius* (EN)	**Shrimps**: Bagda chingri (tiger shrimps), *Penaeus monodon* (NE); Chapda/sada chingri (Indian white prawn), *Penaeus/Fenneropenaeus indicus* (NE); Chapda/sada chingri (green tiger prawn), *P. semisulcatus* (NE); Harina chringri (speckled shrimp), *Metapenaeus monoceros* (NE), *Metapenaeus* spp., *Parapenaeopsis pargasias*
Gutum (Guntea loach) – *Lepidocephalichthys guntea* (LC)	**Sisor** (Sisor catfish) – *Sisor rhabdophorus* (EN)

(continued)

Table 17.3 (continued)

Common name – *scientific name*	Common name – *scientific name*
Hilsa/ilish – *Tenualosa ilisha* (LC)	**Tengra**: Golsha/kabashi tengra (Gangetic mystus), *Mystus cavasius* (VU); Bujuri/tengra, *M. tengara*; Tengra, *M. vittatus* (LC); Tengra nona, *M. gulio* (LC); Tengra (Assamese batasio), *Batasio tengana* (EN); Golsha (long whiskered catfish), *M. cavasius* (LC)
	Taki (spotted snakehead) – *Channa punctata*
(C). Amphibians	
Frog: Indian bullfrog – *Hoplobatrachus tigerinus/Rana tigrina* (LC)	
(D). Reptiles	
Cobra: spectacled cobra/Indian cobra, *Naja naja* (NT); king cobra, *Ophiophagus hannah* (VU)	**Python:** Indian python/black tailed python – *Python molurus* (NT)
Crocodile: mugger crocodile or marsh crocodile, *Crocodylus palustris* (VU); Saltwater/Indo-Pacific crocodile, *Crocodylus porosus* (LC)	**Terrapin:** river terrapin – *Batagur baska* (CR)
Gharial – *Gavialis gangeticus* (CR)	**Turtle:** leatherback turtle, *Dermochelys coriacea* (VU); loggerhead turtle, *Caretta caretta* (EN); peacock soft-shell turtle, *Trionyx hurum* (NT); black pond turtle, *Geoclemys hamiltonii* (VU); green turtle, *Chelonia mydas* (EN); Indian flap-shelled turtle, *Lissemys punctata* (LC); hawksbill turtle, *Eretmochelys imbricata* (CR); olive ridley turtle, *Lepidochelys olivacea* (VU); Sylhet roofed turtle, *Kachuga sylhetensis* (EN)
Lizard: yellow monitor – *Varanus flavescens* (LC)	
(E). Birds	
Adjutant: greater adjutant, *Leptoptilos dubius* (EN); lesser adjutant, *L. javanicus* (VU)	**Lapwing:** spur-winged lapwing, *Vanellus spinosus* (LC); yellow-wattled lapwing, *V. malabaricus* (LC); red-wattled lapwing, *V. indicus* (LC)
Bittern: black bittern, *Ixobrychus flavicollis* (LC); chestnut bittern/ cinnamon bittern, *I. cinnamomeus* (LC)	**Openbill:** openbill: Asian openbill, *Anastomus oscitans* (LC)
Cock: water cock – *Gallicrex cinerea* (LC)	**Osprey:** Osprey – *Pandion haliaetus* (LC)
Cormorant: little cormorant – *Phalacrocorax niger/Microcarbo niger* (LC)	**Oyster catcher**: Eurasian oyster catcher – *Haematopus ostralegus* (NT)
Crake: ruddy-breasted crake – *Porzana fusca* (LC)	**Pelican:** Dalmatian pelican, *Pelecanus crispus* (VU); Pelican, spot-billed pelican, *P. philippensis* (NT)

(continued)

Table 17.3 (continued)

Common name – *scientific name*	Common name – *scientific name*
Curlew: Eurasian curlew – *Numenius arquata* (NT)	**Pintail**: northern pintail – *Anas acuta* (LC)
Darter: darter/snakebird/oriental darter – *Anhinga melanogaster* (NT)	**Plover:** Kentish plover, *Charadrius alexandrinus*; common ringed plover, *C. hiaticula* (LC); American golden plover, *Pluvialis dominica* (LC); little ringed plover, *Charadrius dubius* (LC); Mongolian plover/lesser sand plover, *C. mongolus* (LC)
Dowitcher: Asian dowitcher, *Limnodromus semipalmatus* (NT)	**Pochard:** Baer's pochard – *Aythya baeri* (CD)
Duck: white-winged duck – *Cairina scutulata/Asarcornis scutulata* (EN)	**Pratincole:** small Indian pratincole/oriental pratincole – *Glareola maldivarum* (LC)
Eagle: Pallas's fishing eagle, *Haliaeetus leucoryphus* (VU); gray-headed fish eagle, *Ichthyophaga ichthyaetus* (NT); white-bellied sea eagle, *Haliaeetus leucogaster* (LC); imperial eagle, *Aquila heliacal*	**Quail:** Manipur bush quail – *Perdicula manipurensis* (EN)
Egret: large egret, *Egretta alba* (LC); Western reef-egret, *E. gularis* (LC)	**Rail:** western water rail – *Rallus aquaticus* (LC)
Finfoots: masked finfoot – *Heliopais personatus* (DD)	**Ruff:** ruff – *Philomachus pugnax/Calidris pugnax* (LC)
Francolin: swamp francolin – *Francolinus gularis* (VU)	**Sanderling**, *Calidris alba* (LC)
Goose: cotton teal/cotton pygmy goose, *Nettapus coromandelianus* (LC); greylag goose/bar-headed goose, *Anser indicus* (LC); greylag goose, *A. anser* (LC)	**Sandpiper:** marsh sandpiper, *Tringa stagnatilis* (LC); sandpiper, spoonbill sandpiper, *Eurynorhynchus pygmeus/Calidris pygmaea* (CR)
Grebe: little grebe – *Tachybaptus ruficollis* (LC)	**Shank:** Nordmann's greenshank/spotted greenshank, *Tringa guttifer* (EN); common redshank, *Tringa tetanus*; common greenshank, *Tringa nebularia* (LC)
Gull: black-headed gull, *Larus ridibundus* (LC); brown-headed gull, *Larus brunnicephalus* (LC); great black-headed gull/Pallas's gull, *Larus ichthyaetus* (LC)	**Skimmer:** Indian skimmer/Panikata – *Rynchops albicollis* (VU)
Hen: white-breasted water hen, *Amaurornis phoenicurus* (LC); moorhen/purple swamphen, *Porphyrio porphyrio* (LC)	**Snipe**: pintail snipe, *Gallinago stenura* (LC); common snipe, *G. gallinago* (LC); fantail snipe, *Gallinago gallinago*
Heron: gray heron, *Ardea cinerea* (LC); white-bellied heron, *Ardea insignis* (CR)	Stilt: black-winged stilt – *Himantopus himantopus* (LC)
Ibis: bar-headed goose/red-naped ibis, *Pseudibis papillosa* (LC); white ibis/black-headed ibis, *Threskiornis melanocephalus* (NT)	**Teal:** lesser whistling teal – *Dendrocygna javanica* (LC)

(continued)

Table 17.3 (continued)

Common name – *scientific name*	Common name – *scientific name*
Jacana: bronze-winged jacana – *Metopidius indicus* (LC)	**Tern**: gull-billed tern, *Gelochelidon nilotica* (LC); whiskered tern, *Chlidonias hybrida* (LC); little tern, *Sterna albifrons* (LC); Indian river tern, *Sterna aurantia* (NT); hirundo tern/common tern, *Sterna hirundo* (LC)
Kestrel: lesser kestrel – *Falco naumanni* (LC)	**Vulture:** cinereous vulture – *Aegypius monachus* (NT)
Kingfisher: brown-winged kingfisher, *Pelargopsis amauroptera* (NT); ruddy kingfisher, *Halcyon coromanda* (LC); stork-billed kingfishers, *Pelargopsis capensis* (LC); Blyth's kingfisher, *Alcedo hercules* (NT)	**Whimbrel** – *Numenius phaeopus* (LC)
Knot: eastern knot – *Calidris tenuirostris* (EN)	
(F). Mammals	
Bear: Asiatic black bear, *Ursus thibetanus* (VU); hog deer, *Axis porcinus* (EN); sloth bear, *Melursus ursinus* (VU)	**Langur**: capped langurs – *Trachypithecus pileatus* (VU)
Boar: wild boar – *Sus scrofa* (LC)	**Leopard:** clouded leopard, *Neofelis nebulosa* (VU); leopard, *Panthera pardus fusca* (NT)
Cat: Asiatic golden cat, *Catopuma temminckii* (NT); fishing cat, *Prionailurus viverrinus* (EN); marbled cat, *Pardofelis marmorata* (VU); jungle cat, *Felis chaus* (LC); leopard cat, *Prionailurus bengalensis* (LC)	**Rabbit:** hispid hare/Assam rabbit – *Caprolagus hispidus* (EN)
Civets: Bengal civets – *Viverra zibetha* (NT)	**Rhinoceros**: Javan rhinoceros, *Rhinoceros sondaicus* (CR); Indian rhinoceros/single-horned rhinoceros, *Rhinoceros unicornis* (VU)
Dog: Asiatic wild dog – *Cuon alpinus* (EN)	**Monkey:** rhesus macaques/monkey – *Macaca mulatta* (LC)
Deer: barasingha/swamp deer, *Rucervus duvaucelii* (VU); barking deer, *Muntiacus muntjak* (LC); spotted deer/chital, *Axis axis* (LC)	**Otter:** Asian small-clawed otter, *Aonyx cinerea* (VU); smooth-coated otter, *Lutrogale perspicillata* (VU)
Dolphin: Gangetic/South Asian river dolphin/Ganges susu/shushuk, *Platanista gangetica gangetica* (EN); Indo-Pacific bottlenose dolphin, *Tursiops aduncus* (DD); Indo-Pacific humpbacked dolphin, *Sousa chinensis* (NT); Shushuko/Irrawaddy dolphin, *Orcaella brevirostris* (VU)	**Porpoise:** finless porpoise – *Neophocaena phocaenoides* (VU)
Fox: Bengal/Indian fox – *Vulpes bengalensis* (LC)	**Tiger:** Royal Bengal tiger – *Panthera tigris tigris* (EN)
Gayal: gaur/gayal – *Bos frontalis*	**Wolf:** gray wolf – *Canis lupus* (LC)

(continued)

Table 17.3 (continued)

Source: [d,e]Reptiles, birds, and mammals following Nishat et al. (1993), Islam et al. (2015), IUCN Red List of Threatened Species, and various other sources

CR critically endangered, *EN* endangered, *VU* vulnerable, *NT* near threatened, *LC* least concern, *DD* data deficient, *NE* not evaluated

[a]http://www.iucnredlist.org/

[b]http://fisheriesbd.at.ua/news/threatened_to_extinct_fishes_of_bangladesh /2012-11-09-27

[c]http://www.iucnredlist.org/

[d]http://www.iucnredlist.org/

[e]http://fisheriesbd.at.ua/news/threatened_to_extinct_fishes_of_bangladesh/2012-11-09-27

N. stellata, Nymphoides sp., *Nelumbo nucifera, Euryale ferox, Phragmites karka, P. communis, Chara* sp., *Najas* sp., *Vetiveria zizanioides, Alternanthera philoxeroides, Enhydra fluctuans, Aponogeton* sp., *Hygrophila auriculata, Trapa bispinosa* and *T. maxitnowizii, Ottelia alismoides,* and *Asparagus racemosus*. However, many of these have now become scarce because of overexploitation (see Table 17.3a for common names and conservation status of plants).

Many submergent and floating hydrophytes are used as leafy vegetables. Rootstocks of *Aponogeton* sp., *Nymphaea* spp., *Nymphoides* sp., *T. bispinosa*, and *T. maxitnowizii* and seeds of *E. ferox* are relished by the rural people. Wild species of rice jhora dhan (*Oryza rufipogon*) of inland wetlands are used as a substitute for cultivated rice. In some wetlands of central (Faridpur, Gopalganj, Muksudpur, Kashiani and Kotalipara, Jessore), southern (Jhalokathi, Pirojpur, Sharupkathi, Najirpur, Banaripara, and Ujirpur), and northeastern areas (Kishoreganj, Netrokona, Brahmanbaria, Sunamganj) of Bangladesh, floating garden made on heaps of decomposed water hyacinth (*E. crassipes*), locally called *baira*/*daap* (Haq et al. 2002), a century-old practice to grow vegetables in flood-prone areas (see below), is evident.

Farming on floating beds (locally known as *baira*, *geto*, *bed*, or *daap)*, soil-less agriculture or hydroponics (Fig. 17.3), is an indigenous practice in the southwestern part of Bangladesh (Haq et al. 2002). This practice is now receiving renewed interest as a potential solution for farmers whose lands have been waterlogged and for landless people. This farming technique uses masses of rotting water hyacinths (*E. crassipes*) that choke the waterways, and it offers opportunities for the participation of men as well as women. Such agriculture/gardens can be an adaptation to adverse environmental conditions from waterlogging or prolonged flooding (Fig. 17.3). Here plants derive their nutrients not from soil but from water (UNEP 2012; Kibria et al. 2013). The approach employs beds of rotten vegetation, which acts as compost for crop growth. These beds are able to float on the surface of the water, creating areas of land suitable for agriculture within waterlogged regions. Mostly vegetables such as sweet gourd, pumpkin, brinjal, green chili, red and green amaranth, and beans are grown during the flood season. In winter when the water recedes, the farmers use the land to crop winter vegetables such as potato, tomato, radish, carrot, turnip, cabbage, cauliflower, and other crops such as onions and garlic depending on the local situation. Harvesting water hyacinth allows clearing the invasive weed, with the beneficial side effect of reducing breeding grounds for mosquitoes and improving conditions for open water fishing. This practice of floating agriculture

Fig. 17.3 Farming on floating beds, *baira/daap* (Photo courtesy: A. W. R. Hassan, FAO, Bangladesh)

also helps to supplement the income of local communities and contributes to poverty alleviation, greater food security by increasing the land output, and supporting capacity for poor and landless people. As both men and women can carry out floating agriculture, it also leads to improvements in gender equity. However, there is a possibility of transfer of pollutants such as trace/heavy metals accumulated in water hyacinth as compost to crops and vegetables grown on them (Kibria et al. 2016).

Fish The inland capture fishery is based on the vast freshwater fish resources with around 260 species of finfishes (most of them native) and 25 shellfishes. Economically important fishes include *Labeo rohita*, *L. gonius*, *L. calbasu*, *L. nandina, L. angra, Catla catla*, *Cirrhinus cirrhosus*, *C. reba, Tor tor, T. putitora, Wallago attu*, *Pangasius pangasius*, *Aorichthys/Sperata aor*, *A. seenghala*, *Bagarius bagarius, Rita rita*, *Clarias batrachus*, *Heteropneustes fossilis*, *Ompok bimaculatus*, *O. pabo*, *Mystus tengara, M. cavasius, M. vittatus*, *Lepidocephalichthys guntea*, *Anabas testudineus, Notopterus notopterus, N. chitala, Rhinomugil corsula, Botia dario, Pseudeutropius atherinoides*, *Puntius sarana, P. ticto, P. sophore, Puntius* sp., *Chela laubuca, Colisa fasciata, Ctenops nobilis, Nandus nandus, Ambassis ranga, A. nama, Macrognathus aculeatus, M. armatus, M. pancalus, Gudusia chapra, Glossogobius giuris, Channa gachua*, *C. punctatus*, *C. striatus*, *C. marulius*, *Xenentodon cancila, Amblypharyngodon mola*, *Osteobrama cotio*, *Danio rerio*, *D. devario, Esomus danricus*, and *Salmostoma laubuca* (Siddiqui et al. 2007a). These once common species are now threatened due to various anthropogenic interventions including pollution, climate change, and water diversion (see Table 17.3b for common names of fishes and their conservation status).

Prawns Among the freshwater prawns, *Macrobrachium rosenbergii, M. malcolmsonii, M. rude, M. lamarrei*, and *Palemon styleferus* are important and common.

17.2.1.2 Case Study: Hakaluki Haor

Hakaluki *ha*or (see Fig. 17.1 for Its Location) is a marsh wetland located in northeastern part of Bangladesh. It is the country's largest inland freshwater wetland. From the wetland, 558 species of animal species have been recorded that includes 417 species of birds. Of 417 avifaunal species, 26 are threatened, two are vulnerable, 10 are endangered, and 14 critically endangered.[1] Hakaluki haor is a very important wetland for its wide variety of waterfowl, particularly Anatidae (IUCN and CNRS 2006) (see Table 17.4). A variety of snakes, turtles, frogs, and tortoises are gradually getting extinct (Nishat et al. 1993), (e.g., Black Soft-shell Turtle, *Aspideretes nigricans*, is now extinct).

17.2.2 Tidal Saltwater Coastal Wetlands

These wetlands cover almost 25% of the land area of Bangladesh and include mangroves, saltmarsh, lagoons, deltaic islands, sand dunes and beaches, barrier islands, seagrass, and coral habitats. The major coastal wetlands are the Sundarbans mangrove forests, the Chakaria mangrove forest, Sonadia Island, Moheshkhali Island, and St. Martin's Island (Fig. 17.1). These coastal wetlands support a rich diversity of plants and animals (see Sect. 17.2.2.1). These habitats are dynamic and are susceptible to change due to coastal processes, lack resilience, and have a low threshold to irreversible damage. The physical and ecological characteristics of these habitats make them especially vulnerable to degradation. Coastal wetlands are also important for fishery, water resources, agriculture/land resources, and biodiversity.

17.2.2.1 Biodiversity of Coastal Wetlands

The coastal wetland vegetation in Bangladesh consists of 35 angiosperm species, 26 dicots, and 9 monocots. *Ipomoea pes-caprae, Ipomoea* spp.*, Leucas aspera, Clerodendrum viscosum,* and *Argyreia nervosa* are common creepers that act as sand binders in the primary dunes. The grasses in these dunes include *Cynodon dactylon, Panicum repens*, *Cynodon* sp., *Paspalum scrobiculatum*, *P. vaginatum, Cyperus* sp., and *Fimbristylis* sp. The mature inland dunes consist of trees, shrubs, and herbs; common ones are *Phyllanthus reticulatus*, *Cassia tora, Clerodendrum inerme*, *Vitex trifolia, V. pubescens, Ziziphus mauritiana, Z. jujuba*, *Casuarina equisetifolia*, *Streblus asper, Pandanus odoratissimus, Calotropis gigantea, Porteresia coarctata, Myriostachya wightiana, Avicennia officinalis, A. marina, A. alba, Sonneratia apetala, Aegiceras corniculatum, Ceriops decandra,* and *Aegialitis rotundifolia.*

Vegetation The mangrove vegetation of Sonadia Island consists of 27 species. The common ones are *Avicennia officinalis, A. marina, A. alba, A. corniculatum,*

[1] http://en.banglapedia.org/index.php?title=Hakaluki_Haor

Table 17.4 List of amphibians, reptiles, birds, and mammals reported from Hakaluki haor

(A). Amphibians
Frog: Indian Bullfrog, *Rana tigrina/Hoplobatrachus tigerinus*
(B). Reptiles
Lizard: Calcutta Oval-grain Lizard, *Varanus flavescens*; Bengal Monitor Lizard/Common Indian Monitor, *Varanus bengalensis*
Turtle/tortoise: Black Spotted Turtle, *Geoclemys hamiltonii*; Assam Roofed Turtle, *Kachuga sylhetensis*; Indian Flap-shelled Turtle, *Lissemys punctata*; Assam Roofed Turtle, *Kachuga sylhetensis/Pangshura sylhetensis*; Black Soft-shell Turtle, *Aspideretes nigricans*; Indian Peacock Soft-shell Turtle, *Aspideretes hurum/Nilssonia hurum*; Three-keeled Land Tortoise, *Melanochelys tricarinata*
Snake: Indian Rat Snake, *Ptyas mucosa*; monocled cobra, *Naja kaouthia*; cobra, *Naja*; Burmese python, *Python molurus/Python bivittatus*
(C). Birds
Adjutant: Lesser Adjutant, *Leptoptilos javanicus*
Babbler: Marsh Babbler, *Pellorneum palustre*
Coot: Common Coot, *Fulica atra*
Cormorant: Little Cormorant, *Phalacrocorax niger/Microcarbo niger*; Great Cormorant, *Phalacrocorax carbo*
Crane: Sarus Crane, *Grus antigone*; Demoiselle Crane, *Anthropoides virgo*
Duck: White-winged Duck, *Cairina scutulata/Asarcornis scutulata*; Knob-billed Duck, *Sarkidiornis melanotos*; Lesser Whistling Duck, *Dendrocygna javanica*; Indian Spot-billed Duck, *A. poecilorhyncha*; Ferruginous Duck, *Aythya nyroca*; Tufted Duck, *A. fuligula*; Fulvous Whistling Duck, *Dendrocygna bicolor*
Eagle: Gray-headed Fish Eagle, *Ichthyophaga ichthyaetus*; Pallas's Fish-Eagle, *Haliaeetus leucorhyphus;* Eastern Imperial Eagle, *Aquila heliaca*
Egret: Cattle Egret, *Bubulcus ibis*; Little Egret, *Egretta garzetta*; Intermediate Egret, *E. intermedia, E. alba*
Falcon: Peregrine Falcon, *Falco peregrinus*
Francolin: Swamp Francolin, *Francolinus gularis*
Gadwall: Gadwal, *Anas strepera*
Garganey: Garganey, *A. querquedula/Spatula querquedula*
Goose: Cotton Pygmy Goose, *Nettapus coromandelianus*; Greylag Goose, *Anser anser*
Grebe: Little Grebe, *Tachybaptus ruficollis*; Great Crested Grebe, *Podiceps cristatus*
Greenshank: Spotted Greenshank, *Tringa guttifer*
Gull: Black-headed Gull, *Larus ridibundus*
Heron: White-bellied Heron, *Ardea insignis*
Jacana: Pheasant-tailed Jacana, *Hydrophasianus chirurgus*; Bronze-winged Jacana, *Metopidius indicus*
Kingfisher: Blyth's Kingfisher, *Alcedo hercules*
Kestrel: Lesser Kestrel, *Falco naumanni*
Pelican: Dalmatian Pelican, *Pelecanus crispus*; Spot-billed Pelican, *Pelecanus philippensis*
Pintail: Northern Pintail, *Anas acuta*
Pochard: Common Pochard, *Aythya ferina*
Quail: Manipur Bush Quail, *Perdicula manipurensis*

(continued)

Table 17.4 (continued)

Shoveler: Northern Shoveler, *A. clypeata/Spatula clypeata*
Skimmer: Indian Skimmer, *Rynchops albicollis*
Swamphen: Purple Swamphen, *Porphyrio porphyrio*
Teal: Common Teal, *A. crecca*
Tern: Black-bellied Tern, *Sterna acuticauda*; Common Gull-billed Tern, *Gelochelidon nilotica*; Whiskered Tern, *Chlidonias hybrida*
Vulture: Cinereous Vulture, *Aegypius monachus*
Watercock: Watercock, *Gallicrex cinerea*
(D). Mammals
Cat: Jungle Cat, *Felis chaus*; Fishing Cat, *Prionailurus viverrinus*
Dolphin: Ganges River Dolphin, *Platanista gangetica*
Fox: Bengal Fox, *Vulpes bengalensis*
Hare: Hispid Hare, *Caprolagus hispidus*
Jackal: Golden Jackal, *Canis aureus*
Mongoose: *Herpestes* sp.
Otter: Asian Small-clawed Otter, *Aonyx cinerea*; Smooth-coated Otter, *Lutra perspicillata*; Eurasian Otter, *Lutra lutra*
Squirrel: Hoary-bellied Squirrel/Irrawaddy Squirrel, *Callosciurus pygerythrus*

Source: Nishat et al. (1993)

C. decandra, A. rotundifolia, *and Sonneratia apetala.* Unlike mangroves of the Sundarbans, *Nypa fruticans* and *Heritiera fomes* are completely absent in Sonadia. *Sonneratia griffithii*, which was once common in the Chakaria Sundarbans (Chittagong), including Sonadia Island, is no longer available in other existing mangrove areas in Bangladesh. The population of *Porteresia* spp. at Sonadia Island is more salinity tolerant than any of its other land races along the central and western coast of Bangladesh. *P. coarctata* formerly classified as *Oryza coarctata*, a wild relative of rice, is native to the coastal saline areas of Bangladesh and eastern India. This species of brackish water is often used as a substitute for cultivated rice.

Seaweeds Common genera of seaweeds in Bangladesh include *Hypnea* (red seaweeds), *Ceramium* (red seaweeds), *Acanthophora* (red seaweeds), *Polysiphonia* (red seaweeds), *Sargassum* (brown seaweeds), *Dictyota* (brown seaweeds), *Ulva* (green seaweeds), *Sphacelaria* (brown seaweeds), *Padina* (brown seaweeds), *Chaetomorpha* (green seaweeds), *Enteromorpha* (green seaweeds), *Caulerpa* (green seaweeds), and *Halimeda* (calcareous green seaweeds). Species of seagrasses reported from the coastal wetlands of Bangladesh include ocean turfgrass, *Halophila beccarii*, *H. decipiens*, *H. pinifolia*, and *Halodule uninervis*, and beaked tasselweed, *Ruppia maritima* and *Spartina* sp. (Hoq et al. 2012). A total of 154 species of marine algae (including seaweeds) were reported from St. Martin's Island of Bangladesh (Thompson and Islam 2010).

Corals The rocky subtidal habitat supports diverse coral communities, of which 39 species have been identified as hard corals (reef-building *corals)* and 14 species as soft. Living corals (coral bleaching, ocean acidification, and diseases may cause mortality of corals) include species of *Porites*, *Favites*, *Goniopora*, *Cyphastrea*, and *Goniastrea*. The soft corals include species of *Sinularia*, *Lobophytum*, *Anthelia*, *Dendronephthya*, *Palythoa*, *Nemanthus*, *Telemectius*, and *Discosoma*. Besides, four coral species of the genus *Acropora* (*A. pulchra*, *A. horrida*, *A. humilis*, and *A. variabilis*) were reported from neritic waters of the St. Martin's Island. In addition, *Stylocoeniella*, *Pocillopora*, *Stylophora*, *Porites*, *Pavona*, *Favia*, *Favites*, *Pseudosiderastrea*, *Goniastrea*, and *Montastrea* were recorded. Taxonomy of a good portion of corals occurring around the island is yet unknown. St. Martin's Coral Island is the only continental island in Bangladesh with coral communities.

Fishes The ichthyofauna of the coastal wetlands of Bangladesh includes 492 species (422 species are bony fish and 70 cartilaginous). About 89 fish species are coral associated. Major fish species are listed in Table 17.5.

Sharks, Skates, and Rays 70 species of sharks, skates, and rays (Haroon 2010) and at least seven species of edible oyster are reported from Bangladesh (Siddiqui et al. 2007b).

Shrimps Commercial shrimp and prawn species of coastal wetlands of Bangladesh are *Penaeus monodon* (jumbo tiger shrimp), *P. indicus* (Indian white shrimp), *P. semisulcatus*, *Metapenaeus monoceros* (speckled/ginger shrimp), *Parapenaeopsis sculptilis* (rainbow shrimp), and *Macrobrachium rosenbergii* (giant freshwater prawn).

Crabs Seven species of crabs have been reported from the coastal waters of Bangladesh (Siddiqui et al. 2007b).

Molluscs Gastropods, like *Conus striatus*, *C. textile*, and *C. geographus*, are abundant. Two economically important Gastropods, *Trochus niloticus* and *Turbo marmoratus*, are also reported.

Reptiles (Turtles, Snakes) Five species of marine turtle (*Chelonia mydas*, *Caretta caretta*, *Lepidochelys olivacea*, *Eretmochelys imbricata*, and *Dermochelys coriacea*) have been reported (Hussain and Acharya 1994). Other reptiles include *Varanus salvator* and the sea snakes *Laticauda laticauda*, *L. colubrina*, and *Enhydrina schistosa*. Altogether, coastal area supports 27 reptile species. Entire coastal beach of 710 km from the Sundarbans in the southwest up to Teknaf in the southeast and the St. Martin's Island is particularly important as nesting area for marine turtles.

Birds More than 200 species of birds have been recorded from coastal wetlands, of which 67 species are resident and 53 migratory. Major bird species are *Amaurornis phoenicurus*, *Anhinga melanogaster*, *Eurynorhynchus pygmeus*, *Ardea cinerea*, *Dendrocygna javanica*, *Egretta alba*, *E. gularis*, *Gallicrex cinerea*, *Gelochelidon nilotica*, *Ixobrychus flavicollis*, *Glareola maldivarum*, *Himantopus himantopus*,

Table 17.5 Major fish species reported from coastal wetlands of Bangladesh

Scientific name	Remarks
Tenualosa ilisha	Native; anadromous fish; found in the Bay of Bengal, estuaries, and tidal rivers; contributes about 12% of the total fish production, 10% of fish protein supply, and about 1% of gross domestic product (GDP) in Bangladesh; hilsa forms a single large inland fishery. Immature hilsa, known as "jatka," are fished extensively in rivers near Chandpur between February and May; large-sized fishes mainly contribute to the monsoon fisheries (May–October), and smaller individuals form the fishery during the winter months (November–January). There is now a ban on "hilsa" fishing in Bangladesh at the height of "hilsa" breeding season for 20 days (October–November). More than 450,000 people are directly involved in catching "hilsa" for livelihoods, and around 4–5 million people are indirectly involved in the "hilsa" trade. Overfishing, pollution, and lack of water in the rivers are believed to be reasons for the decline of "hilsa" fisheries in Bangladesh https://sites.google.com/site/pollutionwqbangladesh/news
Pangasius pangasius	Native, found in freshwater and brackish waters of Bangladesh including Choto Jamuna and the Ganges rivers
Lates calcarifer	Native; catadromous fish; found in the Bay of Bengal; very common in estuaries of Barisal, Patuakhali, and Khulna
Stromateus chinensis/Pampus chinensis	Native, found in brackish and marine waters of Bangladesh
Polynemus indicus/ Leptomelanosoma indicum	Native, found in the Sundarbans estuaries and Bay of Bengal
Herpadon nehereus	Native
Rastrelliger kanagurta	Native
Pomadasys hasta	Caught along in coastal brackish and saltwaters of Bangladesh
Johnius diacanthus	Marine, caught from the Bay of Bengal
Sardinella melanura	–
Sardinella gibbosa	Native, Bay of Bengal
Sardinella fimbriata	Native, Bay of Bengal, marine; brackish
Dussumieria acuta	–
Dussumieria elopsoides	–
Parastromateus niger	Native
Arius maculatus	Native
Arius thalassinus	–
Psettodes erumei	Native
Decapterus russelli	Native
Pellona ditchella	–
Scomberoides commersonnianus	Native

(continued)

Table 17.5 (continued)

Scientific name	Remarks
Scomberomorus commerson	Native
Congresox telabonoides	–
Eleutheronema tetradactylum	Native
Sillago sihama	–
Caranx melampygus	Native
Lobotes surinamensis	Native
Otolithoides pama	Native, found in the Bay of Bengal, very common in the river Meghna during monsoon
Panna microdon	–
Pampus argenteus	Native
Gerres filamentosus	Native

Sources: [a,b,c]Siddiqui et al. (2007b)
[a]http://www.iucnredlist.org/search
[b]http://mail.nbfgr.res.in/cgi-bin/fbis/barcodeinfo.pl?202
[c]http://fishbase.org/country/CountryChecklist.php?resultPage=3&what=list&trpp=50&c_code=050&csub_code=&cpresence=Reported&sortby=alpha2&ext_CL=on&ext_pic=on&vhabitat=fresh

Ixobrychus cinnamomeus, *Metopidius indicus*, *Nettapus coromandelianus*, *Phalacrocorax niger*, *Porphyrio porphyrio*, *Porzana fusca*, *Rallus aquaticus*, *Sterna albifrons*, *Sterna aurantia*, *Tachybaptus ruficollis*, *Vanellus malabaricus*, *V. indicus*, *V. spinosus*, *Anastomus oscitans*, *Gallinago stenura*, *G. gallinago*, *Calidris alba*, *Limnodromus semipalmatus*, *Halcyon coromanda*, *Chlidonias hybrida*, *Leptoptilos dubius*, *L. javanicus*, *L. dubius*, *Limnodromus semiplamatus*, and *Tringa guttifer*. St. Martin's Island is particularly an important wintering area for a wide variety of migratory shorebirds, gulls, and terns. This island supports two globally threatened birds *Vanellus cinereus* and *Sterna acuticauda* and two marine mammals *Sousa chinensis* and *Neophocaena phocaenoides*. Common avian migrants and winter visitors are *Anas acuta*, *Pluvialis dominica*, *Charadrius dubius*, *C. alexandrinus*, *C. hiaticula*, *C. mongolus*, *Numenius phaeopus*, *N. arquata*, *Tringa totanus*, *T. nebularia*, *T. stagnatilis*, *T. guttifer*, *Gallinago stenura*, *G. gallinago*, *Calidris alba*, *Chlidonias hybrida*, *Larus ridibundus*, *Philomachus pugnax*, *Sterna hirundo*, *Anastomus oscitans*, *Threskiornis melanocephalus*, *Pseudibis papillosa*, *Anser indicus*, *A. anser*, *Haematopus ostralegus*, *Calidris tenuirostris*, *Larus ichthyaetus*, *L. brunnicephalus*, *Rynchops albicollis*, *Eurynorhynchus pygmeus*, *Limnodromus semipalmatus*, and *Haliaeetus leucogaster*.

Mammals Important terrestrial mammal species include *Canis lupus*, *Cuon alpinus*, *Catopuma temminckii*, *Neofelis nebulosa*, *Pardofelis marmorata*, *Melursus ursinus*, *Ursus thibetanus*/*Selenarctos thibetanus*, *Prionailurus viverrinus*, *Amblonyx cinerea*, *Lutrogale perspicillata*, and *C. hispidus* (Khan 1986). Dolphins include *Platanista gangetica*, *Sousa chinensis*, and *Neophocaena phocaenoide.*

17.2.2.2 Case Study: Sundarbans Mangrove of Bangladesh

The Sundarbans, the largest continuous natural mangrove forest in the world, is located at the southern extremity of the Ganges river delta, i.e., bordering the northern margin of the Bay of Bengal spreading over the southern part of Bangladesh and West Bengal, India. The Sundarbans mangrove forest covers an area of about 10,000 km^2 of which 62% falls within the territory of Bangladesh, while the remaining (38%) area belongs to West Bengal, India. Of the total area, approximately 70% is lands. This forest has been managed for more than a century (Curtis 1933). At present the forest is divided almost in a north-south direction into polyhaline (>10 ppt), mesohaline (≥5–10 ppt), and oligohaline (<5 ppt) zones. This happened since 1982 due to Farakka Barrage in West Bengal, India. The Sundarbans occupies a flat deltaic swamp rarely exceeding 0.9–2.1 m above mean sea level, with a maximum of 10 m amsl. It is generally tidally flooded on a twice-daily basis with most of the area being under water during the high spring tides of the monsoon. Some parts of the mangroves are characterized by the presence of acid sulfate soils, especially in the Chakaria mangroves of Chittagong. The World Heritage Convention (WHC) declared Sundarbans as the natural and cultural site of outstanding universal value. Over 3.5 million people live within 20 km boundary of the Sundarbans mangrove forest (SMF) and are directly or indirectly dependent on its fisheries resources (Hoq 2008; Kibria 2014).

Mangrove ecosystem is a suitable feeding, breeding, and nursery ground for several marine, estuarine, and freshwater species. The intermingled root system of the mangrove acts as a coastal stabilizer and binders of sediment, thus aiding in preventing erosion in the mangrove areas (Hoq 2008; Hoq and Haroon 2012). The name “Sundarbans” is due to the dominance of the plant *Heritiera fomes*, locally called as Sundari gach. Other major plant species are *H. littoralis*, *H. minor*, *Excoecaria agallocha*, *Xylocarpus granatum*, *X. mekongensis*, *X. moluccensis*, *Bruguiera conjugata*, *B. gymnorrhiza*, *Sonneratia apetala*, *S. caseolaris*, *Avicennia officinalis*, *Ceriops decandra*, *C. tagal*, *Aegiceras corniculatum*, *A. corniculatum*, *Rhizophora mucronata*, *R. apiculata*, *Pandanus tectorius*, *Poresia coaractata*, *Myriostachya wightiana*, *Phoenix paludosa*, *Cynometra ramiflora*, *Hibiscus tiliaceus*, *Imperata cylindrica*, *Phragmites karka*, and *Nypa fruticans*. Since 1989, timber extraction has been banned in order to conserve the natural resources, although exemptions have been made for the harvest of some species for poles, sawlogs and hardboard (e.g., *H. fomes*), pulpwood (*E. agallocha*), thatching material (*N. fruticans*), and some non-timber species for fuelwood. While mangrove formation of the St. Martin’s Island is quite different from other mangroves in the country in that, it is a pure *Lumnitzera racemosa* formation (large shrubs or small trees up to 8 m tall, locally known as *Kirpa*).

The Bangladesh Sundarbans supports diverse biological resources including at least 150 species of commercially important fishes, 270 species of birds, 42 species of mammals, 35 reptiles, and eight amphibian species. This represents a significant proportion of the species present in Bangladesh (i.e., about 30% of the reptiles, 36% of the birds, and 34% of the mammals) and includes a large number of species that are now extinct elsewhere in the country. Two amphibians, 14 reptiles, 25 aves, and five mammals are at present endangered. The Sundarbans is an important wintering area for migrant water birds and is an area suitable for watching and studying them. Eighteen snake species including *Ophiophagus hannah*, *Naja* sp., *Python molurus*, green vine snake, checkered keelbacks and rat snakes, vipers, and sea snakes are reported. Monitor lizards found are *Varanus bengalensis*, *V. flavescens*, and *V. salvator*.

Waterways of the Sundarbans mangrove forest are now considered as the global "hot spot" of endangered Gangetic river dolphin, *Platanista gangetica gangetica*, and Irrawaddy dolphin, *Orcaella brevirostris* (Fahrni et al. 2008). Although there is no global population estimate for either species, both have disappeared from major portions of their range. However, both species occur in the Sundarbans in sufficient numbers that it may serve as a global safety net for preventing their extinction. Besides, world's second largest documented population, about 1,144 individuals of Indo-Pacific bottlenose dolphin, *Tursiops aduncus*, lives at the northern tip of the Swatch of No Ground in the Bay of Bengal, Bangladesh (Smith et al. 2008, 2010).

The varied and colorful birdlife includes about 315 species including 95 species of waterfowl and 38 species of raptors (Sarker 1985). Most readily seen are no less than nine species of kingfisher, including *Pelargopsis amauropterus*, *P. capensis*, *Haliaeetus leucogaster*, and *Ichthyophaga ichthyaetus*; raptors, the globally threatened *Leptoptilos javanicus*, *Heliopais personatus*, *Pandion haliaetus*, and *Ichthyophaga ichthyaetus*; herons; egrets; storks; sandpipers; whimbrel; curlew; and numerous other waders are seen along the muddy banks and on the chars or sandbanks. There are many species of gulls and terns, especially along the coast and the larger waterways. Apart from those species particularly associated with the sea and wetlands, there is also a considerable variety of forest birds such as woodpeckers, barbets, shrikes, drongos, mynahs, minivets, babblers, and many others (Salter 1984; Scott 1991).

The area is famous for the eponymous flagship species Royal Bengal tiger (*Panthera tigris tigris*) and leopard (*Panthera pardus fusca*), apart from the numerous faunal species. It is estimated that there are now about 500 Royal Bengal tigers and about 30,000 spotted deer in the area. In addition, there are several other threatened mammal species, such as the capped langur (*Semnopithecus pileatus*/*Trachypithecus pileatus*) (Vulnerable or VU), smooth-coated otter (*Lutrogale perspicillata*) (VU), Asian small-clawed otter (*Aonyx cinereus*) (VU), and large Indian civet (*Viverra zibetha*) (NT). The eco-region also harbors several smaller predators such as jungle cat (*Felis chaus*), fishing cat (*Prionailurus viverrinus*), leopard cat (*P. bengalensis*), Javan rhinoceros (*Rhinoceros sondaicus)*, Indian rhinoceros (*R. unicornis*), water buffalo (*Bubalus bubalis*), *C. duvauceli*, and gayal (*Bos frontalis*, *A. porcinus*). Other mammals include chital/spotted dear (*Cervus axis*/*Axis axis*), barking deer (*Muntiacus muntjak*), wild boar (*Sus scrofa*), saltwater crocodile (*Crocodylus porosus*), mugger (*C. palustris*), gharial (*Gavialis gangeticus*), common gray mongooses, foxes, jungle cats, flying foxes, and pangolins.

17.3 Significance of Wetlands

17.3.1 Significance of Wetlands as Biodiversity "Hot Spots"

About 400 species of vertebrates and 300 species of plants in Bangladesh are solely dependent upon the wetlands for their life or a part of it. About 260 species of freshwater fish live in the wetlands and are the main source of daily protein supplement (70%) in the country. The deepwater rice or floating rice had been the main source of food supplement in those areas before the introduction of high-yielding varieties (HYV) in the 1960s. It is widely believed that Bangladesh's aquatic diversity has not yet been adequately described. At any rate, the known levels of endemism in the Ganges-Meghna-Brahmaputra (GMB) basin are very high, 25% of the aquatic species found in this basin being endemic. Indigenous fish and prawn residents in wetlands of Bangladesh move into the floodplains to reproduce, and their offsprings use the wetlands for feeding and growth**.** Similarly, catadromous freshwater giant prawn (*M. rosenbergii*) and others needing an estuarine environment to reproduce migrate to the coasts from the rivers. Postlarvae of freshwater giant prawn again migrate upstream into the freshwater rivers and then laterally move into the floodplains to feed and grow. At the end of the flood season, fish and prawn on the floodplains move, with the receding waters, back into deeper permanent water bodies such as rivers, canals, and *beels* to survive through winter and dry season. They become the mother fishery stock to breed and multiply in the inundated floodplain in the following monsoon. In addition, several species of freshwater mussels and snails also occur in the floodplains. Several species of freshwater mussels bear pink pearls. Mussel/snail shells are also used to make lime for use with betel leaves and nuts. Snails are harvested to use their meat for feeding the freshwater giant prawn under cultivation. The country supports 650 species of birds[2] within an area of 144,000 km^2. This represents about 30% of the total number of bird species recorded from the entire Indian subcontinent and over 7% of the globally known bird species. The Assam plains in eastern Bangladesh are identified as Endemic Bird Area (EBA) by BirdLife International with the status of "urgent conservation priority."

17.3.2 Significance of Wetlands as Livelihoods of People

Poorer section of the society near any wetland depends totally on the goods and services of the wetland for livelihood. The rich biodiversity in wetlands of Bangladesh (as discussed in Sects. 17.2.1 and 17.2.2) contributes significantly to diversify livelihoods of people. It is estimated that about two-thirds of people living in rural Bangladesh (mostly poor) depend on wetlands for a variety of purposes such as water for drinking, irrigation, food production (agriculture, aquaculture), fishing (fish, prawn, crabs), livestock grazing/fodder, bird hunting, medicines, snail, honey, vinegar, glue, wax, firewood, timber, thatching materials, harvesting grasses

[2] https://www.cbd.int/doc/world/bd/bd-nr-04-p2-en.pdf

and seaweeds, and tourism/recreational business (Islam 2010; Kibria 2014). It has been estimated that over 60 million people are dependent on aquatic resources every day in Bangladesh, of which about a million are full-time and part-time fisher folk. The fishery and agriculture sectors employ 5% and 64.5% of the country's total workforce, respectively.[3] Over 500,000 fishers are involved in catching hilsa, and over 2,000,000 people are indirectly involved in the distribution and sale of the fish and other ancillary activities such as net and boat making, ice production, processing, and export.[4] About 600,000 people are employed directly in shrimp aquaculture in Bangladesh that supports approximately 3.5 million dependents.[5] The Sundarbans alone provides livelihood and employment to an estimated 112,000 people (http://iucn.org/about/union/commissions/ceesp/?21654). Out of 3700 people on St. Martin's Island, most are fishermen depending solely on fishing, shrimp fry collection, fish drying, exporting dry seaweeds, agriculture, and ecotourism business (Thompson and Islam 2010). About 200,000 people depend on resources of Hakaluki *haor* for agriculture (rice, oil seeds, pulses), fishing, duck rearing, cattle grazing, fish culture/aquaculture, snail collection, bird hunting, fuelwood collection (reeds), and sand extraction[6] (Islam 2010). Tanguar *haor* supports livelihood for more than 60,000 people (agriculture, commercial fishing, and trade in fuelwood, hunting/trapping waterfowl, the harvesting and sale of grasses and reeds, and coal collection). The principal activities of people living in Tanguar *haor* are agriculture (36.78%), fishing (21.56%), day labor (21.07%), business (7.55%), sand and coal collection (3.4%), and others (9.8%) (Alam et al. 2012). A significant number of people are employed in waterway transportation and ecotourism associated with wetlands across Bangladesh; but there is no statistics available on this.

17.3.3 Significance of Wetlands as Source and Sink of Greenhouse Gas

Wetlands used for rice farming (in waterlogged areas) emit significant quantities of methane (Yan et al. 2003). Dams/reservoirs emit GHG (greenhouse gas: methane, carbon dioxide) in several ways, from breakdown/decomposition of soil and plant carbon (by bacteria) and anaerobic conversion of organic carbon to methane and rotting/decay of vegetation at the bottom of dams/lakes (Bates et al. 2008). Though wetlands such as lakes/reservoirs are important sources of GHG emissions, they also provide an important role in climate change mitigation, for example, by exporting C and N, as fish biomass in fisheries and aquaculture. Afforestation, reforestation, and mangrove restoration remove CO_2 from the atmosphere and act as carbon sinks (carbon sequestration). Mangrove forests store more carbon than any other

[3] http://iucn.org/about/union/commissions /ceesp/?21654

[4] http://www.boblme.org/documentRepository /BOBLME-2012-Brochure-02.pdf

[5] https://www.academia.edu/7146833/Present_Status_and_Potentiality_of_Shrimp_in_Bangladesh

[6] https://en.wikipedia.org/wiki/Hakaluki_Haor; http://en.banglapedia.org/index.php?title= Hakaluki_Haor

tropical forests. In particular, mangrove-sediment stores about five times more carbon (Stecker and Wire 2012). Thus, restoration of mangrove forest would be an environment-friendly solution for mitigating climate change or global warming. Wetland systems have significant quantities of carbon stored in the vegetation and soil and hence have received increased attention for playing an important role to reduce GHG emissions (Box 17.1). As wetland soils are saturated with water creating an environment low in oxygen, the carbon that is sequestered is buried remaining relatively stable without decaying. When drained, such as through development, conversion to agriculture, or aquaculture, the carbon in the soil is exposed and oxidized, and that releases the stored carbon as CO_2 into the atmosphere.

17.3.4 Significance of Wetlands in Disaster Mitigation

Wetlands such as mangroves play an important role in the protection of the coast from natural and climate change-related disasters (cyclones, storm surges, tsunamis, rise in sea level). Wetlands could act as a barrier (live seawalls) against disasters and help minimize damage to property and life. In India, the Philippines, and Vietnam, people have been protected and suffering less damage to lives and property from disasters like tsunamis, cyclones, and other natural disasters in locations where mangroves were intact (shielded with dense forest). On the contrary, people suffered extensively in locations where either mangroves were lost, cleared, or absent or mangroves have been converted to shrimp farms (MSSRF 2005).

Box 17.1 Why Wetlands Are a Good Carbon Sink? (Lehmann et al. 2006)

- Only 6% of the world's land is wetlands and about 14.5% of the world's soil carbon is found in wetlands.
- Coastal wetlands (salt marshes, mangroves, and seagrass beds) can store large quantities of carbon. Some of the carbon that wetland plants capture gets added to soils either via internal transport in the plant or as plant parts, such as leaves and roots, which die and become incorporated into the soil.
- Since wetland soils are largely anaerobic (without oxygen), carbon that is incorporated into the soils decomposes very slowly and can persist for hundreds or even thousands of years. Decomposition of organic plant material is much slower when oxygen is not present, so the carbon present in this plant material remains intact, rather than being broken down by microbes and respired back to the atmosphere. As a result, wetlands are very good carbon sinks (i.e., wetlands store a lot of carbon).

Bangladesh frequently experienced extreme cyclones, *viz*., Bhola cyclone 1970, Bangladesh cyclone 1991, Cyclone Sidr 2007, and Cyclone Aila 2009.

17.4 Conclusion

Wetlands provide a wide range of economic, social, and ecological benefits. Wetlands of Bangladesh are "lifeblood" since two-thirds of people (mostly poor) depend on wetlands for water, agriculture, aquaculture, fishing, wild food, medicines, fuelwood, furniture wood, honey, thatching materials, bird hunting, sand extraction, river transportation, and ecotourism business. Apart from biodiversity and livelihood support, wetlands of Bangladesh provide other ecosystem services such as flood control (store excess water), climate change mitigation (forests and wetland sediments as carbon sinks), and disaster mitigation (mangrove acting as live walls to reduce impact of cyclones, tsunamis). However, wetlands of Bangladesh and its ecology and biodiversity are under increasing threats due to pollution (pesticides, metals), climate change (rise in sea level), population increase, conversion and drainage of wetlands for agriculture and development, deforestation, irrigation and flood control projects, water diversion, nature siltation, overexploitation of resources (fish, water birds, plants), overgrazing by livestock, and transboundary water regulation.

Conservation, restoration, afforestation, and management of wetlands would be vital since a healthy biodiversity-rich environment is more resilient to climate and environmental shocks and various other stresses. In addition, livelihood diversification, awareness, and education of local communities on preservation and conservation of wetlands are needed to reduce pressure on wetland resources. Community-based participatory wetland resource management (bottom-up approach) looks good for conserving wetland biodiversity and aquatic resources and is being followed in Bangladesh since long. But this would not be just enough without comprehensive policies, strategies, and management plans combining political, economic, social, and technological approaches to prevent further degradation of wetlands.

Acknowledgment The authors express their acknowledgment to S. N. Islam for permitting us to reproduce Fig. 17.1 from their earlier publication (Islam 2010) and to the anonymous reviewer(s) for their kind review of the earlier version of the manuscript.

References

Alam ABMS, Chowdhury MSM, Sobhan I (2012) Biodiversity of tanguar haor: a ramsar site of Bangladesh volume I: wildlife. IUCN Bangladesh, Dhaka, p xi+234

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water. Technical paper of the intergovernmental panel on climate change. IPCC Secretariat, Geneva, p 210

Curtis SJ (1933) Working plan for the forests of the sundarbans division for the period from 1st April 1931 to 31st March 1951. Bengal Government Press, Calcutta

Fahrni M, Smith EBD, Mansur RM, Diyan MAA (2008) Two incidences of fishing gear entanglement of Ganges River dolphins *Platanista gangetica gangetica* in waterways of the Sundarbans mangrove forest, Bangladesh. Aquat Mamm 34(2):362–366

Fischlin A, Midgley GF, Price JT, Leemans R, Gopal BC, Turley C et al (2007) Ecosystems, their properties, goods, and services. In: Parry ML, Canziani OF, Palutikof JP, Van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 211–272

Haq AHMR, Asaduzzaman M, Ghosal TK (2002) Soil-less agriculture in Bangladesh. A Grameen Trust, Bangladesh publication under the component of research for poverty alleviation. Grameen Bank Bhaban, Mirpur, p 111

Haroon AKY (2010) Shark fishery in the Bay of Bengal, Bangladesh. In: Hoq ME, Haroon AKY and Hussain MG (eds) Shark fisheries in the Bay of Bengal, Bangladesh:Status and potentialities. p 11–32. Workshop Proceedings of the Support to Sustainable Management of the BOBLME Project, Bangladesh Fisheries Research Institute, 76 p

Haroon AKY, Pittman KA (1997) Rice-fish culture: feeding, growth and yield of two size classes of *Puntius gonionotus* Bleeker and *Oreochromis* spp. in Bangladesh. Aquaculture (The Netherlands) 154:261–281

Haroon AKY, Dewan S, Karim SMR (1992) Rice-fish production systems in Bangladesh. In: Dela Cruz CR, Lightfoot C, Costa-Pierce BA, Carangal VR (eds) Rice-fish research and development in Asia. ICLARM conference proceeding, Philippines, pp 165–171

Hoq ME (2008) Sundarbans mangrove: fish and fisheries ecology, resources, productivity and management perspectives. Graphic Media, Dhaka

Hoq ME, Haroon AKY (eds) (2012) National consultation meeting report on sundarbans fisheries of Bangladesh: current status and potentialities. SBOBLME Pub./Rep. 6. Support to sustainable management of the Bay of Bengal Large Marine Ecosystem (BOBLME) Project, Bangladesh Fisheries Research Institute (BFRI), Bangladesh, p 56. ISBN:978–984–33-5527-0. http://www.scientificamerican.com/article.cfm?id=restoring-mangroves-may-prove-cheap-way-to-cool-climate

Hoq ME, Haque MA, Haroon AKY (2012) Coastal and marine fisheries resources management-conservation. Training manual for awareness building of fishers and fish traders (In Bangla). Support to Bay of Bengal Large Marine Ecosystem (SBOBLME) Project. Bangladesh Fisheries Research Institute, Maskanda, p 76

Hussain KZ, Acharya G (eds) (1994) Mangroves of the Sundarbans. Vol. 2: Bangladesh. IUCN, Bangkok, Thailand

Islam SN (2010) Threatened wetlands and ecologically sensitive ecosystems management in Bangladesh. Front Earth Sci China 4(4):438–448

Islam MN, Kitazawa D (2013) Modeling of freshwater wetland management strategies for building the public awareness at local level in Bangladesh. Mitig Adapt Strateg Glob Chang 18:869–888

Islam MA, Islam MZ, Barman SK, Morshed F, Marine SS (2015) Study on present status of fish biodiversity in wetlands of sylhet district, Bangladesh. Agric For Fish 4(6):296–299

IUCN and CNRS (2006) Natural resource economic evaluation of Hakaluki haor. Coastal and wetland biodiversity management project: Hakaluki haor component (BGD/99/G31). International Union for Conservation of Nature and Center for Natural Resource Studies. Ministry of Environment and Forests, Government of Bangladesh, p 64

IWRB (1992) Action programme for the conservation of wetlands in South and West Asia. Northeast regional water resources development project (FAP 6), 1992. Draft thematic study. Regional Water Resources Development Status, Flood Plan Coordination Organization, Government of Bangladesh, Dhaka

Khan MAR (1986) Wildlife in Bangladesh mangrove ecosystem. J Bombay Nat Hist Soc 83:32–48

Kibria G (2014) Mangrove forests- its role in livelihoods, carbon sinks and disaster mitigation. https://www.researchgate.net/publication/261178318_Mangrove_Forests-Its_Role_in_Livelihoods_Carbon_Sinks_and_Disaster_Mitigation

Kibria G, Haroon AKY, Nugegoda D, Rose G (2010) Climate change and chemicals: environmental and biological aspects. New India Publishing Agency, New Delhi

Kibria G, Haroon AKY, Nugegoda D (2013) Climate change and agricultural food production: impacts, vulnerabilities and remedies. New India Publishing Agency, New Delhi, p 300

Kibria G, Haroon AKY, Nugegoda D (2016) Climate change and water security: impacts, future projections, adaptations and mitigations. New India Publishing Agency, New Delhi, 312 p. (with 58 Tables & 36 Figs.); ISBN:978-93-85516-26-9. https://www.researchgate.net/publication/303218799_Climate_Change_Water_Security_-_A_Book_Summary

Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems – a review. Mitig Adapt Strateg Glob Chang 11:403–427. doi:10.1007/s11027-005-9006-5

MSSRF (2005) MS Swaminathan Research Foundation. 2005 Tsunami & Pichavaram mangroves. http://www.mssrf.org/

Nishat A (1993) Freshwater wetlands in Bangladesh: status and issues. In: Nishat A et al. (eds) Freshwater wetlands in Bangladesh: issues and approaches for management. Published by IUCN-The World Conservation Union, Dhaka

Nishat A et al. (eds) (1993) Freshwater wetlands in Bangladesh: issues and approaches for management. Published by IUCN-The World Conservation Union, Dhaka

Salter RE (1984) Integrated development of the Sundarbans, Bangladesh: status and utilization of wildlife. FAO: TCP/BGD/2309(MF). Report No. W/ROO34. FAO, Rome, p 59

Sarker SU (1985) Density, productivity and biomass of raptorial birds of the Sundarbans, Bangladesh. Proceedings of SAARC seminar on biomass production, Dhaka, pp 84–92

Scott DA (1991) Asia and the Middle East in wetlands. Finlayson M, Moser M (eds). Oxford, pp 151–178. ISBN: 0-8160-2556-8

Siddiqui KU, Islam MA, Kabir SMH, Ahmad M, Ahmed ATA, Rahman AKA, Haque EU, Ahmed ZU, Begum ZNT, Hassan MA, Khondker M, Rahman MM (eds) (2007a) Encyclopedia of flora and fauna of Bangladesh, Freshwater fishes, vol 23. Asiatic Society of Bangladesh, Dhaka

Siddiqui KU, Islam MA, Kabir SMH, Ahmad M, Ahmed ATA, Rahman AKA, Haque EU, Ahmed ZU, Begum ZNT, Hassan MA, Khondker M, Rahman MM (eds) (2007b) Encyclopedia of flora and fauna of Bangladesh, Marine fishes, vol 24. Asiatic Society of Bangladesh, Dhaka

Smith BD, Ahmed B, Mansur RM, Strindberg S (2008) Species occurrence and distributional ecology of near shore cetaceans in the Bay of Bengal, Bangladesh, with abundance estimates for Irrawaddy dolphins, *Orcaella brevirostris* and finless porpoises, *Neophocaena phocaenoides*. J Cetacean Res Manag 10(1):45–58

Smith BD, Diyan MAA, Mansur RM, Fahrni-Mansur E, Ahmed B (2010) Identification and channel characteristics of cetacean 'hotspots' in waterways of the eastern Sundarbans mangrove forest, Bangladesh. Oryx 44(2):241–247

Stecker T, Wire C (2012) Restoring mangroves may prove cheap way to cool climate

Thompson PM, Islam MA (eds) (2010) Environmental profile of St. Martin's Island. United Nations Development Programme, Dhaka

UNEP (2012) Ecosystems based adaptation guidance. Moving from principles to practice (Lead authors: Ailbhe Travers, Carmen Elrick, Robert Kay and Ole Vestergaard). United Nations Environment Programme. http://www.unep.org/climatechange/adaptation/Portals/133/documents/Ecosystem-Based%20Adaptation/Decision%20Support%20Framework/EBA%20Guidance_WORKING%20DOCUMENT%2030032012.pdf

Yan X, Ohara T, Akimoto H (2003) Development of region-specific emission factors and estimation of methane emission from rice field in East, Southeast and South Asian countries. Glob Chang Biol 9:237–254

18 Valuing the Attributes of Wetlands in Coastal Areas of South Asia: Incorporating the Economic Value into Policy Making

Prosun Kumar Ghosh

Abstract

In recent years, understanding the economic consequences resulting from the loss of wetland goods and services because of intensifying threats, both geogenic and anthropogenic, to the coastal wetlands of South Asia has received great attention Greater need for conservation of these wetland ecosystems and preserving their natural resource bases have become apparent. Consequently, over the last two decades, economic valuation of the attributes of wetlands is being widely recognized in South Asia as the popular means of developing strategies for wetland resources management under such threats. The chapter, thus, endeavors to review comprehensively the theoretical and methodological aspects involved in the economic valuation of wetland attributes in general and presents a case study of a coastal wetland from Bangladesh for better understanding the valuation approaches in particular. The chapter also examines the challenges and issues commonly faced during the wetland valuation especially in the South Asian region. Finally, the chapter concludes that a better socially acceptable, economically viable, and environmentally sound policy action can be achieved for wetland conservation and management if all the economic values of the wetland are carefully considered.

Keywords

South Asia • Total economic value • Valuation approaches • Wetland attributes

P.K. Ghosh (✉)
Environmental Science Discipline, Khulna University, Khulna 9208, Bangladesh
e-mail: prosun_buet@yahoo.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_18

18.1 Introduction

Wetlands in coastal areas, whether fresh or saline, are important natural resources and are gaining increasing recognition in recent years as they play a central role in the coastal sedimentary environments where the freshwater inflow in combination with the tidal flow action develops wetland ecosystems at the continental margin. Therefore, the coastal wetlands constitute critical transition zones between continental landmasses, freshwater habitats, and the sea and are ecologically sensitive systems (Turner et al. 2000). These transition zones provide many essential ecosystem services including shoreline protection, organic decomposition, carbon sequestration, flood control, nutrient cycling, water quality improvement, habitat for migratory and resident animals, and regulation of fluxes of nutrients, water, particles, and organisms between land, rivers, and the ocean (Costanza et al. 1997; Levin et al. 2001). It is estimated that wetland ecosystems occupy approximately 6% of the global land area (Turner et al. 2004; Kirwan and Megonigal 2013). In terms of global land area coverage, it ranges from 917 to more than 1275 million ha with an estimated economic value of US$15 trillion per annum (Finlayson and Spiers 1999; Lehner and Döll 2004; MEA 2005). The estimated economic value of the wetland ecosystems highlights the value of wetlands to human population. Aside from the supply of numerous goods and services provided by wetlands to humankind resulting in a high wetland economic value, they have significant bearing on maintaining rich compositions of the biodiversity in natural ecosystems (Levin et al. 2001; Sathirathai and Barbier 2001; Turner et al. 2004). But these multiple goods and services provided by the wetlands are often overlooked resulting in indiscriminate exploitation of wetland resources (Ghosh and Mondal 2013). As a result, wetlands are one of the most threatened and vulnerable natural resources especially in coastal areas worldwide (Turner et al. 2004; Kirwan and Megonigal 2013).

The South Asian region (India, Pakistan, Bangladesh, Nepal, Bhutan, Maldives, Afghanistan, and Sri Lanka) possesses extensive coastal wetland ecosystems that provide a wide variety of goods and services for the coastal population through maintaining an inextricable relationship between livelihoods and community people in this region (WIAP-WB 2000; UNDP 2012). Of the South Asian countries, in Bangladesh the combined floodplains of the Ganges and Brahmaputra rivers largely support the country's wetlands especially in coastal areas. However, in recent years the wetlands in the South Asian region encounter ever-increasing threats from both natural and anthropogenic sources, thereby impacting their goods and services potentials. The major threats include development interventions, excessive harvesting of wetland resources, coastal water pollution, an increasing occurrence of disasters, and vulnerability to climate change (WIAP-WB 2000; MEA 2005; UNDP 2012). Moreover, over the past few decades, the wetlands in the coastal areas of the South Asian regions have increasingly experienced over-exploitation of coastal wetland resources, agricultural expansion with excessive use of fertilizers and pesticides, pollution from urban conglomerates, and oil spillage (Sharma 1996; UNDP 2012). So, the wetland ecosystem degradation in this region is mainly because the intrinsic economic values the wetlands possess are often overlooked and not duly considered by the policy makers. However, effective and efficient management of the wetland ecosystems in coastal areas of South Asia is imperative for achieving sustainable wetland resources management under different environmental vulnerabilities and/or threats in the future. The economic valuation of wetland ecosystems can give an important insight for effective and efficient management and into environmental decision-making relating to the wetlands. Therefore, the chapter endeavors to review comprehensively the theoretical and methodological aspects involved in the economic valuation of wetland attributes and presents a case study from Bangladesh for better understanding the valuation approaches and its application for wetland resources management in coastal areas.

18.2 Wetland Categorization

In order to estimate the economic value of wetlands, understanding the nature and type is very important because the nature and type of wetlands have important bearing on the multiple benefits provided by wetlands. Understanding of the wetland category is also imperative for estimating the economic value comprehensively. A wide variety of wetlands are found in the South Asian region. The seasonal rainfall and extensive floodplains in the region make up wetland habitats in this region. Although professionals have categorized wetlands in different ways, a specific categorization of wetlands is required in the South Asian region for sustainable management of the wetland resources in the region. Therefore, the classification system proposed by Gopal and Krishnamurthy (1993) for categorizing the wetlands in the South Asian region has been adopted in this chapter. As per the classification system, the wetlands in South Asia can be categorized into freshwater and saline water wetlands based on their hydrological nature (i.e., type of water body, duration of flooding during monsoon) and the characteristics of vegetation (i.e., herbaceous or woody) that the wetland supports. The wetland categories are illustrated in Table 18.1, while more details of the proposed classification and nature of the wetlands in South Asia can be found elsewhere (Gopal and Krishnamurthy 1993; Haque et al. 2011). The table depicts that the wetlands either freshwater or saline water can be associated with permanent flooding or temporary flooding and have diverse vegetation attributes. Understanding vegetative attributes of wetlands is important because the types of goods and services provided by the wetland ecosystems are dependent on their natural setting and vegetation attributes.

Of the freshwater wetlands, temporary wetlands can be flooded or retain water for 3–9 months in a year, while in the case of saline water wetlands, water retention in the depressed basin exists for 1–3 months in a year. In Bangladesh, temporary freshwater wetlands, which are locally called as *beels*, are abundantly found in coastal areas. The case study described in the last section (see Sect. 18.7) of this chapter deals with such wetland ecosystems.

Table 18.1 Wetland categorization in South Asia

Major category	Subcategory	Nature of wetland	Vegetation attributes
Freshwater wetland	Permanent freshwater wetland (flooding throughout the year)	Lotic freshwater wetland (e.g., rivers, streams)	Herbaceous (reeds, bamboos, grasses) and woody (riparian fringing forests)
		Lentic freshwater wetland (e.g., lakes, ponds, reservoirs)	Herbaceous (submerged and floating macrophytes, sedges, reeds) and woody
	Temporary freshwater wetland (3–9 months of flooding)	Lotic freshwater wetland (e.g., floodplains of streams and rivers)	Herbaceous (reeds, grasses, sedges, cattails and other herbs) and woody (floodplain forests)
		Lentic freshwater wetland (e.g., lakes, ponds, reservoirs)	Herbaceous (submerged and floating macrophytes, sedges, reeds and other tall emergent vegetations)
Saline water wetland	Permanent saline water wetland (flooding throughout the year, e.g., mangroves)		Herbaceous (coastal beds of kelp and angiosperms) and woody (mangroves)
	Temporary saline water wetland (1–3 months of flooding, e.g., inland saline habitats)		Herbaceous (halophytes) and woody (saline scrubs)

Modified from Gopal and Krishnamurthy (1993)

18.3 Attributes of Wetland Ecosystems

18.3.1 Goods and Services of Wetlands

Wetlands in coastal areas support many of the life forms including human population on Earth as it generates essential ecosystem services that are required for sustenance of life. In economic valuation literature, these ecosystem services provided by the wetland can be termed as attributes. Inextricable interactions among physical, biological, and chemical components of a wetland ecosystem enable the wetland to perform many vital functions and consequently generate wetland goods and services. Coastal wetlands also make coastal population more adaptive and resilient by providing important functions and services through storing floodwater, buffering storm surges, controlling erosion, improving water quality, etc. that are presented in Table 18.2.

The wetland ecosystem services are categorized into four major groups proposed by MEA (2005), *viz.*, provisioning, regulatory, supporting, and cultural services. The provisioning services of coastal wetlands are the benefits that people directly obtain from the wetland. These involve the resources or products of the wetlands such as food, freshwater, raw materials (wood), genetic resources (biotechnology), medicinal resources, ornamental and resources (skin, shells, flowers). The regulatory services of coastal wetlands involve the benefits that are related to the essential ecological processes and life support systems such as gas and climate regulation, erosion control, water supply and regulation, waste treatment, and pollination. For

Table 18.2 Important goods and services of coastal wetlands

Wetland services	Wetland goods	Wetland ecosystem functions
Provisioning	Food	Production of fish, invertebrates
	Freshwater	Filtering, retention, and storage of fresh water (e.g., in aquifers)
	Fiber and fuel	Production of timber, fuel wood, peat, and fodder
	Biochemical products	Extraction of materials from biota
	Genetic resources	Genetic material and evolution in wild biota
Regulating	Climate regulation	Regulation of global temperature, precipitation etc. at global or local levels
	Pollution control	Recovery of mobile nutrients and detoxification
	Water regulation	Regulation of hydrological flows
	Erosion control	Retention of soil within an ecosystem
	Natural hazards	Controlling floods and storms
	Pollination	Role of biota in movement of floral gametes
Supporting	Biodiversity	Habitat for resident and transient populations
	Nutrient regulation	Role of biota in storage and recycling of nutrients
	Soil formation	Weathering of rocks
Cultural	Recreation	Providing opportunities for recreational activities
	Aesthetic information	Appreciation of attractive landscape features
	Spiritual and historic information	Personal feelings
	Science and education	Use of natural systems for excursions and training

Compiled and modified from Costanza et al. (1997) and MEA (2005)

example, estuaries provide regulating services because they absorb the force of storms in coastal areas and regulate changes in air and water temperature. On the contrary, the supporting services of coastal wetlands are the provision of coastal wetlands to provide habitats for flora and fauna in order to maintain biological and genetic diversity such as primary production and soil formation. Finally, the cultural services are the source of inspiration to human culture, education, recreation, spiritual, and historic information. However, more details of the wetland ecosystem services can be found elsewhere (Costanza et al. 1997; MEA 2005).

18.3.2 Wetland Attributes and Human Dependency

Coastal areas constitute approximately 4% of the Earth's total land area and support more than one third of the world's population and 90% of marine fisheries catch (MEA 2005; Barbier 2013). It is also estimated that approximately 400 million people live in coastal areas of South Asia depending extensively on coastal wetland ecosystems for their livelihoods (UNDP 2012). These estimates are indicative of the human dependency on coastal wetlands and pinpoint a direct relation of human population with wetland's provisioning services because these wetlands provide numerous ecosystem goods to a large number of ever-increasing coastal populations and protect them against loss of infrastructures and lives. Coastal wetlands also provide habitats that support seasonal or perennial fisheries essential for not only migratory and resident birds but also coastal people whose livelihoods are dependent on the coastal wetlands. This type of human-wetland dependency relationship is well depicted in the form of a case study in the last section of this chapter wherein the direct relevance of the coastal freshwater wetland for sustenance of local livelihoods is evident.

People living in and around a wetland in coastal areas are directly dependent for their drinking, domestic, irrigation, fishing, washing, bathing, and several other purposes on the wetland. Beside these direct wetland benefits, coastal wetlands provide many important ecosystem services that are not usually transacted in our conventional economic markets such as nutrient cycling, waste assimilation and pollution control, breeding ground for fish species, groundwater recharge, soil erosion and flood control, and local climate regulation. These attributes are often overlooked and undervalued by the community and policy makers, resulting in indiscriminate exploitation of the natural resource bases in wetlands with development interventions including agricultural conversions. Since, the long-term sustainability of the coastal population is related to wetland ecosystem attributes, ensuring wise use of coastal wetland resources is important for sustainable wetland resources management.

18.4 Concept of Total Economic Value

Over the past few decades, economic valuation of wetlands in coastal areas has become a widely recognized means of wetland resources management (Guo et al. 2001; Kumar and Kumar 2008). Understanding of the concept of total economic value (TEV) is a prerequisite to elucidate the economic values of wetlands comprehensively. Whenever we think of a wetland, the value what comes to one's mind is the direct use values derived directly by harvesting the resources such as fish and water lily (as vegetable) for human consumption or fodder for domestic animals. However, the wetland values are widely ranging from such direct and tangible benefits to several non-tangible benefits.

The term "economic valuation of wetlands" is usually defined as the effort to assign quantitative values to the goods and services derived from the wetlands (Kumar and Kumar 2008). Generally, the TEV of a wetland (Fig. 18.1) can be categorized into two broad groups such as use attribute/value (instrumental value) and nonuse attribute/value (intrinsic or passive value).

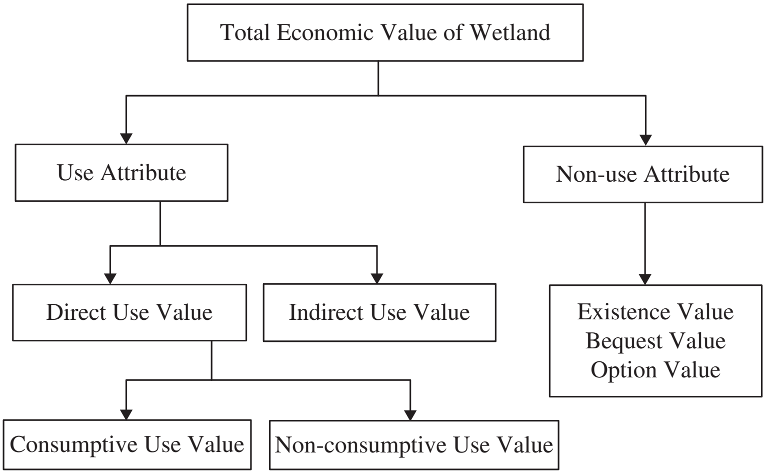


Fig. 18.1 Taxonomy of the economic value of wetlands (compiled and modified from Oglethorpe and Miliadou 2000; Alam and Marinova 2003; Samonte-Tan et al. 2007; Nijkamp et al. 2008)

The components of the use attribute are the benefits individuals derive from using wetland resources, whereas the components of the nonuse attributes reflect the values individuals attach to wetlands even if they themselves do not use it (Smith 1987; Cameron 1992; Bateman et al. 2002). The use attributes can be further subdivided into direct use values and indirect use values. Direct use values are derived from the actual use of wetlands either in a consumptive way (may be also called extractive value, e.g., timber harvesting, fishing, and fodder collection) or a nonconsumptive way (e.g., bird watching, boating, or other recreational activities). Indirect use values of wetlands reflect the environmental services derived from wetland ecosystem functions such as watershed protection, soil stabilization, and carbon sequestration.

On the contrary, nonuse attributes of wetlands are inherent characteristics of the wetlands and are measures of the satisfaction (in terms of economic welfare) we derive from the wetland ecosystem. Thus, nonuse attributes are associated with the benefits derived simply from the knowledge that wetland resources such as species or habitat are maintained. By definition, such a value is not associated with the use of the resource or the tangible benefits derived from wetland's resource use. Hence, nonuse values are intangible benefits that people derive from preservation of environmental assets or wetland resources (Thomas et al. 1991; Stevens et al. 1995). These nonuse attributes can be further divided into existence, bequest, and option values, which are presented in Fig. 18.1 (Oglethorpe and Miliadou 2000; Alam and Marinova 2003; Samonte-Tan et al. 2007; Nijkamp et al. 2008). First is the existence value, which is not associated with the use of the wetland goods but reflects a value that will continue to exist independently. In the case of existence value, an individual derives satisfaction from simply knowing that a wetland resource exists. A good example of existence value is the dolphin usually observed in the South

Asian region. Many people, who have never seen dolphin, will nevertheless be willing to contribute money or even time for dolphin protection and conservation program so that they are not hunted. Second is the bequest value that arises from the benefits derived by individuals from the awareness that future generations may benefit from the use of the wetland resources. Thus, in the case of bequest value, individuals assign monetary values to wetland resources for the benefit of future generations. Third is the option value, which is associated with an individual's knowledge that the wetland resources will be available for future use or enjoyment. Thus, the TEV of wetlands is regarded as a result of the aggregation between various uses and nonuse attributes (commonly called as values), and understanding of the TEV of wetlands is useful for informed decision-making for better wetland resources management.

18.5 Overview of Valuation Approaches

In environmental economics literature, it is well recognized that the annual net benefits generated from coastal ecosystems are the sum of all net benefits obtained from use and nonuse attributes of the wetland (Samonte-Tan et al. 2007). To understand these benefits from coastal wetland ecosystems, valuing its attributes is necessary and, thus, adopting valuation methods is compulsory to comprehensively understand the multiple benefits from wetland ecosystems. An array of valuation techniques is commonly adopted to estimate the multiple benefits provided by the wetland ecosystems. As discussed earlier that the use attribute is one of the two broad categories of the TEV, the valuation techniques adopted to estimate the value of the use attributes of wetlands are very straightforward, while in the case of the nonuse attributes, it is often more complex and problematic. Moreover, selection of a proper valuation method to estimate the value of the attributes of wetlands is also challenging and complex and often needs to be justified. However, the techniques commonly applied to estimate the economic value of wetlands are shown in Fig. 18.2.

Generally, the valuation technique can be categorized into two broad groups such as market valuation and nonmarket valuation approaches (Fig. 18.2). The market valuation method depends on quantification products and is based on the estimates of quantities produced, prices, and costs of inputs (Turpie et al. 2010). Direct consumptive and nonconsumptive use values can be estimated using market-based approaches, whereas nonmarket approaches can be classified into two groups such as revealed preference and stated preference approaches. The first one (i.e., revealed preference approach) is based on observed methods or observed economic behavior in which benefits or damages from changes in wetland services are estimated by observing wetland user's behavior in simulated markets or in markets for related private goods (Haque et al. 2011). For example, the value of a national park can be estimated in terms of consumer surplus by the costs or expenditures incurred by an individual for travelling purpose to that national park. Moreover, if you think of valuing water pollution, then the cost of water pollution can be estimated by analyzing residential property value near the polluted site. However, production function

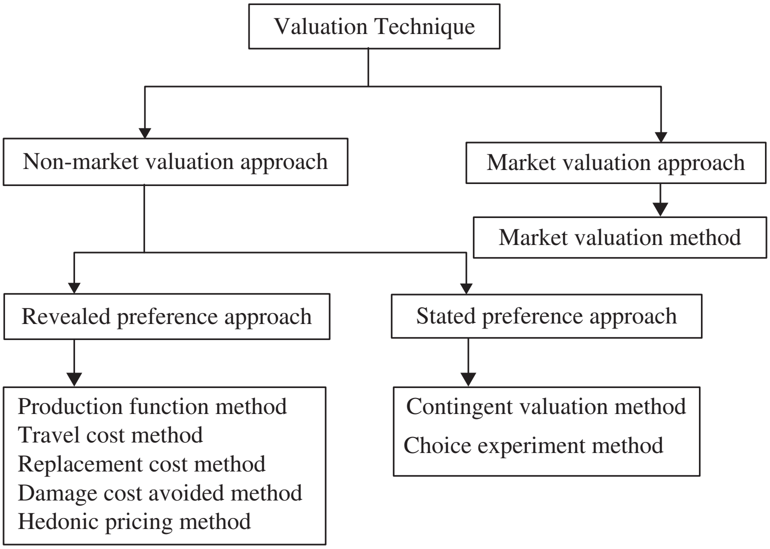


Fig. 18.2 Valuation methods for estimating economic values of the wetland ecosystems

methods are based on economic input-output production functions. In this method, the wetland resources are considered as inputs in production processes for an economic output. For example, the economic value of mangrove wetlands can be estimated by recognizing its role in fisheries production. Another example includes the estimation of the economic value of groundwater recharge function as an indirect use value of coastal wetlands, and in that case the welfare changes due to the increase in water table can also be estimated by the production function approach.

The travel cost approach is a technique popularly employed in estimating the monetary benefit obtained from the cultural ecosystem service of coastal wetlands like recreational services. The main assumption underlying the approach is that the cost an individual incurred by visiting a wetland site including his/her spending time in the site will represent his/her recreational value of such wetland site. Accordingly, it is assumed that an individual's utility obtained from visiting a coastal wetland site is a function of the attributes of such coastal wetland and the individual's socioeconomic characteristics, which results in travel cost modeling of the visitation. The travel cost approach can be categorized into two methods, *viz.*, individual travel cost method and zonal travel cost method. In the first case, the annual number of visits by an individual to the wetland site is modeled with the travel cost and an individual's socioeconomic characteristics, resulting in a trip-generating demand curve. Thereafter, the area under the demand curve is calculated by integration, and an individual's consumer surplus is obtained. For the second method, different zones are demarcated around a wetland site to where an individual travels for his/her recreation in such a way that the travel cost from each zone to the wetland site is approximately same. After that, the trip-generating function as zonal visitation rate is modeled with the zonal travel costs and individual's characteristics, resulting in zonal travel cost modeling. It is notable that in the zonal travel cost method, the demand curve is prepared using the zonal visits instead of the individual's visits adopted in the individual travel cost modeling.

Hedonic pricing methods are also largely employed in wetland valuation, and the hedonic pricing model is grouped into hedonic property value models and hedonic wage models. For the first case of the hedonic pricing model, the basic underlying assumption is that there is an intrinsic relationship between a housing unit and coastal wetland amenities. Thus, the model is developed by taking into account the influences of environmental or wetland attributes on property or house values. The model assumes that an individual's utility is a function of the individual's consumption of a Hicksian composite private good and a vector of amenities associated with the individual's occupying house, *viz.*, the structural characteristics of the house (e.g., size, number of rooms, construction type), neighborhood characteristics (e.g., location of nearby schools, parks, hospitals, markets, working places), and environmental amenities (e.g., the presence of good water quality, clean air, the absence of noise pollution). On the other hand, the hedonic wage model is based on the assumption that employers always want to work in a pleasant or good environmental condition, and the environmental conditions are associated with the environmental, cultural, and social amenities of that working environment. Therefore, wage differentials in different areas are assumed to be the differences in the levels of environmental quality, and, thus, the wage differences of individuals are modeled to derive a hedonic wage model (Freeman et al. 2014).

Replacement cost method is used to estimate regulatory services of the wetland. For example, the cost of building embankments or dams is usually considered while estimating the value of flood control service of wetlands. Even damage cost avoided method can also be used instead, and in that case the costs of the damage to infrastructures, life, etc. due to flooding are estimated (Turpie et al. 2010). Benefit transfer method is usually used while estimating nonmarket values of the wetland services, and the method involves transferring values in monetary terms from another similar situation or location to the current situation or location for the same wetland good or service. Generally, this method is applied in the cases where there is a lack of available data for the wetland of interest and limited study time. For example, the method can be applied to estimate the value of the impact of water quality improvement on recreational value and public health in an urban area. Thus, the benefit transfer method could be most suitable in the case of urban wetlands.

The second set of approach under "nonmarket valuation approach" is the stated preference approach that is a survey-based methodology wherein valuation of wetland services is made through appropriately constructed questionnaire surveys. In this, individuals are asked to state their preferences for the valuation of the wetland services. The stated preference approach can be broadly categorized into (i) contingent valuation method and (ii) choice experiment method (Fig. 18.2). In contingent valuation method, individuals are asked to place a monetary value on wetland goods or services in question in a hypothetical market and then, the wetland benefits can be estimated using appropriate econometric models through eliciting individual's responses. The practical applicability of this method is shown by a case study from

Bangladesh in the last section of this chapter. However, the choice experiment method is further classified into conjoint analysis and choice modeling. In the case of conjoint analysis, respondents or individuals are required to assess preference and, thereby, choose between alternatives based on different levels of characteristics of the attributes of wetland ecosystems. The preference by the respondent is generally done through applying one of the three techniques such as contingent ranking, rating, and paired comparison. On the other hand, in choice modeling method, respondents are at first presented with a range of wetland use alternatives in which each alternative is characterized by several attributes with different levels. The choice modeling method is commonly applied for estimating wetland benefits in the case where multiple wetland use alternatives are in question. However, in the South Asian region, the application of different valuation approaches described herein can be found elsewhere (e.g., Haque et al. 2011).

18.6 Challenges of Wetland Valuation Studies in South Asia

Although a large number of wetland valuation studies have been conducted in developed countries, few studies on wetland valuation in the South Asian region have been done over the last two decades. The beginning of the wetland valuation studies in the region started during the late 1990s, and, now, valuation studies of the wetlands are increasingly being recognized in the region because of degradation and loss of the wetland ecosystem services abruptly (Haque et al. 2011). However, a number of challenges during the wetland valuation studies are well recognized in the region. The experiences of such challenges are presented in this section through reviewing relevant literature from the South Asian region and developing world (Alam 2006; Korsgaarda and Schou 2010; Haque et al. 2011; Christie et al. 2012).

In wetland valuation studies, a wide range of information and data are required to successfully estimate the economic values of wetlands. Usually, along with primary data, secondary data are also required. In South Asian countries, obtaining secondary data and information are very problematic because, on the one hand, in few cases environmental economists usually get published data in a very limited scale, but in most cases they do not get secondary data in published forms (e.g., air/water pollution data for valuing air/water pollution abatement benefit), and, on the other hand, a complex and unfriendly official system of the government often undermines the applicability of the wetland valuation approaches in the region.

Delineating clearly the spatial and temporal scale of the wetland is vital in wetland valuation. Without considering those scales, the estimation of wetland values does not represent the true value. The spatial scale of the wetland is the geographical extent of the wetland ecosystem services being valued and includes the location of stakeholder beneficiaries, whereas the temporal scale is the changes in the values of the services of wetland ecosystems over time (Korsgaarda and Schou 2010). The temporal scale should carefully be considered while estimating the economic values of wetlands. Since the natural setting and vegetation attributes of wetlands are influenced by the seasonal variability of different environmental factors, the goods and services provided by the wetlands are also influenced thereby. Hence, examining the wetland in specified spatial and temporal scales is challenging while valuation.

It is well reported that the South Asian region is vulnerable to climate change impact, and the mountainous ecosystems of South Asia are highly vulnerable to fragmentation because of changing climate (MEA 2005; Korsgaarda and Schou 2010). Thus, coastal areas including the coastal wetlands in this region would be affected, while intensity of flooding, storm surges, and rainfall would accelerate erosion and landslide problems in the region (Korsgaarda and Schou 2010). These events will affect the ecosystem services of the wetlands, and, therefore, identification of future uncertainties during the wetland valuation in this region is urgent. This is because wetland ecosystems may show catastrophic and/or irreversible and strong resilient responses under changing climate, and, consequently, the responses influence the degree of the diversity of wetland ecosystem services (Limburg et al. 2002).

In South Asian region, ignorance of the wetland values by the policy makers especially the nonmarket values is more common, and, thus, development interventions are commonly made at the cost of wetland ecosystem services without proper consideration of its non-tangible benefits. Another important issue is the survey design used in estimating the economic values of wetlands. The survey design for valuation of wetlands in this region is more complex compared to developed countries because of relatively high cost for the survey, and lack of public awareness of environmental problems makes the survey design challenging. Moreover, in many cases, people, during eliciting their willingness to pay (WTP) in contingent surveys, often show interest to spend time instead of money, and, thus, we need to adopt various approaches to the valuation of time such as the wage rate approach. However, it would be complex in valuing time if individual's income sources are not fixed and permanent as evident in this region (Alam and Marinova 2003). Therefore, the WTP survey design should incorporate this valuation issue in order to properly estimate the economic value of wetlands in this region. The inclusion of time in WTP survey can be better realized by a case study described in the following section of this chapter, and it is evident that a considerable number of people are willing to contribute time instead of money for the wetland management program in Bangladesh.

18.7 Case Studies from Coastal Area of Bangladesh

18.7.1 Coastal Wetlands of Bangladesh

Located in the southeastern part of the Indian subcontinent, Bangladesh with a 710 km long irregular coastline is surrounded by India in the north, west, and east and in the south by the Bay of Bengal (Islam 2010). There are a large number of wetlands occupying 7–8 million ha of the geographical area in Bangladesh. The types of wetlands include permanent rivers and streams (480,000 ha), estuarine and mangrove swamps (610,000 ha), shallow lakes and marshes (120,000–290,000 ha), large reservoirs (90,000 ha), small ponds and tanks (150,000–180,000 ha), shrimp farms (90,000–115,000 ha), and seasonally flooded floodplains (5,770,000 ha, Nishat 1993). Five categories of wetlands are identified in Bangladesh, *viz.*, saltwater wetlands, freshwater wetlands, palustrine wetlands, lacustrine wetlands, and manmade wetlands. The wetlands of Bangladesh can also be broadly classified into six major groups such as the Brahmaputra-Meghna floodplain, the Haor Basin of northeast region, lower *Punarbhaba* floodplain, Gopalganj-Khulna *Beels*, Chalan *Beel*, and Surma-Kushiyara floodplain (Islam 2010). Wetlands in the coastal area of Bangladesh play a crucial role in life support systems. The wetland ecosystems of the country are rich in biodiversity and house a large number of endangered and economically important species of national and international significance (Nishat 1993; Islam 2010). Moreover, the wetlands of the country support millions of coastal population in thousands of villages in rural Bangladesh providing employments, food, fuel, fodder, transportation, irrigation, etc. (Nishat 1993). Approximately 2.1 million ha of wetlands has been lost in the Ganges-Brahmaputra-Meghna floodplain mainly because of flood control, drainage, and irrigation development (Khan et al. 1994), indicative of the large extent of anthropogenic threats (Islam 2010). Therefore, understanding of the multiple benefits of coastal wetlands including its non-tangible benefits is necessary, and this can be achieved by a comprehensive valuation of the wetlands.

18.7.2 Case Study of Human Dependency on Coastal Wetlands

The economic valuation study presented here was conducted to realize the hidden values of the nonuse attributes of a particular type of coastal freshwater wetland (i.e., the Chanda *Beel* wetland ecosystem) in Bangladesh. The *beel* is a specific type of coastal freshwater wetland located in the southwestern coastal Bangladesh (Fig. 18.3). It falls under temporary freshwater wetland category as per the classification described in the previous section (see Sect. 18.2). The Chanda *Beel* wetland is a low-lying *beel* wetland in the Madhumati river floodplain ecosystem. It is located in Gopalganj district (an administrative unit) of Bangladesh at about 120 km south of Dhaka, the capital of Bangladesh, and the area experiences tidal influences. The district has five *Upazilas* (sub-administrative unit of a district in Bangladesh), namely, Gopalganj Sadar, Muksudpur, Kotalipara, Kashiani, and Tungipara. The freshwater wetland covers a total area of 10,890 ha of which about 60% fall under Muksudpur *Upazila*, 30% fall under Kashiani *Upazila*, and the remaining 10% fall under Gopalganj *Sadar Upazila* (LGED 2007).

The Madaripur *Beel* Route Canal (MBRC) and tributaries of the Kumar River supply water to the Chanda *Beel* freshwater wetland. Both the MBRC and the Kumar River receive waters from the Ganges river system. The wetland is connected with the MBRC by eight major canals and tidal water enters the wetland from the MBRC. Usually, inundation of the wetland starts from the middle of May, and the wetland remains inundated about 4–6 m during monsoon (i.e., June through October). In the early October, water starts receding, and the wetland dries

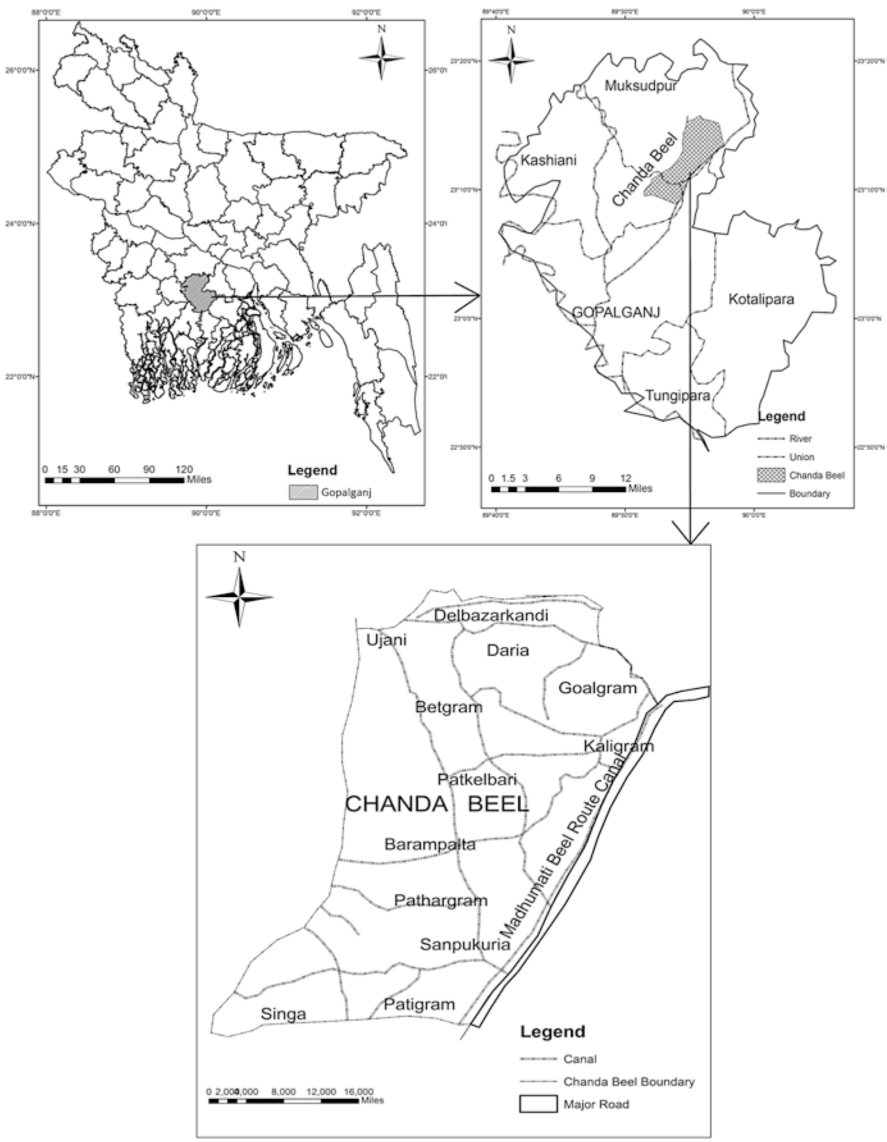


Fig. 18.3 Location of the *Chanda Beel* in southwestern coastal Bangladesh

up by December except for some natural trenches (Ghosh 2010; Ghosh and Mondal 2013). The people living in and around the Chanda *Beel* are dependent on various resources of the wetland for their livelihoods. In total, 216 naturally growing species of plants, comprising 50 species of trees, 38 species of shrubs, and 100 species of herbs, are found in the Chanda *Beel* wetland. The wetland also supports a rich diversity of faunal resources including fishes, crustaceans and shellfishes, amphibians, reptiles, and terrestrial and aquatic birds. Of the 57 fish species reported from the wetland, 16 species are rare and seven species are extinct. In the wetland, 16 prawn species, six species of crabs, and 15 species of molluscs (*viz.*, *Pila globosa*, *Bellamya bengalensis*, *Lymnaea acuminate*, etc.) are also found (BCAS-CDI 2006). Chanda *Beel* makes provision for livelihoods of the community as many people living around the wetland area are largely dependent on fishing and collection of snail, wild vegetable, fodder, and water hyacinth for subsistence. Thus, the dependency on the freshwater wetland has reached a level of over-exploitation of animal and plant resources.

18.7.3 Valuation Methods

Contingent valuation (CV) method was used to estimate the nonuse values of the *Chanda Beel*. The CV questionnaire was designed following the guidelines set by the National Oceanic and Atmospheric Administration (NOAA) Panel of the USA (Arrow et al. 1993). Stratified systematic random samples of 250 households were selected for the CV interviews. Of these, 179 were from region 1 (Gopalganj Sadar, Muksudpur, and Kashiani *Upazilas* and comprising people who were closely related to direct use of the wetland or had close contact with the wetland), 48 were from region 2 (Kotalipara *Upazila* and comprising people who were likely to have visited the wetland at least once before conducting the CV survey), and 23 were from region 3 (Tungipara *Upazila* and comprising those people who were unlikely to have visited and known the wetland). The questionnaire was divided into three parts that included respondent's eagerness to take part in the CV survey, demographic and economic information, respondent's perception, attitudes, and awareness towards the environmental condition of the wetland. A hypothetical wetland management program was explained to respondents clearly, and if the respondents supported the hypothetical wetland management program, they were asked whether they were willing to participate in the same program. If the response from a respondent was affirmative, the WTP was elicited, and respondents were asked to distribute their monetary values over the nonuse value components. More details of the CV survey and its design can be found in Ghosh and Mondal (2013).

18.7.4 Major Findings from the Case Study

The major results and conclusion presented in this section briefly are based on the wetland valuation conducted by Ghosh (2010) and Ghosh and Mondal (2013). Usable responses are vital in a contingent valuation study, and, thus, 214 usable responses to the CV questionnaire were identified in the study conducted by Ghosh and Mondal (2013). Examining protest bids in a CV survey is also very important as they reflect individuals' behavior in a hypothetical market for environmental improvements. Protest bids are found in a CV survey when an individual votes against a proposed hypothetical market for environmental improvements. In the

Table 18.3 Value of the nonuse attributes for the monetary contribution by the local people

Survey question theme	Minimum WTP (BDTk./month)	Maximum WTP (BDTk./month)	Average WTP (BDTk./month)
Continuous existence of faunal and floral resources of the Chanda *Beel* ecosystem	1.50	15.50	2.12
Enjoyment of the Chanda *Beel* ecosystem services in the future	1.50	35.50	3.47
Enjoyment of the Chanda *Beel* ecosystem services by future generations in the future	1.50	75.50	8.10
Total nonuse value (BDTk./month/household)	4.50 (0.07 US$)	126.50 (1.82 US$)	13.69 (0.20 US$)

Source: Ghosh (2010)

study, 36 protest bids were identified and examined carefully to divide the protest responses further. The respondents who answered "have not enough money but otherwise would contribute" and "don't believe that the wetland resource management program would bring the desired changes" were treated as valid zero bid. The respondents who answered that "it is the government's responsibility" and "it is the responsibility of those who degrade wetland resources should pay for it" or who rejected the contingent market were treated as protest bid in this study. The CV survey results show that 2.8% of the respondents said that they did not have enough money to pay for the program but otherwise would pay. Of the respondents, 61.1% said that they would not get benefit from the wetland resource management program, 33.3% said that it is the sole responsibility of the government to pay for the program, while 2.8% said that people who degrade wetland resources should pay. Therefore, 63.9% responses were identified as valid zero bids, whereas 36.1% responses were identified as protest bids. Moreover, the total nonuse values were divided into three categories (Table 18.3) in the case of willingness to contribute money (as shown in Bangladesh taka – BDTk – with respective US$) for the wetland management program. The results reveal that the bequest value was the largest monetary value that the respondents placed among all the nonuse value attributes, suggesting that the local people are aware of their future generations.

In the region, many people in coastal areas are reeling under poverty, yet show their interest in wetland resources management program. However, the people who have shown their interest in the program may be willing to spend their time instead of money. Therefore, the inclusion of monetary benefits from the contribution of time by the local people during the WTP estimation is necessary to elucidate the true WTP. Thus, the study incorporated the monetary benefits obtained from the contribution of time (as a resource) by the local people into estimation of the total nonuse value for the wetland improvement program following Alam and Marinova (2003). Accordingly, during the CV survey, the types of works were fixed. The types of works included physical labor, campaign and public awareness building, office works, and arrangement of meetings, and the respondents were allowed to

Table 18.4 Value of the nonuse attributes for the time contribution by the local people

Type of work	Minutes	Hours	Average rate per hour (BDTk.)	Monetary value (BDTk.)
Physical labor	547	9.12	20	182.4
Campaign and public awareness building	2966	49.44	30	1483.2
Office works	431	7.19	100	719
Arrangement of meetings	866	14.44	20	288.8
Total	4810	80.19	–	2673.4 (38.35 US$)

Source: Ghosh (2010)

Table 18.5 Total value of the nonuse attributes of the Chanda *Beel* freshwater wetland

Feature	Monetary benefit (million BDTk.)
Total number of households in Gopalganj district	247,972
Household's monthly average WTP (BDTk.)	13.69
Proportion of households willing to contribute money	81.60
Annual average monetary contribution by the households (million BDTk.)	33.24
Household's monthly average monetary value of time (BDTk.)	55.70
Proportion of households willing to contribute time	19.20
Annual average monetary value of time by the households (million BDTk.)	31.82
Total annual monetary benefits derived from the non-use attributes of the Chanda *Beel* freshwater wetland (million BDTk.)	65.06 (US$ 0.94 million)

Source: Ghosh (2010)

allocate their time to these different works. The respondent's time allocation was recorded on a time range basis, and the average time value of each time range was used in calculating the total time (Ghosh 2010) as shown in Table 18.4. The wage rate approach was used in valuing time, and the average monetary rate for each type of physical work was calculated following Alam and Marinova (2003).

All the monetary conversions used in this study from Bangladesh taka (BDTk.) to US$ are done as per September 2010 rates (1 US$ = 69.71 BDTk.). The components of the estimation of the TEV derived from the nonuse attributes of a specific type of freshwater wetland in the southwestern coastal Bangladesh are shown in Table 18.5. The annual aggregate nonuse value for the nonuse attributes of the freshwater wetland is estimated to be about BDTk. 65.06 million (US$ 0.94 million). This aggregate estimate suggests that the monetary benefits derived from the contribution of time by the local people cannot be ignored and need to be incorporated while estimating the total WTP. Since the economic valuation of the nonuse attributes of the specific type of coastal freshwater wetland is a first attempt in the southwestern coastal Bangladesh, it was not possible to compare the estimated nonuse value with other published wetland valuation studies.

18.8 Policy Implication of Wetland Valuation Studies

Estimated economic values of wetlands have significant policy implications. Ignoring such values would lead to misinformation about public preferences for wetland conservation among the policy makers and can result in misallocation of wetland resources and conflicts among different users of the resources. The estimated economic value can guide policy makers about how to allocate and manage wetland resources in an efficient and effective way. Generally, the estimated economic value reflects societal preferences for the wetland resources management in question and helps choose a management strategy ensuring sustainable uses. The economic valuation of wetlands can help policy makers prioritize sectors for environmental development. Thus, the main aim of the present exercise was to provide data and information for policy makers so that the wise use of wetland resources is achieved.

Cost-benefit analysis (CBA) is an economic tool mostly applied to public decision-making that attempts to quantify the advantages (i.e., benefits) and disadvantages (i.e., costs) associated with a particular policy, program, or action. CBA primarily determines whether society as a whole would benefit from the implementation of a policy, program, or action. Thus, CBA is a decision-making tool that is fully consistent with the use of economic value, and estimated economic values can help policy makers analyze cost-benefit for a development policy or action in the wetland area. The estimated economic value expressed in monetary terms can also provide significant incentives, and, thus, the estimated values need to be brought to the attention of policy makers and wetland resource managers in order to ensure the sustainable use of wetland resources. It is found that estimated economic values of wetlands reflect not only public attitudes towards wetland conservation but also provide a number of opportunities and advantages to wetland management. Even, the results of the economic valuation of wetlands act as significant inputs to mechanism of exploring the public demand for wetland conservation and development considering the relationship between wetland services as economically free goods and dependency of human being. Understanding the relationship between local people and wetlands along with their perception and knowledge on such public goods is vital in designing a socially acceptable, economically viable, and efficient wetland management strategy or policy. This warrants policy makers to take into account public preferences and, consequently, involve dependent community in environmental decision-making relating to the wetland. Failure to consider these may lead to degradation of wetland ecology. So, an incorporation of the values of the use and nonuse attributes of wetlands is imperative in the planning and decision-making process for wetland resources management.

18.9 Conclusion

The compilation and syntheses of coastal wetland valuation approaches and the case studies presented from Bangladesh reveal that coastal wetlands possess a considerable economic value as they are productive natural resources in coastal areas. The non-tangible economic benefits that policy makers often overlook constitute a considerable portion of the total economic value of the wetlands, necessitating careful and proper consideration of the economic values of coastal wetlands in environmental decision-making. Understanding of the ecosystem services of coastal wetlands and their valuation approaches is vital in environmental policy making for wetland resources management. Thus, if all the wetland values are not incorporated into wetland management policies or actions properly, a better socially acceptable, economically viable, and environmentally sound outcome would not result from such policies or actions.

References

Alam K (2006) Valuing the environment in developing countries: problems and potentials. Asia Pac J Environ Dev 13(1&2):27–44

Alam K, Marinova D (2003) Measuring total value of a river cleanup. Water Sci Technol 48(7):149–156

Arrow K, Solow R, Portney PR et al (1993) Report of the NOAA panel on contingent valuation. Fed Regist 58(10):4602–4614

Barbier EB (2013) Valuing ecosystem services for coastal wetland protection and restoration: progress and challenges. Resources 2:213–230

Bateman I, Carson R, Day B et al (2002) Guidelines for the use of expressed preference methods for the valuation of preferences for non-market goods. Edward Elgar, Cheltenham

BCAS-CDI (2006) Impact of development interventions on wetlands, its resources and livelihoods of people in Chalan Beel and Chanda Beel freshwater wetland. Bangladesh Centre for Advanced Studies (BCAS) and Caritas Development Institute (CDI), Dhaka

Cameron TA (1992) Non-user resource values. Am J Agric Econ 74:1133–1137

Christie M, Fazey I, Cooper R et al (2012) An evaluation of monetary and non-monetary techniques for assessing the importance of biodiversity and ecosystem services to people in countries with developing economies. Ecol Econ 83:67–78

Costanza R, d'Arge R, de Groot R et al (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260

Finlayson CM, Spiers AG (eds) (1999) Global review of wetland resources and priorities for wetland inventory. Supervising Scientist, Canberra

Freeman AM, Herriges JA, Kling CL (2014) The measurement of environmental and resource values- theory and methods, 3rd edn. RFF Press, London

Ghosh PK (2010) Economic valuation of the use and non-use attributes of a coastal wetland for better management of its resources. Unpublished M Sc thesis, Bangladesh University of Engineering and Technology

Ghosh PK, Mondal MS (2013) Economic valuation of the non-use attributes of a south-western coastal wetland in Bangladesh. J Environ Plan Manag 56(9):1403–1418

Gopal B, Krishnamurthy K (1993) Wetlands of South Asia. In: Whigham D, Dykyjova D, Hejny S (eds) Wetlands of the world I-inventory, ecology, and management, vol I. Kluwer Academic Publishers, The Netherlands, pp 345–414

Guo Z, Xiao X, Gan Y et al (2001) Ecosystem functions, services and their values-a case study in Xingshan County of China. Ecol Econ 38:141–154
Haque AKE, Murty MN, Shyamsundar P (eds) (2011) Environmental valuation in South Asia. Cambridge University Press, New Delhi
Islam SN (2010) Threatened wetlands and ecologically sensitive ecosystems management in Bangladesh. Front Earth Sci China 4(4):438–448
Khan MS, Haq E, Huq S et al (1994) Wetlands of Bangladesh. Holiday Printers Limited, Dhaka
Kirwan ML, Megonigal JP (2013) Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504:53–60
Korsgaarda L, Schou JS (2010) Economic valuation of aquatic ecosystem services in developing countries. Water Policy 12:20–31
Kumar M, Kumar P (2008) Valuation of the ecosystem services: a psycho-cultural perspective. Ecol Econ 64:808–819
Lehner B, Döll P (2004) Development and validation of a global database of lakes, reservoirs and wetlands. J Hydrol 296(1–4):1–22
Levin LA, Boesch DF, Covich A et al (2001) The function of marine critical transition zones and the importance of sediment biodiversity. Ecosystems 4:430–451
LGED (2007) District water resources assessment of Gopalganj district. Local Government Engineering Department (LGED), Dhaka
Limburg K, O'Neill RV, Costanza R et al (2002) Complex systems and valuation. Ecol Econ 41:409–420
MEA (2005) Ecosystems and human well-being: wetlands and water synthesis. World Resources Institute, Washington DC
Nijkamp P, Vindigni G, Nunes PALD (2008) Economic valuation of biodiversity: a comparative study. Ecol Econ 67:217–231
Nishat A (1993) Freshwater wetlands in Bangladesh: status and issues. In: Nishat A, Hussain Z, Roy MK et al (eds) Freshwater wetlands in Bangladesh: issues and approaches for management. IUCN, Gland, pp 9–21
Oglethorpe DR, Miliadou D (2000) Economic valuation of the non-use attributes of a wetland: a case-study for lake Kerkini. J Environ Plan Manag 43(6):755–767
Samonte-Tan GB, White A, Tercero MA et al (2007) Economic valuation of coastal and marine resources: Bohol Marine Triangle, Philippines. Coast Manag 35:319–338
Sathirathai S, Barbier EB (2001) Valuing mangrove conservation in southern Thailand. Contemp Econ Policy 19:109–122
Sharma C (1996) Coastal area management in South Asia-a comparative perspective. Background paper for South Asia workshop on fisheries and coastal area management. International Collective in Support of Fishworkers, Chennai, pp 3–24
Smith KV (1987) Non-use values in benefit cost analysis. South Econ J 54:19–26
Stevens TH, Benin S, Larson JS (1995) Public attitudes and economic values for wetland preservation in New England. Wetlands 15:226–231
Thomas DHL, Ayache F, Hollis GE (1991) Use and non- use values in the conservation of Ichkeul National Park, Tunisia. Environ Conserv 18:119–130
Turner RK, van der Bergh JCJM, Soderqvist T et al (2000) Ecological-economic analysis of wetlands: scientific integration for management and policy. Ecol Econ 35(1):7–23
Turner RK, Bateman IJ, Georgiou S et al (2004) An ecological economics approach to the management of multipurpose coastal wetland. Reg Environ Chang 4:86–99
Turpie J, Lannas K, Scovronick N et al (2010) Wetland ecosystem services and their valuation: a review of current understanding and practice. Wetland valuation volume 1. Water Research Commission, Gezina

UNDP (2012) A toolkit for integrating disaster risk reduction and climate change adaptation into ecosystem management of coastal and marine areas in South Asia. United Nations International Strategy for Disaster Reduction Asia and Pacific and the United Nations Development Programme (UNDP), New Delhi, pp 1–38

WIAP-WB (2000) Wetlands in Asia-a booklet to accompany the map of wetlands of international importance in Asia. Wetlands International Asia Pacific (WIAP) and World Bank (WB), Institute of Advanced Studies, Kuala Lumpur, pp 22–26

19 Restoration Initiatives and Dependency Reduction on Mangrove Wetlands: A Case Study of Ashirawandh Village, Kachchh, Gujarat, India

G.A. Thivakaran

Abstract

Mangrove wetlands in tropical countries provide enormous ecological and economic services to coastal communities. In the semiarid district of Kachchh, northwestern state of Gujarat, India, dependency of coastal communities on mangrove resources for fodder is considerable. Kachchh has the largest (789 km^2) mangrove formation in the Indian west coast composed mainly of *Avicennia marina* though two other species were reported sporadically. Mangrove stand near human settlements in this coastal district is the main source of fodder since fodder from terrestrial sources is sparse due to pronounced aridity of the region. With a livestock population of 1,021,454 during 2011 in coastal blocks that predominantly depends on mangrove biomass for fodder, mangroves face severe threats in the district. This chapter presents the attempts made to create a model for mangrove regeneration with participation of a selected coastal community in order to reduce dependency on natural mangroves. One coastal village with total dependency on mangroves was involved to regenerate 251 ha of mangroves and to manage the created resource to ensure sustainable fodder security. This totally mangrove-dependent village, whose 274 livestock fully depend on the mangroves for fodder, was enabled to raise mangrove plantation and to sustainably manage it. Through village participation, 251 ha of mangroves were regenerated, which besides ensuring their long-term fodder security also generated employment to the villagers to the tune of 17,375 man-days over a 5-year period. The resource management capacity of the target community was simultaneously enhanced through 62 programs on ecological and economic significance of mangroves and training on organizational and technical aspects of mangrove plantation. The gender equated village committee formed was trained in collective

G.A. Thivakaran (✉)
Gujarat Institute of Desert Ecology (GUIDE), P.B. No. 83, Mundra Road,
Bhuj, Kachchh 370 001, Gujarat, India
e-mail: athivakaran028@gmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_19

decision making on different issues of mangrove regeneration and means of rendering the present dependency sustainable. Dependency on mangrove resources was also reduced by creation of 47 ha grassplots, which served as an alternative to meet fodder requirements of the target community. It is expected that the raised resource will meet the entire mangrove fodder requirement after a period of 7 years when the planted trees reach harvestable size.

Keywords
Dependency • Fodder • Mangrove plantation • *Avicennia marina* • Stakeholders

19.1 Introduction

Mangrove wetlands at the interface of land and sea are hugely valuable to coastal communities as its tangible and intangible ecosystem services were estimated to cost around US$14 trillion annually worldwide. Mangrove wetlands are an important coastal ecological entity identified by the Ramsar Convention. Numerous resources of mangrove wetlands such as fish, fodder, construction material, traditional medicine, and honey have been, by tradition, the source of income and livelihood for coastal communities. Hence, degradation of this wetland ecosystem and the concomitant loss of services affect the coastal communities in numerous ways. This problem is a serious concern in many tropical countries where dependency of coastal mass on mangrove wetlands is huge. The role of mangrove wetlands in the livelihood of coastal communities is particularly important in India. For example, nearly 90% of the east Godavari delta population in Andhra Pradesh, India, depends completely on mangrove wetland for sustaining their livelihood (Dahdouh-Guebas et al. 2006). Similarly, in Mahakam delta of Indonesia, 40% of the households depend on mangrove wetlands (Bosma et al. 2012). Indian mangroves are no exception to this worldwide trend in supporting local coastal communities in their livelihood. This high level of dependency calls for initiatives to render it sustainable. The present chapter narrates an attempt wherein a model was created in order to utilize the mangrove resources sustainably.

Kachchh district in the northwestern part of India in the state of Gujarat has the largest arid zone mangrove stand in the Indian west coast comprising 118 km^2 dense and 671 km^2 sparse patches (FSI 2013) constituting 17% of the country's and 71.5% of the state's mangrove extent. The entire mangrove stand is constituted mostly by the species *Avicennia marina (Forsk.)* Vierh though sporadic occurrence of two other true mangrove species *Rizhophora mucronata* and *Ceriops tagal* has been reported (Sawale and Thivakaran 2012). Dependency of coastal communities in Kachchh on mangrove wetlands in terms of fodder is enormous, exerting pressure on the mangrove resources (Singh 2000). This is especially true in mangrove peripheral areas where villages are clustered. By far, the single dominant factor contributing to the unabated mangrove resource utilization is the presence of huge livestock population, which often exceeds human population, in the coastal villages. Tending livestock and selling milk is the major income-generating activity in most of the Kachchh coastal villages that demands enormous fodder supply. High aridity coupled with poor fodder availability from sparse terrestrial vegetation further renders mangroves as the only biomass for grazing. The presence of a nomadic community called *Maldhari* whose sole profession is rearing camel that feeds mostly on the mangroves accentuates the level of dependency on mangroves. In the light of this extensive resource utilization that often leads to resource degradation, community-participated mangrove regeneration is perceived as a viable alternative. Though the state forest department regularly undertakes mangrove plantation, it has no stakeholder participation with total ban on resource utilization that is often considered economically inefficient besides undermining sustainability (Glaser et al. 2003). Hence, community resource management is suggested as a viable option that, besides stemming the process of resource depletion, renders the local resource users as responsible stewards of forest (Conklin and Graham 1995; Eghenter 2000).

This chapter presents the extent of people's dependency on this wetland resource and the process and outcome of an attempt made to enable a mangrove-dependent coastal community to raise, maintain, and sustainably manage mangrove resources that will ensure long-term livelihood security besides reducing their dependence on natural mangroves.

19.2 The Mangrove-Dependent Community

The target community Ashirawandh is a hamlet of 35 families located in the northwestern coast of Kachchh district. The nearest township is Naliya, the headquarter of Abdasa block (a minor administrative unit). The dependent community at Ashirawandh is highly marginalized with low literacy rate and is lacking in basic civic amenities. Milk selling through tending livestock and fishing are the mainstay of the villagers practiced simultaneously with both having strong reliance on mangroves. To begin with, the level and extent of dependency on mangrove resource was quantified which provided a strong impetus to take up this village for restoration activities through mangrove plantation. The total population of the village is about 210. Though they belong to a cattle-tending nomadic *Maldhari* community, their nomadic lifestyle was given up long back with the permanent settlement in the present hamlet due to its proximity to mangroves that offer good fodder to the livestock and rich fishery resource in the mangrove-lined creeks. Out of 35 families, 28 (80%) practice livestock tending and milk selling as their primary occupation, while fishing in the near shore and mangrove creek waters supports seven families (20%) who also own few livestock, which sustain them during lean fishing period. Hence, quantifying resource utilization and involving them in a mangrove restoration program through plantation was attempted.

19.3 Approach

The level of dependency of the village on mangrove resource was ascertained by gathering primary information on livestock population in the village and their fodder source, mangrove fodder collection schedule, daily consumption rate for a drought, and normal rainfall year through a household survey. The data strongly suggested the extent of dependency on mangrove resource as fodder and provided an impetus for involving the villagers in participatory mangrove plantation and its sustained management. In order to institutionalize the plantation initiative, several basic activities such as formation of a gender equated village level committee with elected office bearers and its legal registration and identification of crusaders who constituted the executives of the plantation activities were put in place. While the ecological and economic importance of mangroves was imbibed through series of intensive awareness programs and exposure visits, technical and management capacity to selected female and male members was imparted through indoor and *in situ* demonstration of site selection, mangrove nursery preparation, and plantation activity. Sustained efforts for enhancing the villagers' capacity were undertaken through gender equity workshops and account keeping training utilizing the services of other nongovernmental organizations (NGOs). Throughout the implementation, female members of the village were encouraged to participate actively since they are the sole collectors of mangrove fodder. Once the villagers strongly imbibed the ecological and economic importance of mangroves through awareness programs, mangrove plantation in an area of 251 ha was taken up in the chosen intertidal belt near the village after obtaining required legal permission. The created village committee with a sustained technical input from the facilitating team solely orchestrated this plantation effort. Simultaneously, with the aim to reduce dependency on mangroves, 47 ha grass plots were created within the village boundary in a suitable site with the grass species *Cenchrus ciliaris* and *Cenchrus setigerus*. Fodder from this newly created ranch was harvested in a period of 4 months. Appropriate benefit sharing mechanism in tune with the livestock owned by each family to share the harvest was ensured. The village committee formed to execute mangrove plantation decided to save 10% of the daily wage of all labors to create a corpus fund in order to support future maintenance and sustainable management of the newly developed resources. The corpus thus created amounted to INR 0.347 million after 3 years. Since village dependency on the mangrove resources was significant, villagers' response for these activities was quite positive and all resource creation and maintenance activities were coordinated by the village committee.

19.4 Degree of Dependency on Mangrove Resource

Ashirawandh has a livestock population of 274, which is equivalent to total adult cattle unit (ACU) of 368.3 (Table 19.1). With a requirement of 7.5 kg/ACU, Ashirawandh requires 4.62 tons of fodder per day (Table 19.1). If camel population numbering 50 is excluded due to their free grazing in mangroves and on other

Table 19.1 Livestock population in the village and their fodder needs

Livestock category	Number	Cattle units—ACU[a]	Per day fodder demand (tons)[b]	Annual fodder demand (tons)
Cows	8	8	0.06	21.9
Bull	6	6	0.045	16.425
Buffalo	210	294	2.205	804.825
Camel	50	70	2.205	843.15
Total	274	368.3	4.62	1686.3

[a]Adult cattle unit (ACU): numbers of different types of livestock are converted into a uniform number (ACU), based on the biomass requirement, which is determined based on the body weight of animal. The conversion units are one adult cattle = one ACU, one buffalo = 1.4 ACU, one sheep or goat = 0.25 ACU, and one camel = 1.4 ACU (Geevan et al. 2003)
[b]Per day fodder demand in Kg at 7.5 kg dry fodder/day

Table 19.2 Monthly mangrove fodder collection by the Ashirawandh villagers

Months	Womenfolk/day	Avg wt/d/women (kg)		Collection/m (kg)	
		Seeds	Leaves	Leaves	Seeds
January	30	–	90	81,000	–
February	35	–	85	89,250	–
March	33	–	75	74,250	–
April	35	–	90	94,500	–
May	35	–	70	73,500	–
June	26	–	75	58,500	–
July	9	11	30	8100	2970
August	8	12	25	6000	2880
September	7	12	20	4200	2520
October	30	7	75	67,500	6300
November	35	–	70	73,500	–
December	33	–	65	64,350	–
Average	26.3	10.5	64.16	694,650	14,670
Annual collection					709,320

terrestrial vegetation, the fodder need for the remaining 224 cattle (308 ACU) is around 2310 kg/day (843.15 tons/year). Out of this annual fodder requirement of 843.15 tons, mangrove leaves and seeds fetch 709.32 tons annually meeting 88.2% of the requirement.

Mangrove fodder collection by the target community is being done in two ways, namely, direct collection from mangroves and free grazing by camels in the mangrove forest. Mangrove fodder, mostly leaves, is collected from both revenue and reserve mangrove forest stands. On a yearly average, 26.3 womenfolk visit mangroves twice in a day and collect around 64.16 kg/head of leaves (Table 19.2). About 9599.5 woman-days in a year is expended for mangrove fodder collection. Besides this, an average of 10.5 kg of seeds was collected during July–October (Table 19.2). Overall, around 615,904 kg of mangrove leaves and 14,670 kg of seeds by an average of 26.3 womenfolk are being collected in a year that amount to 1687.4 kg/day of biomass removal (Table 19.2). The number of womenfolk increases during the summer months of March–June concomitant with the quantum of fodder requirement for the livestock (Table 19.2). However, during monsoon months the fodder collection reduces drastically to 37.5 kg/women/day, due to the availability of fodder from terrestrial sources. The collected fodder is transported to the village by boat and truck at a cost of INR 25 per head load weighing 25–70 kg. Since the sole collection of leaves is meant to stall feed milking cattle, camels are let loose freely to graze mostly on mangroves. Camels, which are mostly nonproductive, except for their sale value, on an average, consume 10–15 kg/day of mangrove biomass.

Mangrove propagule collection during fruiting season of July–October is done along with mangrove leaves, the requirement for which during the monsoon months is low due to availability of fodder from terrestrial vegetation. Womenfolk interviewed unanimously expressed their preference to mangrove seeds since it is believed to increase milk yield. A woman in a day gathers around 10.5 kg of propagules in 3–4 h of low tide periods. It is estimated that 14,670 kg of seeds, with which cattle are fed as a supplementary fodder, during July–October is collected by the village women (Table 19.2). Collection of seeds is detrimental for the mangroves since it affects their regenerating potential.

A clear pattern of enhanced mangrove fodder collection during summer and winter, which becomes low during monsoon, could be gleaned from the data. Maximum number of households, the percentage ranging from 95 to 100, uses mangroves during summer and winter. The data presented in Table 19.2 relate to a normal monsoon year with an annual average rainfall of 350 mm. Often, rainfall in Kachchh is erratic. During 3 out of 10 years in Kachchh, the rainfall is lesser than 120 mm and rainfall totally fails in every 2 years in a 5-year cycle (Thivakaran 2011). The grazing and fodder collection pressure during years of low rainfall or drought could be manifold higher than the one recorded presently. Exploitation of mangrove resource in Kachchh is confined to fodder collection, and exploitation of timber, honey, and firewood is totally absent here although high rate of firewood collection from mangroves of neighboring Jamnagar district was reported earlier (Singh 2000). In Kachchh mangroves, firewood is seldom collected since *Prosopis juliflora*, a terrestrial woody plant, meets all the firewood requirements.

19.5 Ashirawandh Mangrove Committee

The gender equated and legally registered village committee, *Ashirawandh Cheriya Vikas Samithi* (ACVS), with its general and executive committee was instrumental for implementing the participatory mangrove regeneration endeavor. The committee's confidence and commitment was enhanced through financially empowering the committee members who handled project accounts, prompt labor wage distribution and daily plantation activities, and development activities like building community hall, check dam, and water tank in the village. Regular monthly meetings with majority of the villagers' participation would prepare the monthly work schedule detailing the assigned works for all core members of the committee. With regular monthly meetings, the whole community was instilled with adequate organizational capacity and team spirit. With clearly set responsibility with regard to mangrove plantation, grass plot creation and yearly equitable grass sharing based on cattle holding per household, and transparent financial dealings, total transparency was ensured with monthly expenditure statements placed before the committee followed by discussions. With the committee well in place and functioning, the implementers' role was restricted to facilitation and assistance.

19.6 Capacity Building

In the initial years of the project, much attention was paid to build the perceptional, technical, and managerial capacity of the villagers in view of their strong dependence on the mangrove resources. In a span of 5 years, 27 awareness programs, 25 capacity-building workshops, and 10 exposure visits were conducted (Table 19.3). This enhanced villagers' managerial and perceptional ability considerably, which was ascertained through a survey that reported substantial increment in their technical and managerial skills. While awareness programs generally dealt with ecological, economic, and livelihood importance of mangrove resources, managerial capacity was built through proper record keeping, bank transactions, and account maintenance. Likewise, exposure visits to similar community-based organizations and mangrove hotspots (Sundarbans West Bengal, Bhitarkanika Orissa) enabled them to gain insights into conservation significance of mangroves in particular and coastal resources in general.

Table 19.3 Details of capacity building in Ashirawandh

S. No	Nature of program	No	Subject covered
1	Awareness programs	27	Coastal ecology and its importance; ecological, economic, and livelihood importance of mangroves; sustainable approach; legal aspects of coastal zone; impacts of indiscriminate resource exploitation
2	Capacity building	25	Gender equity, technical aspects of mangrove regeneration, financial handling, income generation, record keeping, grass plot management, sustainable resource exploitation
3	Exposure visits	10	Visit to similar communities; important mangrove hotspots; JFM sites of Sundarbans, Tamil Nadu; sites of traditional fodder conservation

19.7 Fodder Plot and Mangrove Dependency Reduction

In order to ensure greater sustainability and reduce the target community's degree of dependence on mangrove resources, the village committee was encouraged to raise a grass fodder plot of 47 ha with terrestrial grass species such as *C. ciliaris* and *C. setigerus* in the village vicinity during the monsoon of 2002 with required technical input from the facilitators. Though the grass yield was low during the first year (2002), in subsequent years, it rose to 550 kg/ha per annum with a total yield of around 26 tons during 2006 monsoon. A robust benefit sharing mechanism by dividing the grass yield with total cattle population and distributing it in tune with cattle holding of each household was worked out by the committee, which ensured equated distribution of gross production. Though the annual grass yield of 26 tons met only a fraction of the annual fodder requirement during intense fodder collection period of summer, during monsoon months, grass yield met a higher portion of requirement, while the rest of the fodder requirement was met from other terrestrial sources. However, it amply demonstrated how an alternative fodder resource could be raised to supplement instead of totally relying on a single resource.

19.8 Mangrove Regeneration

Mangrove regeneration and rehabilitation in an area of 251 ha has been completed by the village *samithi* in a span of 5 years from 2002 to 2006 (Table 19.4). Three different plantation techniques, namely, planting nursery-raised saplings, direct seed sowing (dibbling), and planting wild seedlings, were adopted though the latter was given up due to poor results. During 2002, germination and subsequent survival rate in the 35 ha plantation was only 35% in spite of more than normal rainfall of

Table 19.4 Year-wise plantation details, technique, species, and targets

Year	Plantation area (ha)	Species	Plantation method	Survival rate (%)
2002	20	*Avicennia marina*	Nursery saplings	35
2003	35	*A. marina*	Nursery saplings	65
	20	*A. marina*	Direct dibbling	55
	10	*R. mucronata*	Direct dibbling	10
	10	*Ceriops tagal*	Direct dibbling	8
2004	35	*A. marina*	Nursery saplings	71
	10	*A. marina*	Direct dibbling	38
	3	*R. mucronata*	Direct dibbling	10
	2	*Ceriops tagal*	Direct dibbling	65
2005	20	*A. marina*	Nursery saplings	73
	6	*Ceriops tagal*	Direct dibbling	55
2006	55	*A. marina*	Direct dibbling	69
	25	*Ceriops tagal*	Direct dibbling	71

550 mm during that year. Reasons identified were poor quality propagules and proximity of the intertidal site to lower tidal mark, which resulted in large number of saplings being carried away in tidal currents. Besides, the use of mangrove propagules sourced from Jamnagar mangroves acclimatized to lesser salinity regime, in contrast to the more than normal salinity range of 38–44 ppt prevailing in Kachchh creek waters, also resulted in poor survival rate during that year. However, these shortcomings were rectified in the subsequent years through better technical input to villagers. Identifying better site, the use of locally available propagules that could withstand higher salinity and proper treatment of propagules yielded better results (Table 19.4). Throughout the plantation exercise, a consistent spacing of 1 × 1.5 m was followed for all the three candidate species, namely, *A. marina*, *R. mucronata*, and *C. tagal*. However, *A. marina* was predominantly used in both direct dibbling and nursery development in view of its local prevalence and endemicity besides high tolerance to drought and seawater and soil salinity. Of the three candidate species, *R. mucronata* showed the poorest survivability not exceeding 10% in all the 5 years, whereas *C. tagal* showed a better survivability with 20–25% in later years though it was poor in initial years of 2002–2003. Due to high survival rate of *A. marina*, it was the preferred candidate species and planted in large scale in subsequent years.

The whole plantation exercise was conceived and carried out by the villagers with the implementing organization confining its role to technical inputs like site selection and nursery preparation that became least toward the latter years of implementation. All through the 5 years of plantation work, a total employment of 17,375 human-days was generated with each household getting around 500 human-days in a span of 5 years with womenfolk constituting the bulk of labor force. A corpus fund of INR 0.347 million was generated out of labor wages (20% of the daily labor wage), which would form the core fund for future maintenance and management of the created resources. Control of the corpus fund was solely entrusted to the three-member village committee with appropriate governing norms such as wages for maintenance and gap filling, fencing, and physical protection of the plantation. The core committee would decide its mode of utilization within the larger objective of mangrove resource maintenance and its long-term sustainability.

Based on the observed growth rate of 35 and 21 cm/year during 2003 and 2004 of the mangroves planted in 2002, it is presumed that by seventh year the afforested mangrove area could be harvested for foliage biomass by the villagers. Considering an annual biomass yield of 14 tons/year/ha, with 10% increment in annual fodder demand by the year 2011, the afforested mangrove area of 251 ha is likely to meet the fodder requirement of the village, which will in turn check their natural mangrove exploitation (Table 19.5). However, this assumption is subject to factors like normal growth, less drought years, and not more than 10% increment in village livestock. Even in the event of less growth, the enhanced foliage yield will reduce dependency on natural mangroves rendering it more sustainable.

Table 19.5 Fodder requirement and projected fodder yield from the raised plantation

Year of plantation	Planted area—ha	Foliage yield 14 tons/year[a]	Projected fodder requirement of the village with 10% yearly increment—tons/year	Total biomass budget—tons/year
2009	20	280	1623.394	−1343.39
2010	95	1330	1785.733	−455.733
2011	145	2030	1964.307	65.693
2012	171	2394	2160.738	233.262
2013	251	3514	2376.811	1137.189

[a]A total removable biomass of 14 tons/ha was considered

19.9 Viability of Participatory Mangrove Afforestation

Participatory mangrove afforestation is being attempted in many tropical countries with the well-documented examples from the Philippines and is now presumed to be a widespread phenomenon (Posey and Balee 1989; Anderson 1990; Redford and Padoch 1992). In India, community-based mangrove restoration efforts are yet to be taken up in large scale. One successful attempt, which regenerated mangroves in an area of 293 ha with total community participation, was reported from Pichavaram mangroves of Tamil Nadu (Selvam et al. 2003). The experience gained in Tamil Nadu and in other tropical countries led to a rethinking on the state-controlled ownership and management of forest resources in which the locals, who have more stake to conserve, have no role to play. Initial results obtained in the present effort of community-based mangrove regeneration and management, though encouraging, are yet to be fully evaluated as to how the community is going to manage the resources raised in the absence of the inputs and facilitation provided during implementation. The much-publicized participatory management of Philippine mangroves differs from the present case in one important aspect, i.e., the kind of forest produce utilized. While in the present case only mangrove foliage is exploited (as fodder), in other instances, it is the timber and firewood gathering necessitating removal of whole aboveground biomass rendering it highly unsustainable. Although it is yet to be quantified, there are strong reasons to suggest that the present effort, in due course of time, will serve to reduce pressure on the natural mangrove forests by providing alternative source of fodder. With natural resources very inaccessible, further refinement of participatory resource raising seems to be the only alternative. Current outright ban by the government on state-controlled forest resource utilization is considered to undermine biological sustainability besides being economically inefficient (Glaser et al. 2003). If proved successful, the present attempt will lead to a paradigm shift transforming the local stakeholders as conservers and protectors rather than destructors of natural resources.

Widespread failures of community-based mangrove planting have been reported elsewhere (Calumpong 1994; Pomeroy et al. 1996; Primavera and Agbayani 1997). These failures mostly happened when the planted mangroves failed to yield expected economic benefits, which consequently led to their neglect and indiscriminate exploitation. In the present case, though adequate sustainability was ensured by means of establishing a maintenance fund, other unforeseen factors like extreme drought and coastal developmental activity may lead to indiscriminate exploitation with the stakeholders losing sight of all sustainability principles. However, it is essential in the present case to keep track of changes in the stakeholder's behavior *vis-a-vis* the raised resources and its maintenance. Several instances during the project period like voluntarily selling off their camels whose maintenance does not give much economic returns suggested the strong willingness of the community to protect and sustainably use the created resources.

19.10 Conclusion

Kachchh coast, of late, is witnessing intensive mangrove plantation initiatives with more than 25,000 ha of mangroves raised by government and nongovernment agencies in the last two decades. Majority of these mangrove restoration efforts are single institutional without community participation, and the widespread failures reported in many plantation initiatives are solely attributable to lack of community participation. Community as an active stakeholder in such ventures has proved to be beneficial as it ensures success and viability of the restoration effort. As a partner, stakeholding community is bound to ensure the physical protection and sustainable resource use since they play a major role in resource creation. The issue of grazing which is a major menace to many natural mangroves in Kachchh is negated since a social fencing is ensured by involving the coastal community. The present effort of mangrove plantation wherein community is the implementer amply demonstrates the sustainability of the venture.

Acknowledgments The present chapter is the outcome of the India-Canada Environment Facility (ICEF), New Delhi-supported project, Regeneration of Mangroves in Gujarat (REMAG). The author is thankful to Gujarat Institute of Desert Ecology (GUIDE), Bhuj, India, for providing facilities and Gujarat Ecology Commission (GEC), Gandhinagar, India, the Nodal agency of the REMAG project.

References

Anderson AB (ed) (1990) Alternatives to deforestation: steps towards sustainable use of the Amazon Rain Forest. Columbia University Press, New York

Bosma R, Sidik AS, Zwieten PV, Aditya A, Visser L (2012) Challenges of a transition to a sustainably managed shrimp culture agro-ecosystem in the Mahakam Delta, East Kalimantan, Indonesia. Wetl Ecol Manag 20(2):89–99

Calumpong HP (1994) Status of mangrove resources in the Philippines. In: Wilkinson C, Sudara S, Ming CL (Eds) Proceedings of the third ASEAN-Australia symposium on living coastal resources, Bangkok, Thailand, 1: 215–229

Conklin B, Graham L (1995) The Shifting Middle ground: Amazonian Indians and eco-politics. Am Anthropol 97(4):695–710

Dahdouh-Guebas F, Collin S, Seen DL, Rönnbäck P, Depommier D, Ravishankar T, Koedam N (2006) Analysing ethnobotanical and fishery-related importance of mangroves of the East-Godavari Delta (Andhra Pradesh, India) for conservation and management purposes. J Ethnobiol Ethnomed 2(1):1–24

Eghenter C (2000) What is *Tana Ulen* good for? Consideration of indigenous forest management, conservation, and research in the interior of Indonesian Borneo. Hum Ecol 28(3):331–357

FSI (2013) India state of forest report 2013. Forest Survey of India (Ministry of Environment & Forests), Government of India, Dehradun, pp 33–37

Geevan CP, Dixit AM, Silori CS (2003) Ecological-economic analysis of grassland systems: resource dynamics and management challenges – Kachchh District (Gujarat). Gujarat Institute of Desert Ecology, Bhuj

Glaser M, Berger U, Macedo, R (2003) Local vulnerability as advantage: mangrove forest management in Para State, north Brazil, under conditions of illegality. Reg Environ Chang 3:162–172

Pomeroy RS, Pollnac RB, Predo CD, Katon BM (1996) Impact evaluation of community based coastal resource management projects in the Philippines. International Center for Living Aquatic Resources Management (ICLARM), Makati City

Posey DA, Balee W (eds) (1989) Resource management in Amazonia: indigenous and folk strategies. In: Advances in economic botany, 7, New York Botanical Garden, Bronx, New York

Primavera JH, Agbayani RF (1997) Comparative strategies in community based mangrove rehabilitation programmes in the Philippines. In: Hong PN, Ishwaran N, San HT, Tri NH, Tuan MS (eds) Proceedings of Ecotone V, community participation in conservation, sustainable use and rehabilitation of mangroves in Southeast Asia. UNESCO, Japanese Man and the Biosphere National Committee and Mangrove Ecosystem Research Centre, Vietnam

Redford K, Padoch C (eds) (1992) Conservation of Neo-tropical forests: working from traditional resource use. Columbia University Press, New York

Sawale AK, Thivakaran GA (2012) Structural Characteristics of mangrove forest of Kachchh. J Mar Biol Assoc India 54(2):121–129

Selvam V, Ravichandran KK, Gnanappazham L, Navamuniyammal M (2003) Assessment of community based restoration of Pichavaram mangrove wetland using remote sensing data. Curr Sci 85:6–25

Singh HS (2000) Mangroves in Gujarat: current status and strategy for conservation. Gujarat Ecological Education and Research Foundation (GEER), Gandhinagar

Thivakaran GA (2011) Coastal ecology of Kachchh-Status, issues and problems. In: Kathju K, Vijay Kumar V, Thivakaran GA, Patel PS, Devi V (eds) State of environment in Kachchh. Gujarat Institute of Desert Ecology Bhuj and GEER Foundation, Gandhinagar, pp 59–88

Dependence on Ecosystem Goods and Services: A Case Study on East Kolkata Wetlands, West Bengal, India

20

Nitai Kundu and Anita Chakraborty

Abstract

The age-old practice of utilizing wastewater into fishpond in the East Kolkata Wetlands (EKW), India, is a unique example of resource recovery. The wetlands, providing a range of ecosystem services, form the base of ecological security of the entire region and livelihoods of the dependent communities. Being a dynamic ecosystem, the wetland is subject to influence from various natural as well as human factors. Integrated management of this ecosystem is crucial for maintaining the rich productivity of the wetland ecosystem as well as achieving wise use of resources. The present chapter is an effort to present broadly the ecological-economic linkages of the wetland uses with emphasis on the economics of aquaculture, horticulture, and agriculture under the waste recycling practices.

Keywords

Aquaculture • *Bheries* • Biodiversity • Horticulture • Macrophytes • Wetland

N. Kundu (✉)
Institute of Environmental Studies and Wetland Management, Kolkata, India
e-mail: npk1967@yahoo.co.in

A. Chakraborty
Centre for Environmental Management and Participatory Development,
HB-150, Saila Bhawan, Sector-III, Salt Lake City, Kolkata 700106, India

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_20

20.1 Introduction

A natural ecosystem delivers a range of benefits for people, known as ecosystem services. The concept of ecosystem goods and services allows for identification of the various benefits that human derive from functioning ecosystems such as wetlands. The concept provides the example of human-centered exploitation of resources, which has emerged as the motivation to conserve and maintain ecosystem, and it is a relatively new approach. Historically strong arguments had been put forth for conservation justifying on ethical reasons or intrinsic value of nature's organisms, populations, species, and ecosystem (Turner and Daily 2008), and many people also support the fact the species ought to exist and have the right to exist (Barnosky et al. 2011).

Wetland ecosystem, including rivers, lakes, marshes, rice fields, and coastal areas, provides many ecosystem services that contribute to human well-being and poverty alleviation (MEA 2005). From an economic point of view, ecosystems can broadly be seen as part of our natural capital and the flow of ecosystem services the "interest" on the capital that society receives (Costanza and Daly 1992). Two of the most recognized wetland ecosystem services affecting human well-being are fish supply and water availability. India, owing to wide variations in rainfall, hydrology, physiography, geomorphology, and climate, has a rich diversity of inland wetlands. As per the National Wetland Atlas (SAC 2011), of the 15.26 million ha area under wetlands in the country, inland wetlands constitute 69.22% (10.56 million ha). The country's inland fisheries are of particular importance as they are the primary source of animal protein to which rural communities have access (MEA 2005). Another positive example of wetlands is the case of East Kolkata Wetlands (EKW), West Bengal, India, where untreated wastewater[1] from the city is used in fishpond for the purpose of fisheries.

The EKW is a complex and dynamic system providing a wide range of goods (food, water, fuel wood, fodder, etc.) and services (water supply, air purification, natural recycling of waste, etc.) and an example of wise use of wetlands. Farming vegetables, rice, and fish around the city of Kolkata, in the EKW, benefits local people and urban population of Kolkata in several ways:

– By generation of employment through (1) direct employment for thousands of men and women in catching fish, weeding, and cultivating vegetables and as casual laborers and (2) payment in kind for work undertaken on farms, e.g., weed clearing or carrying fish to market
– By indirect employment in supply and distribution networks, e.g., fish seed traders and market vendors

[1] This untreated water, mostly Kolkata city's domestic sewage, through the canals is first collected in primary ponds with heavy growth of macrophytes. The wastewater allowed to stand for considerable period of time is diverted to aquaculture ponds and then agricultural fields for further use. Agriculturalists and aquaculturists believe the whole process help in natural purification of the gray water and its sustainable use.

- Supplying affordable and fresh fish and vegetables to markets serving poor communities
- Through waste reuse, mitigating environmental degradation and reducing health risks
- The overall improvement in environmental quality due to the existence of peri-urban farming and water bodies

The EKW, located on the eastern fringes of Kolkata city, spread over an area of 12,500 ha is perhaps the largest sewage-fed fishponds. These wetlands form a part of the extensive inter-distributary wetland system in the Gangetic delta. The EKW sustains the world's largest and perhaps the oldest integrated resource recovery practice based on a combination of agriculture (including horticulture) and aquaculture. This provides livelihood support to a large, economically underprivileged population of around 20,000 families that depend upon the various wetland products, primarily fish and vegetables for sustenance (WISA 2008). Based on its immense ecological and sociocultural importance and on the recommendation of the Government of India, Ramsar Convention declared EKW as a wetland of international importance in the year 2002. This has drawn attention of international community to these wetlands. Further, "The East Kolkata Wetlands (Conservation and Management) Act, 2006" was a major statutory commitment to preserve the wetlands for current and future generation. This act makes provision for the conservation and management of the EKW and presents a schedule of landholdings within EKW specifying their character and mode of use. The current chapter is an effort to present broadly the ecological-economic linkages of this wetland with special emphasis on aquaculture, horticulture, and agriculture in the wetland complex under the waste recycling practices.[2]

The wetland system currently produces over 15,000 MT fish per annum from its 264 aquaculture ponds, locally called *bheries*. Additionally, nearly 150 tons of vegetable are produced daily. Thus, it is prudent to say that EKW serves as the backbone of food security of the Kolkata city. Further, it sets a typical example of harnessing natural resource in a wetland ecosystem for aquaculture and agriculture

[2] The resource recovery system in EKW follows a scientific approach wherein huge amount of sewage is treated through pisciculture. The wetlands act as waste-stabilizing ponds, while the slow-moving canal system functions as anaerobic and facultative ponds. The removal mechanisms for biochemical oxygen demand (BOD), nitrogen, and phosphorus are the settling of nutrients followed by their incorporation/uptake into algal biomass which is consumed by fishes getting incorporated into fish biomass. According to the aquaculturists, the cumulative efficiency in reducing the BOD of the sewage wastewater in these ponds is above 80% and that in reducing the coliform bacteria is about 99.99% on an average. The solar radiation is also reported about 250 langleys/day, adequate for photosynthesis. In fact, the sewage-fed fishery ponds in EKW act as solar reactors, trapping solar energy by thickly growing plankton, which is consumed by the planktivorous fishes. The plankton plays significant role in degrading the organic matter in the wastewater. The fishes, grazing on the planktons, maintain proper balance of the plankton population in the pond and convert the nutrients in the wastewater into consumable form (fish biomass) for humans. This complex ecological process is made use by the fish farmers of the EKW to produce fish at production cost unmatched in any other freshwater fishponds of this country.

(including horticulture) ensuring community participation and their traditional knowledge in waste recycling. This wetland system is also a testimony of a best practice of drawing local communities into conservation and management. Thus, it stands as one of the 17 case studies of wise use of wetlands by the Ramsar Convention (Bunting et al. 2011).

The genesis of the EKW is strongly connected with the development of the city, changing river courses and waste management of Kolkata. The city of Kolkata was historically a part of the mangrove and forestland of the Sundarban delta system. The rivers in this deltaic region were characterized by distinctive drainage pattern, massive swamps, and numerous wetlands. Earlier, the wetland complex in the eastern fringes of Kolkata was called salt lake (Sengupta 1980). Presently this wetland complex is also a part of EKW, which also represents the remnant beds of mighty tidal Bidyadhari River and its spill areas. Loss of tidal ingress from Sundarban delta and continuous runoff from the catchment facilitated the conversion and dilution of the salinity of the wetland complex rendering it into a freshwater wetland complex in due course of time (Kundu et al. 2008).

During the late eighteenth century, there was disruption of the connecting rivers, tributaries, estuaries, and network of channels connecting the Bidyadhari River. Damodar River, principally contributing to the upland discharge to the Jamuna-Bidyadhari, changed its course in due course (meandering character of river). Thus, in the absence of the upland water and clogging of the interconnected channels, the Bidyadhari became dependent for water solely on rainfall in its drainage basin. The situation was further aggravated with increase in tidal silt ingress, inadequate discharge to flush the silt, and construction of bridges and channels in the area. This event apparently transformed the ecosystem into marshes and swamps of varying sizes that subsequently changed into ponds for both fish and paddy cultivations.

Over the time, Kolkata grew into a large urban and trade center with no proper sewerage and solid waste management systems. This unplanned approach often resulted in drainage congestion and subsequent health impacts. The entire waste was initially dumped into the Hooghly River, a practice that was abandoned due to frequent outbreaks of malaria during 1700–1800 (Kundu et al. 2012). On the recommendation of a duly constituted committee, all the city wastes were transferred to salt lakes as the city has natural eastward slope. The wetlands were nearly 8.5 ft below the highest point of the city, and it was strongly suggested to construct a series of sewers and pumping stations toward the salt lake. In 1864, a portion of the salt lakes was also acquired for dumping solid waste. The first attempt of freshwater aquaculture was made in year 1918 (Kundu et al. 2012). Subsequent development of the wastewater channels in the city and rapid growth of the settlements ensured more sewerage directly promoting adoption of waste-fed aquaculture in the lakes. The wetland system presently has 264 *bheries* (WISA 2008). The solid waste dumping areas on the western fringe of the wetland complex were fully converted to horticulture since 1876. Application of sewage was sequenced skillfully based on detention time needed to improve the water quality appropriate for aquaculture activity (Kundu et al. 2012).

20.1.1 Dependence of the City on the Services Provided by the EKW

Complex ecosystems lying between river and coastal systems are fundamental to the well-being of society as a whole (Sayer et al. 2013). Conventionally, ecosystem services have been described as "the benefits of nature to households, communities, and economies" (Boyd and Banzhaf 2006). The Millennium Ecosystem Assessment (MEA 2005) defined them as provisioning, regulating, cultural, and supporting services and examined how changes in ecosystem services influence human well-being. Human well-being in this context is assumed to have multiple components, including security that encompasses secure access to natural and other resources, personal safety, and security from natural and human-made disasters. EKW is the best existing example, which provides a range of goods and services (Fig. 20.1) that contribute to human well-being and poverty alleviation. Communities living near wetlands are highly dependent on these services and are directly harmed by their degradation.

The economic activities that have mushroomed across the wetland complex is literally converting urban waste into wealth. Hence, this vast wetland has earned the title of Waste Recycling Region (WRR) in India (Kundu et al. 2012). These economic activities, of which agriculture, horticulture, and fisheries (Fig. 20.2 land use and cover) are the most important, have provided employment to thousands of people who live in the EKW region and its outskirts.

For understanding the ecological-economic linkages of EKW, a socioeconomic survey was conducted in the wetland complex. Primary data was collected through a sample survey of 10% of the total households residing in and around the EKW engaged in aquaculture, horticulture, and agriculture conducted from March 2011 to August 2014. Through stratified random sampling, 202 households were interviewed using a socioeconomic survey questionnaire. The investigation of Mukherjee

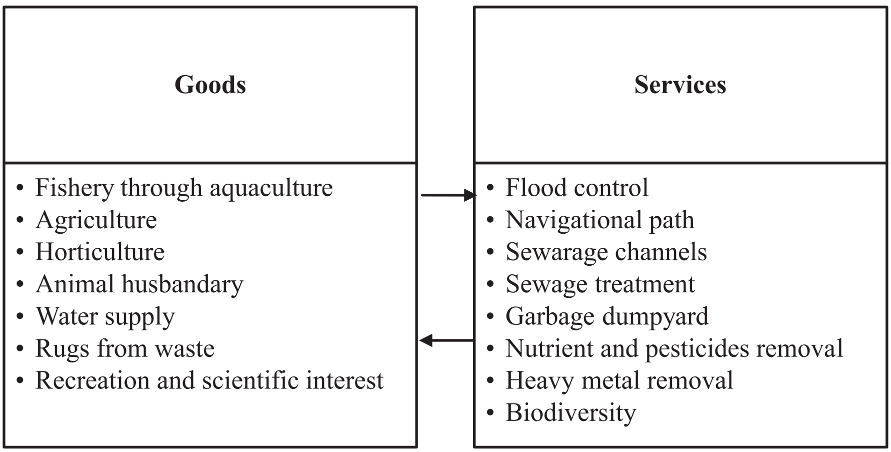


Fig. 20.1 Wetland goods and services provided by the EKW

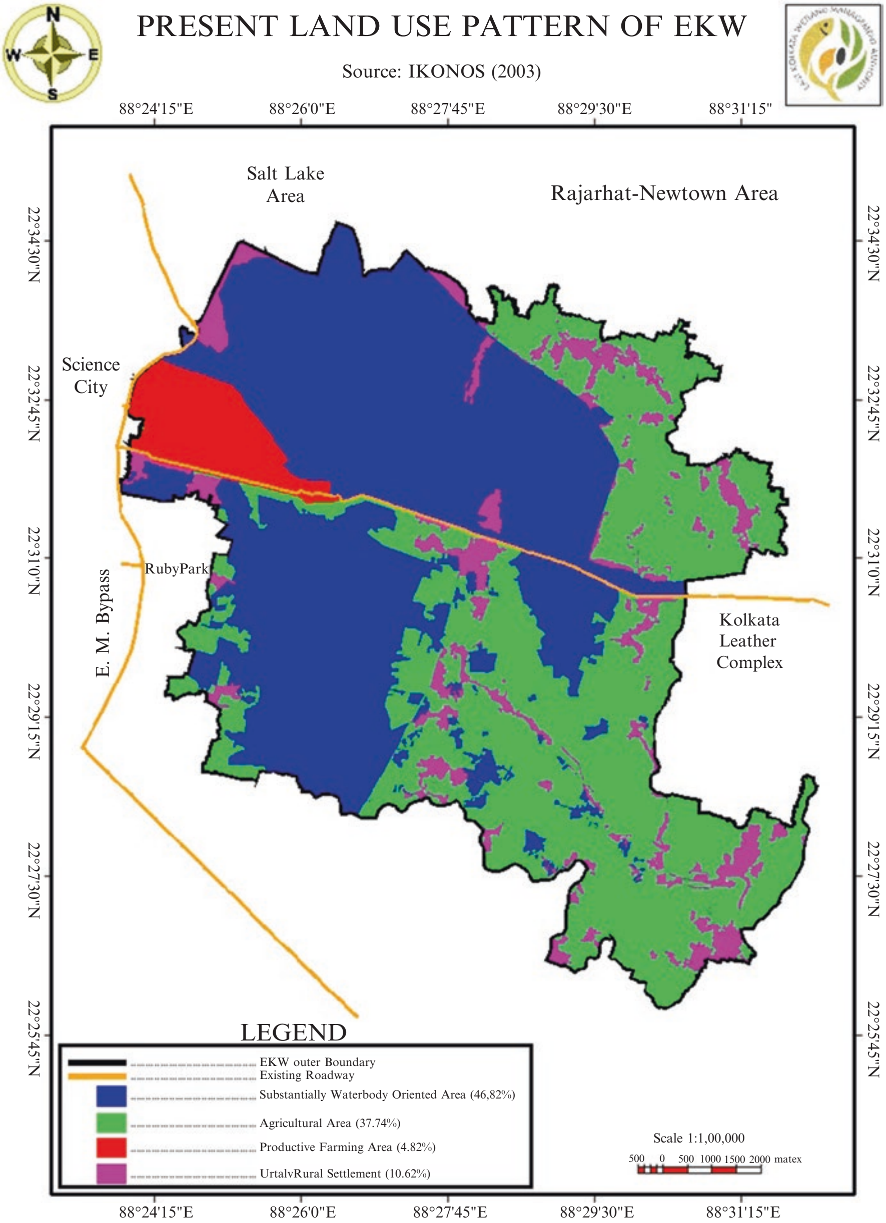


Fig. 20.2 Land use and land cover of East Kolkata Wetlands (Source: CEMPD 2013)

(1996) was used as baseline for aquaculture operation, updated accordingly based on the sample survey. Data was collected to reflect household level demographic profile, economic profile, resource use, ecosystem services, and perception toward management planning. Participatory appraisals were also conducted in 10% of the household to assess community rights and capacity for integrated management. Specific data for eight different areas of landholding for aquaculture ponds were analyzed for economics of aquaculture operation, while the data for agriculture and horticulture were examined for the net profit and issues associated with the operation. There was high reluctance among the stakeholders in sharing information on the gross economic benefit from the culture and cultivation practices although they were more willing to share information on issues related with the operation. A narrative of the range of ecosystem goods and services from this wetland complex is given in the subsequent sections.

20.1.1.1 Agriculture

Agriculture, within the eastern margins of the wetlands and to the south of the dry weather flow (DWF) channels, accounts for 38% of the land use. Paddy is the major crop cultivated thrice in a year. The monsoon crop (locally called *boro*) and winter crop (locally called *aman*) are the major two crops in a year, while the third crop (locally called *aus*) cultivated during summer constitutes the rest. Individually, average yield is highest in *boro* paddy (5 MT ha^{-1}), followed by *aman* (3 MT ha^{-1}) and *aus* (2.5 MT ha^{-1}) (WISA 2008). Assured water and fertile land ensured good harvest on investment, which principally governs the land use practices and conversion. In 1980s, about 2200 ha of ponds have been converted to paddy cultivation. Water for paddy cultivation is principally derived from the effluent from the fish farms. However, recently a trend of decline in sewage inflow and consequent higher dependence on monsoon and pumped water for cultivation is emerging very strong, which require strong interventions and management initiatives.

20.1.1.2 Horticulture

Kolkata generates roughly 3520 MT of garbage (solid waste) a day (Ali 2016), which is collected and dumped at designated sites (*Dhapa*) in the wetlands. The garbage-filled areas are extensively used to raise a variety of vegetables. The area surrounding *Dhapa* in peri-urban Kolkata is a center for vegetable cultivation. The area at present produces 15,000 MT vegetables per annum. Almost 15 varieties of vegetable are grown and sold in local and city markets, supporting small and marginal farmers and providing employment to thousands of poor people in the region. The production meets nearly 20% of the vegetable requirement of the Kolkata city. Of the total area under *Dhapa* (i.e., waste dump yard where vegetables are farmed), 55% area is used for double-cropping, while the rest is used for three crops in a year. The community practicing horticulture in these areas believes that the wastewater from the fishponds provides essential nutrients for the crops and ensures good harvest at the end. Availability of water, nutrient (from city garbage), and good urban market made horticulture as a household activity in the area. Farmers even rent small plots for raising vegetables. These plots are designed with alternate bands of garbage-filled lands and long trench-like ponds for cultivation. Water from the main sewage channels, secondary feeder channels, and freshwater wetlands are used to irrigate the vegetable plots.

20.1.1.3 Aquaculture

Sewage-fed fisheries are practiced mainly in the urban-facing areas of the wetland complex where huge quantity of sewage is ensured. The practice contributes 2% of the inland fish production and 65% of the total sewage-fed fisheries production of the state. Fish from the EKW meets a large share of demand of freshwater fish in Kolkata and adjacent areas. Apart from aquaculture, a large number of people are engaged in supply chain activities like transport, retailing, and processing. About 264 functional (sewage-fed) fishponds, occupying an area of 2858.65 ha, are major means of fish production (CRG 1997). Of this, private-owned *bheries* account for 93%, and farms managed by cooperatives 6%. Ponds managed by the state government are less than 1%. However, despite such a promising future, the effective area under aquaculture is declining rapidly. The major conversion was during 1992–2003 when a considerable part (6117.92–5852.14 ha) of water bodies was filled for agriculture and settlements. At present, the total area under the aquaculture practice is about 12,500 ha only (EKWMA and WI 2010).

20.1.1.4 Animal Husbandry

The EKW with fertile land and swamps supports animal life significantly. The inhabitants of the region have cashed in on the opportunity and set up piggeries, goat farms, duck, and ornamental fish rearing along with food fish cultivation. Such activities require low investment on equipment and infrastructure, and the products have good demand in urban market. Products like pork and ornamental fishes are also exported.

20.1.1.5 Water Supply

The EKW predominantly serves as a source of water for agriculture, horticulture, aquaculture and livestock, and for the use of communities residing within the wetland complex. Water use within the wetland is predominantly governed by the needs of aquaculture, agriculture, and horticulture. There exist no guided water allocation practices in EKW. The outflow from the wetland complex depends on the inflow to the wetlands, which is largely governed by the sewage generated from the Kolkata Municipal Corporation (KMC). An assessment carried by *Jalabhumi Bachao* Committee indicates that on an average 230 MLD with significant reduction during the monsoon is allocated for the agriculture. Ghosh (2005) indicates the overall sewage use by agriculture to be 400 MLD. No assessments are available on the uptake of effluents by the fish farms. The overall demand for the fisheries was estimated at 420 MLD (WISA 2008). Allocation of water supply is done by opening and closing the sluice gates. The operation is principally governed based on mutual consent on demands by farmers and aquaculturists for their respective activities.

20.1.1.6 Rag Picking

The *Dhapa* in EKW was initially conceived as garbage-dumping ground. Eventually, it has emerged as a concentrated one-point hold for huge rags of the city as well. Currently the city generates around 3063 MT of solid waste per day of which 563 MT is industrial waste and 2500 MT of garbage. Ragpickers scout these wastes for objects that can be re-recycled. Mostly these pickers represent major unregistered slums of Kolkata (Kundu 2003). Many areas in Kolkata lack public sanitation services, and ragpickers are the only means of solid waste disposal. A large part of the poorest section of the society depends on ragpicking for their livelihood. They collect about 10% of the total solid waste generated by the city, thereby reducing the enormous burden of waste management on the municipal corporation.

20.1.1.7 Flood Control

The EKW acts as a natural depression between the Kolkata city and Kulti estuary. These depressions have enormous water-holding capacity. Under the natural settings, water-holding capacity enabled the wetlands to regulate the flow regimes and attenuate floods by storing peak monsoon flows as well as tidal flows. However, the landscape of the city has changed or specifically deviated due to the alteration in the natural drainage system for the need of urbanization resulting in frequent flooding. This happens due to the failure of planning process to consider the natural incline-based drainage patterns that formerly existed in the city (WWF 2011, 2013).

20.1.1.8 Hooghly River as the Oldest Navigational Gateway to the Ocean

Historically the entire eastern fringe falls within the water route for transportation of goods through the Hooghly River. Hooghly, a distributary of River Ganges, forms the western boundary of the city and provides filtered water to the city. It is also used as the navigation channel to the ocean. Initially the river and its vast wetland complex were the pathway to the ocean for unimpaired shipment of goods. Thus, it can be said as one of the major services provided by the river and its associated wetland complex during the British era. At present, the river is connected with the EKW via sewage channels only.

20.1.1.9 Sewage Channels

Hydrological regimes within the Kolkata and its sub-basins are through drainage and sewage channels, which connect both the urban and peri-urban Kolkata on the bank of Hooghly to the outfall systems of Kulti. Spread across 545 km^2, the basin flows are ultimately discharged to the two rivers Hooghly and Kulti through 1421 km long drainage system and interconnected network of drains and channels (Fig. 20.3). Four such channels are supporting the whole mechanism, which are briefly mentioned in the subsequent subsections.

20.1.1.9.1 The Dry Weather Flow (DWF) and Storm Weather Flow (SWF)

The Dry Weather Flow (DWF) and storm weather flow (SWF) are the most important channels in the East Kolkata Wetland Recycling Region (EKWRG). These

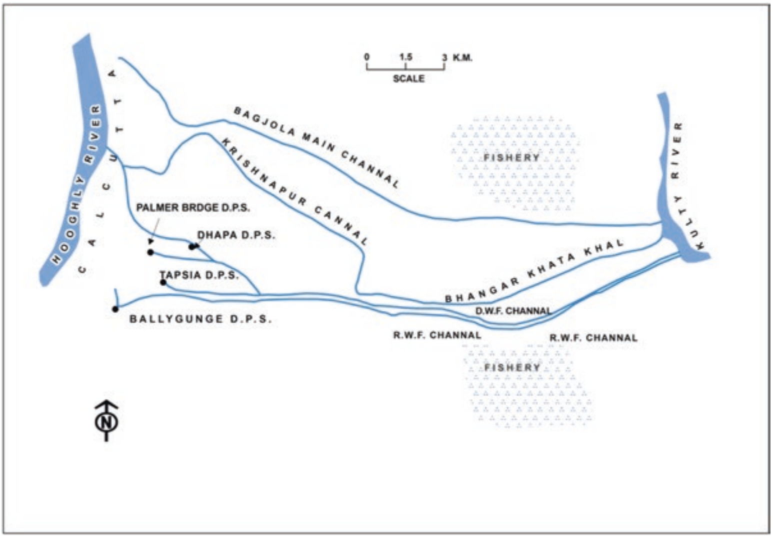


Fig. 20.3 Channel system in Kolkata city and East Kolkata Wetland (Source: CEMPD 2013)

channels ultimately debouch into the Kulti River about 30 km east from the Kolkata city. About 75% of Kolkata's wastewater passes through the SWF/DWF system. There are several points where the channels have interconnecting sluice gates. Currently large amount of Kolkata's DWF is channeled through the SWF.

20.1.1.9.2 The Baghbazar System

The Baghbazar System originates at the Chitpur lock in the Hooghly River about 2 km inland, splitting into circular canal (Beliaghata canal) and Krishnapur canal. The circular canal receives wastewater from unsewered areas of Beliaghata/Manicktala basin and then moves south and eastward for about 12 km to meet the Krishnapur canal. The Krishnapur canal takes a northerly course around Salt Lake City reconnecting with the circular canal at first and then joining the Choreswar Khal resulting in the formation of the Bhangor Kata Khal. This canal continues eastward parallel to the DWF and SWF and empties into the Kulti River, just north of the Ghusighata outfall.

20.1.1.9.3 The Tolly's Nula/Nullah

Tolly's *Nullah* constructed in the 1770s was used for navigation between the Hooghly River and parts of Kolkata's immediate hinterland to the east. The canal originates in the Hooghly River just south of Vidyasagar *Setu* and follows the bed of Adi Ganga, an old distributary of the Ganga River. The main canal goes eastward for about 20 km where it meets the dead Bidyadhari River at Samukpota. Although Tolly's *Nullah* was originally meant for navigation, negligence and lack of proper maintenance have made the canal impassable. The current function of the canal is to drain Chowbaga basin and some of the Suburban basins in Kolkata. Since Tolly's Nullah was not planned to serve as a drainage canal, there are no treatment facilities yet in place to handle the wastewater leading to direct release of untreated wastewater into the Hooghly River.

20.1.1.10 Disposal of City Sewage

The city of Kolkata, situated in a deltaic plain, follows a general elevation from west (Hooghly River) to east (salt lakes and EKW). This topology allowed the drainage committee formed in 1857 to divert the whole city sewage into the wetland instead of the Hooghly River. At present, the drainage system of Kolkata falls under two main systems, they being the town and suburban systems. The town system covers the major part of the city, while the suburban system covers the newly expanded city at Beniapukur, Tiljala, and Beliaghata. The two systems meet at Topsia and ultimately fall in the Bidyadhari River.

20.1.1.11 Treatment of Sewage Through Fisheries

The EKW plays a vital role in sewage management. Management of sewage and garbage has adopted the principle of resource recovery. The wetlands act as "sink" for sewage and waste material from Kolkata that lacks any substitutable sewage treatment facility for its 4.5 million residents (Census of India 2011). About 3500 t of municipal waste and 68 million liters of raw sewage drain into the wetland system on a daily basis. The schematic representation of pathway of sewerage use under different land use practices is presented in Fig. 20.4.

Sewage-fed fisheries, which utilize such large volumes of sewage generated by the city, started functioning as early as 1883. In 1940, about 4682.22 ha of wetland area produced 0.14 t of fish per ha utilizing the municipal sewage. The

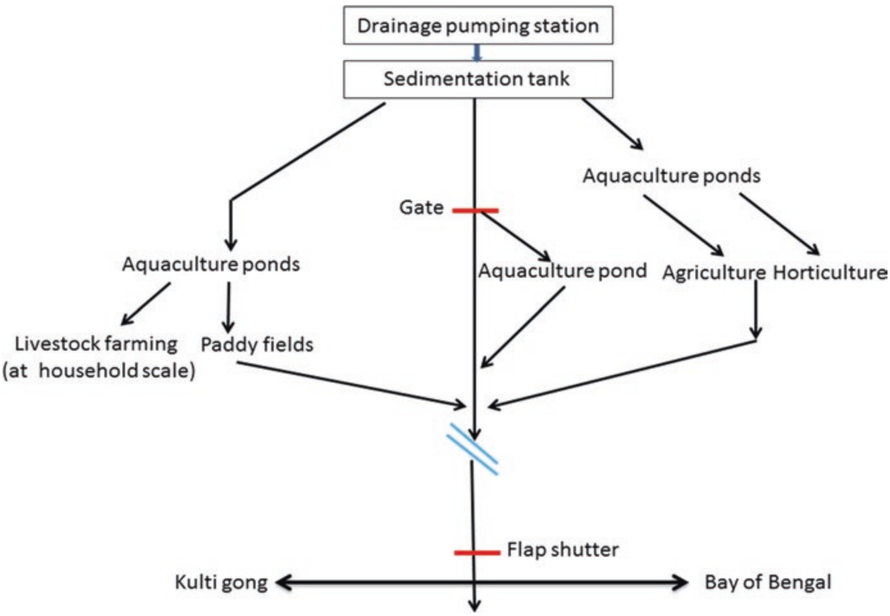


Fig. 20.4 Pathway of sewage being used for different purposes in EKW (Source: CEMPD 2013)

profit-generating potential of the wetlands in terms of aquaculture aroused interest in local farmers as well as local landlords who leased out most of the ponds to commercial managers. The conspicuous result was employment generation through production of fish and vegetables as well as a steady supply of food materials to the urban markets.

20.1.1.12 Disposal of Garbage

The city of Kolkata faces huge problem of disposal of garbage. A part of western region at EKW was acquired in 1864 for dumping the garbage with no concern for wetland conservation. Eventually with the indigenous farming practices, the land was converted into a horticulture ground. At the cost of marshy wetland, major cultivations like sewage-fed agriculture, garbage farming (i.e., growing crops on composted or decaying garbage), and sewage-fed aquaculture were developed. These farming systems eventually turned central to the livelihoods of many local poor people living in the surroundings (Bunting et al. 2001, 2002). The irrigation system for vegetable cultivation is fully dependent on the city sewage, currently producing about 150 tons of vegetables daily at the bargain of the solid waste. Noticeably no report or communication on the health hazard was known due to the practice, harvest, and consumption of the harvest. This makes this wetland globally one of the best examples of waste recycling model for adaptation and dissemination.

20.1.1.13 Nutrient and Pesticide Removal

The presence of *Actinobacteria* and *Firmicutes* indicates the prospect of nitrophenol, nitro-aromatic compound, and pesticide and herbicide degradation in the wetland as well as garbage-dumping ground that receives solid and liquid waste from the entire city (Chaudhuri and Thakur 2006). These microorganisms are also involved in decomposition and humus formation. These microbes are also involved in decomposition and humus formation. The *Proteobacteria* (gram-negative bacteria isolated during an investigation period of 12 months) present at the ECW indicates bioremediation of heavy metals from solid as well as liquid sources (Chaudhuri and Thakur 2006). They are involved in degradation and recycling of woody tissue of plants and biodegradation of oil-contaminated soil and toxic compounds. The presence of cyanobacteria specifies nitrogen fixation. The fact that only bacterial isolates were found does not mean that no Archaea or lower Eukarya are present. Compositional pattern of microbial population was seen to reach saturation on plotting the number of clones against the number of operational taxonomic units observed. Novel sequences falling within *Proteobacteria*, *Firmicutes*, and *Actinobacteria* indicate the probable presence of metal-accumulating (Klaus-Joerger et al. 2001), oil-degrading, antimicrobial compound-producing, as well as enzyme-producing bacteria (Georgalaki et al. 2002).

20.1.1.14 Heavy Metal Removal

Twenty bacterial isolates were found to grow in the presence of different concentrations of various heavy metals, *viz*., Al, Cu, Ni, Co, Fe, Cr, Pb, Ag, and Cd (Chaudhuri and Thakur 2006). The growth of the bacterial colony indicates that the EKW is home for useful bacteria, which effectively utilize heavy metals, helping in the immobilization from the sediment and water effectively.

20.1.1.15 Biodiversity

The wetland complex supports a wide range of both flora and fauna (Figs. 20.5 and 20.6) (IWMED 2004). Thirty species of phytoplankton were reported from the area. The vegetation comprises 55 species of aquatic macrophytes, 90 species of bank flora (including 41 species of herbs, 14 species of climbers), and 35 species of trees/shrubs (IWMED 2004). Moreover, in several parts of EKW, five species of fruit plants and ten species of ornamental plants are extensively cultivated by irrigating with sewage water (IWMED 2004). The wetland harbors 40 species of fishes (De et al. 1989), four species of amphibians (IWMED 2004), 19 species of reptiles (IWMED 2004), about 135 species of birds (Bhattacharya et al. 2008), and 16 species of mammals (IWMED 2004). Seventy-four species of butterflies (Chowdhury and Soren 2011), 10 species of benthos (Mallick 2009), and 17 species of zooplankton (Kundu et al. 2008) have also been recorded. The EKW supports rare mammals such as marsh mongoose (*Atilax paludinosus*), small Indian mongoose (*Herpestes auropunctatus*), Indian civet (*Viverra zibetha*), and the Indian mud turtle (*Lissemys punctata*) (WWF 2011). Bengal mongoose (*Herpestes palustris*) is an extinct mammal endemic to the EKWs (Mallick 2009).

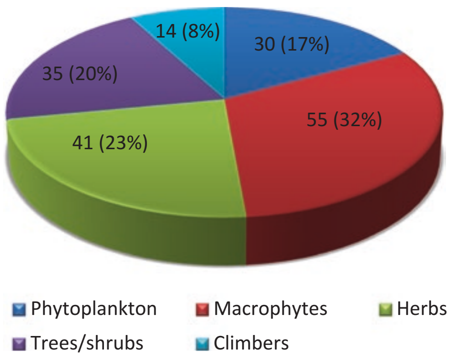


Fig. 20.5 Species (percentage in parenthesis) constituting the floral diversity of EKW

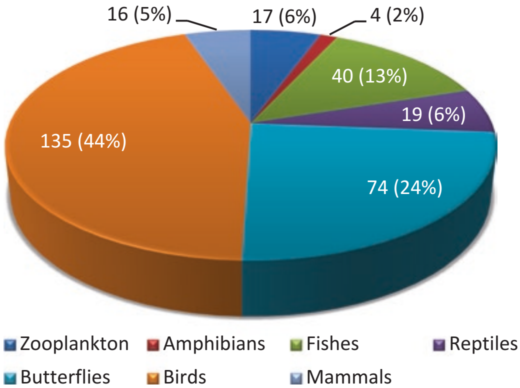


Fig. 20.6 Species (percentage in parenthesis) constituting faunal diversity of EKW

20.1.2 Valuation of East Kolkata Wetlands

The EKW compensate for an efficient, economical, and environment-friendly waste management and sewage treatment facility that the city of Kolkata lacks. The nutrients from the wastewater and human excreta enable the local villagers to practice wastewater-fed pisciculture and garbage-manured productive farming. Inhabitants of Kolkata get to enjoy the ecosystem services offered by the EKW without having to incur any cost. However, what makes the EKW stand out is the fact that it is a public good infringed with private ownerships. The flexibility of the lands, their use, and ownerships are facing major constraints due to the overarching Ramsar Convention and East Kolkata Wetlands (Conservation and Management) Act, 2006. Since a considerable portion of the land of the EKW is under private ownership, it imposes limited or no options to follow their own aspirations. The lands in EKW in fact are used by their owners for the purpose of facilitation of free public services to Kolkata citizens. This attests the principle of non-excludability as pertinent to both consumers and producers of the services. Traditional methodologies of public good pricing do not stand to be appropriate to resolve the predicament of evaluation of this unique public good.

20.1.2.1 Fisheries

Large areas of wetland are leased out to cooperatives and private proprietors for aquaculture. The leased wetlands usually range from 5 to 50 ha. Usually polyculture of eight different species (three species of carps, one species of minor carps, three species of exotic carps, and two species of cichlids) to table-size fishes is the main practice. Field surveys during 2003–2004 show 8500 people as directly engaged in sewage-fed fisheries. Of these about 90% are from local villages within the EKW, the others from adjoining areas of districts 24-Parganas (North) and 24-Parganas (South) and Midnapore, and sometimes from neighboring states of India. Culture practice provides opportunities for various types of skilled and unskilled labor including those engaged in security services, harvesting, loading, unloading, packing, and distribution of fish. Detailed economics of such aquaculture activities in eight representative wetlands are presented in Sects. 20.1.2.1.1, 20.1.2.1.2, 20.1.2.1.3, 20.1.2.1.4, and 20.1.2.1.5 below.

20.1.2.1.1 Inputs

Inputs can be either fixed or variable. Fixed inputs comprise land, initial investment in infrastructure (like huts, pipe channels, and embankment), and equipments (like boats, nets, bamboo, pumps) used in the operation. However, if the land is being leased out or under shareholding, the land costs become variable. There also exist maintenance costs and depreciation expenses on infrastructure and equipments. The variable costs include wages, fish fry-yearlings and fingerlings, pesticides, fish feed, fuel, and taxes.

20.1.2.1.2 Fixed Costs

Land costs are around INR 150,000 ha^{-1}. Land that is rented incurs a yearly variable cost of INR 3000 to INR 10,000 ha^{-1}. The variation in rent is driven by the harvest from the systems. In a shareholding system, between 25 and 50% of the profit goes to the owner, while in the large-sized wetlands' major portion, about 40% went to the owners.

Initial investment to set up aquaculture pond under the production process is difficult to estimate since the pond would have an existing structure left from the previous cycle. The amount usually varies between INR 100,000 and 500,000 for the initial setup of a pond of around 16 ha. These and other fixed costs for setting up the aquaculture operation in 16 ha of pond are presented in Table 20.1.

20.1.2.1.3 Variable Costs

Labor wages account for the major share of variable costs. There are 2.88 workers/ha on average in an aquaculture pond. Thus, 16 ha would have 46 workers, employed as harvesters, guards, carriers, managers, and skilled or unskilled labor. About 25% workers are considered permanent. Depending upon their skill, they get INR 500–1200 per month as well as other benefits such as lodging and medical treatments. It is stipulated that each temporary worker does only one kind of work and gets at least 6 months' work in a year and receives per day INR 166–400 and other benefits such as 250 g of food. Estimations of variable costs for 1993–1994 from eight sample ponds are given in Table 20.2. The data presented is compiled from the balance sheet maintained by an aquaculturist.

20.1.2.1.4 Scale Factor

Economics of scale are the cost advantages that enterprises obtain due to size, output, or scale of operation. The cost per unit output generally decreases with increasing scale as fixed costs are spread out over more units of output. The cost of taxes, pond preparation, weeds clearance, earthwork, and materials such as ropes and nails are scale dependent and increase proportionately with size. However, there are yearly variations in some of these components. On the other hand, certain items, although scale dependent, are used more at an increasing or decreasing rate as the scale increases. Boats are hardly required for very small setups, while their use increases proportionately with size. When the size of aquaculture pond goes above

Table 20.1 Fixed cost for setting up an aquaculture operation

Equipment	Price (INR)	Quantity (No.)	Total (INR)
Hut	2250	8	18,000
Net	5500	4	22,000
Boat	13,500	2	27,000
Bamboo	20,000	1	20,000
Diesel pump	8700	1	8700
Total			95,700

Source: Mukherjee (1996)

Table 20.2 Variable cost (INR) for aquaculture pond preparation and operation per annum

Size (area in ha)	4.8	8	16	24	40	48	80	96
Land lease, share of rent	24,000	25,000	37,000	60,000	598,097[a]	756,740[a]	350,000	250,000
Pond preparation, weed clearance, earth work	5000	10,000	1500	18,000	50,265	45,225	93,570	110,635
Pipelines, sewage distribution, water drainage	2000	2000	8000	10,000	26,623	26,520	43,720	45,792
Repair of office, boats, and purchase of ropes, pesticides	6990	14,175	31,000	17,500	49,918	51,005	82,007	108,055
Repair of nets	3000	4000	4000	6000	10,318	12,320	15,635	17,375
Bamboo	3250	5000	11,000	12500	29,440	25,440	54,500	66,400
Spawn, fry purchase	15,000	50,300	60,000	102,619	207,660	227,620	453,430	499,518
Supplementary feed	10,000	15,000	30,000	50,000	60,000	70,530	100,550	130,700
Energy	1950	3500	9000	18,000	35,000	49,142	91,902	100,750
Taxes	930	1550	Na	2000	6000	8130	15,000	16,450
Puja donations	4000	6500	5000	5000	6136	7985	9000	9370
Travel	Na	500	Na	Na	2000	2220	3000	3630
Wages	101,570	180,350	376,000	484,800	865,148	732,012	1,315,234	1,533,280
Total	177,690	317,875	607,500	786,419	1,348,508 (1,946,605)	1,258,149 (2,014,889)	2,627,548	2,896,925

Source: Mukherjee (1996)
All the variables are expressed in INR, if not mentioned otherwise
[a]40% share

32 ha, the number of boats required increases disproportionately. Per unit managerial and guard costs increase with scale, while the cost of skilled and unskilled permanent employees decreases with scale. Donations (in cash) for rituals are a common phenomenon being claimed from all the stakeholders and community residing near EKW. However, such charges paid on this particular ground do not increase much with size of the *bheries* in fish culture operation. Unit expenditure in energy increases with scale (Table 20.2). Apart from the scale factor, several other causal factors affect the costs. A narrative table (drawn from personal interview with an aquaculturist) on effect of causal factors on the variable cost affecting the overall operation of aquaculture is presented in Table 20.3.

In the present context, the cost was not inversely proportional to size**.** It simply indicates that the optimal size would be large. From the above table (Table 20.4), we can see that the total cost/ha does not move smoothly with size, but it is highest at 08 ha of *bhery* and lowest at 48 ha (Table 20.4). Considering the costs/ha, it is evident that both reduced unit costs and increased productivity are responsible for higher (per unit) profit. As profits per unit area are highest and labor costs per unit lowest for the 08 ha pond, this would be the ideal size for profitable aquaculture operation. With respect to maximizing employment, the 8 and 16 ha *bheries* appeared to be the most useful. It would also be better to have bigger fisheries held either on a partnership basis or by cooperatives.

20.1.2.1.5 Net Returns from the Aquaculture

Comparison of the returns to an owner under two different scenarios (i.e., if he/she sells fishery or kept the culture for longer period running it) is given below. Given that the fisheries cannot be sold for more than INR 15,000 ha^{-1} (on an average), long-term corporate interest would yield INR 3000 $year^{-1}$. Now running the fishery would yield a lease value on an average of around INR 650/year. Thus it is necessary for profit ha^{-1} to be more than INR 23,500/year to make the first scenario a preferred choice.

The profit figures are higher for all *bheries* that are >8 ha, and that would give the owner of bigger *bheries* a smaller incentive to sell. However, it also implies that for

Table 20.3 Effects of other causal factors on variable costs

Causal factor	Increases	Decreases
Supply of sewage to fisheries	Lease rate, productivity, output, cost of spawn, labor, boats, nets, materials, revenue	Expenditure on pipelines, fish feed, and fuel
Poaching	Expenditure on guards, guard huts	
Office/store structure	Repairing cost of mud structures, initial investment of brick and mortal buildings	
Nursery breeding		Spawn or fry purchases
Small *bheries*	Laborers per unit area	Bargaining strength
Large *bheries*		Per unit cost on labor and sewage

Table 20.4 Cost, productivity, revenue, and profit by size for sample fisheries

Size of pond (ha)	4.8	8	16	24	40	48	80	96
Cost (INR)/ha	59,230	63,580	60,750	52,430	53,940	41,930	52,550	48,280
Labor cost (INR)/ha	35,520	38,070	39,250	33,520	36,610	25,900	28,170	27,480
Labor cost (% of total)	57	57	62	62	64	58	50	53
Productivity (kg/ha)	4200	4800	5800	5500	6500	6000	5500	6000
Revenue	2200.50	4200	10,150	14,430.75	28,430.75	31,500	48,120.5	63,000
Profit	420.81	1050.13	4070.50	6570.33	14,950.24	18,910.85	21,840.95	34,030.08
Profit (INR) /ha	14,270	21,030	40,750	43,820	59,800	63,060	43,700	56,720

All the variables are expressed in INR, if not mentioned otherwise. Source: Mukherjee (1996) the owners of *bheries* <8 ha, it makes economic sense to sell them at the current price per ha. Thus, from the narrow perspective of personal net returns, the operation of these fisheries is not wholly justifiable, and that is why it is predicted that they will be wiped out unless production efficiency increases considerably, and the environmental and social benefits yielded by the fisheries are fully recognized.

20.1.2.2 Agriculture

The total agricultural area under the EKW is 4718.56 ha. Table 20.5 shows the variable costs incurred in cultivating paddy, the most widespread crop grown in the EKW. The profit depends on the size of the plot; the price of the output; the price of seed, tractor, and labor; the quality of the rice seed; the price of fertilizers and pesticides; and the use of sewage water. The profit ranges up to INR 17 kg^{-1} of rice with the average profit being INR 11. This high amount of profit earned attracts more farmers to shift to paddy cultivation in recent times.

20.1.2.3 Vegetable Cultivation

Vegetable production in the 1960s was estimated at 56,000 t $year^{-1}$. This particular practice in the EKW might have started due to the abundance of solid waste in the area. But at present, this sector is facing heavy market competition, reduction in solid waste accumulation, and climate uncertainties that largely affect the production. All land farmed by the participants is owned by the Kolkata Municipal Corporation (KMC). The farmers take the land on lease from either the KMC or an intermediary. Since lease is given for 1 year, farmers showed their unwillingness to take any kind of risk through investment in terms of both time and money for long-term benefit of the production system. This has resulted in poor quality of cultivation practices. The total area under productive farming in the EKW is 602.78 ha. The variable costs incurred in cabbage and cauliflower cultivation in the EKW are presented in Table 20.6. The cost of cultivation for cabbage is lower in large farms. The average yields of cabbage and cauliflower are 29 tons ha^{-1} and 15 tons ha^{-1}, respectively.

Table 20.5 Variable costs in paddy cultivation

Item	Price (INR ha^{-1})
Seed	26
Tractor	234
Main fertilizer	9.5
Supplementary fertilizer	6.5
Main pesticide	140.5
Supplementary pesticide	123
Labor	113
Total	652.5

Table 20.6 Variable costs in vegetable cultivation

Item	Price (INR/ha)	
	Cabbage	Cauliflower
Land preparation	1550	1450
Nursery/seedling	8110	7750
Irrigation	500	460
Manure + fertilizers	7250	7150
Plant protection	14,200	14,515
Hired human labor	13,330	1050
Land revenue and depreciation	640	560
Total cost	45,580	32,935

20.2 Issues Affecting the EKW

Changes in the land use within the EKW (Table 20.7), pressures from the metropolitan city as well as the growing human population are the major threats to this wetland complex. Despite their potential to provide multiple natural and social services, the wetlands are under various anthropogenic threats. As such, they need further study, effective maintenance, monitoring, and upgrading. An attempt to analyze the change through interpretation of Survey of India toposheets of 1959–1960 and remote sensing imageries 1989, 1999, and 2002 further indicates that the EKW are changing at a very fast rate. There has been also significant reduction in water spread area due to conversion for agriculture. Water being a critical factor in governing the ecological character and ecosystem services provided by the wetlands, such changes are required to be addressed immediately with appropriate interventions that enhance water spread areas.

Fragmentation of wetland habitats particularly by the dispersed human settlements within the east and southern parts of the wetlands associated with the higher elevation is an emerging potential threat of decreased siltation process (WISA 2008). Construction of the Eastern Metropolitan Bypass has made the EKW accessible, and Salt Lake City apparently provides additional social and economic infrastructures. Protection of the wetlands from developers and real estate agents is becoming increasingly difficult. The existing legal provisions and agencies have clearly been inefficient in preventing such encroachments. Constructions in the wetland areas can eventually hamper recharging of the groundwater and can increase the incidences of floods. Infrastructure development can cause fragmentation of EKW, which will increase social, ecological, and environmental imbalances in local areas. In addition, increased load of pollutants, siltation of ponds, poaching, unsustainable use of ground water, and loss of biodiversity are other major threats to EKW. An unprecedented problem in recent time is the presence of local *mafias* (goons) who are trying to control the fishponds. Moreover, as this is an urban area, there are more competing, conflicting interests and agencies than would be found in a village.

Table 20.7 Changing land use within EKW

Land use classes[a]	1986	1989	1992	1997	2003
Water bodies	6117.91	6117.67	6117.17	5943.82	5852.14
Agriculture	4469.28	4467.56	4470.15	4637.17	4718.56
Horticulture	593.79	594.12	593.23	597.86	602.78
Settlements	1319.02	1320.65	1319.45	1321.15	1326.52
Total	12,500	12,500	12,500	12,500	12,500

[a]All the values are in ha. Source: WISA (2008)

20.3 Opportunities

At present, the wetland complex is overarched by five national and three state regulatory legislations. Almost six authorities in the state are responsible for execution of the provisions and monitoring the wetland complex (Fig. 20.7) for compliance with the provisions. However, the policies and strategies lack integrated management approach. Planning approach often lacks coordination between different development and regulatory actions. Some of the major constraints on accessing the ecosystem goods and services from this wetland complex are:

1. Major gap in strategies to guide coordinated action linking the river basin with the coastal process.
2. Lack of involvement of marginalized communities.
3. Water allocation which do not consider ecological demands.
4. Ineffective institutional mechanism.
5. The economic evaluation of ecosystem goods and services had not been considered and incorporated in developmental plans and interventions by the EKW management authority.

Apart from this, there exist many other site-specific constraints and threats associated with aquaculture. Siltation of canal and fishponds had emerged as a rapidly growing problem to the wetland complex resulting in decline in fish production. Chemical contamination constitutes a widespread threat and poses difficulties in marketing fish and agricultural products adding on to the magnitude to the problem.

However, it can be concluded that sewage-fed fisheries and garbage farms not only provide inexpensive and dependable agri-/aquacultural food products but also help to maintain an eco-friendly environment. However, the prevailing pisciculture practice in the EKW is hardly viable in the sense that it does not function optimally due to multiple problems. Increasing siltation in the channels and fishponds has subsequently reduced the quantity of sewage flowing to the fisheries and rendered many of the fishponds shallower that, in turn, have reduced fish production. While environmentalists are putting in efforts for preservation of the EKW, undue profit-seeking investors are increasing pressure for the right to develop areas for

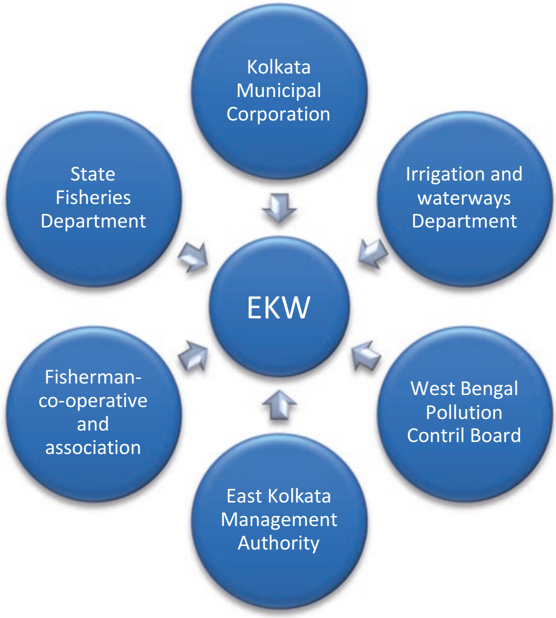


Fig. 20.7 Authorities in state government of West Bengal responsible for management of EKW

residential and other commercial purposes. The sewage-fed fisheries of the wetlands have been constrained due to inadequate management of water regimes, technology integration, weak marketing, post-marketing, and value addition opportunities. Management inefficiencies such as failure to operate sluice gates properly and to run the pumping systems, regulating the storm weather flow and the dry weather flow channels of the Kolkata drainage system in line with the requirements of farmers in East Kolkata, are gradually crushing the system. The current farm management systems are biased toward large private farmers and against the small- and medium-sized cooperatives. The existing aquaculture system needs to adopt upscale technologies to optimize fish production and related economies. The sewage-fed ponds should be dredged at regular intervals. There should be an efficient distribution system of sewage so that all the ponds in the EKW get adequate sewage to culture fishes.

The current institution, East Kolkata Management Authority (EKMA) under the chair of state chief secretary, had taken up these challenges. The said authority has initiated activities and intervention to mitigate the issues. The authority is already taking concerted efforts to implement the EKW (Conservation and Management) Act 2006. Various awareness generation activities were regularly taken up to make people aware of the values and functions of the wetland complex. Apart from this, desiltation of the clogged canal system had also been taken up under various projects. EKMA is also interested toward improving community livelihoods and quality of life with the help of several nongovernment organization and agencies.

However, despite serious problems to be tackled, the wetland complex still actively plays a vital role in managing the sewage from 4.5 million residents of the city of Kolkata. The management of 3,500 t of municipal waste and 68 million liters of raw sewage would not be possible, cost-effective, and sustainable without the integration of waste recycling-based EKW system in place. It has been estimated that an investment of INR 1.4 million would be required to build a conventional wastewater treatment facility to handle the sewage. It is to be emphasized that EKW has been providing a range of other ecosystem goods and services for decades. Hence, policymakers, planners, and stakeholders will have to make major policy decisions to determine how these wetlands will be used in the coming days in the face of growing threats.

20.4 Conclusion

The total area of EKW in the last 50 years has been reduced considerably and alarmingly. In another 25 years perhaps, these wetlands will become part of Kolkata's past despite the fact that these wetland complex accounts for numerous socioeconomic benefits such as employment generation, a moderately healthy rural society, secondary benefits to others (fish seller, net makers, boat makers), and the production of fish near the most important city of the net fish-importing state. Elimination of *bheries* would have grave consequences for the worker on one hand and the fish consumers on the other. It is difficult to imagine what would happen to Kolkata's flood, sewage, and garbage in the absence of this wetland complex. The failure in proper management of flood and sewage on the health and hazard cost cannot be measured by the market economy.

In spite of the importance of EKW in many ways, there has been shift in the land use within EKW. The area under fish farms has reduced from 7300 ha in 1945 to 5842 ha in 2003. Construction of fish farms bunds and roads within the fish farms have further reduced the effective area under water bodies to 2481 ha. The gradual reduction in water spread within the wetlands has reduced its capacity to recycle wastes and attenuate floods.

Decline in sewage and unregulated operation of the sewage canal has not only affected the productivity of agriculture and horticulture but also had grave impact on the people directly and indirectly depending on them. Management of hydrological regimes within EKW is biased toward flood management of Kolkata city without considering the flow requirements for the maintenance of ecological processes within the wetland system.

These had been also a rapid change in biodiversity associated with the wetlands due to changes in hydrological regimes and land use. The wetland, which in early twentieth century was teeming with large spectrum of brackish and freshwater fishes, now only supports cultivated freshwater fishes. The sewage-fed fisheries for which the wetland is known globally had been constrained due to the inadequate management of water regimes, technology integration, and value addition opportunities.

The current institutional arrangements are not effective in implementing the East Kolkata Wetlands (Conservation and Management) Act, 2006. The overall focus on patch management with mainly engineering measures and little awareness activity neglects the basic demand of interlinkages with hydrological processes and biodiversity. Involvement of multiple stakeholders with sectoral approaches limits adoption of a holistic management approach and strategy for the EKW.

Despite living within a highly resource-rich area, the communities living within EKW face higher levels of poverty. It is prudent to say that the wetland despite its multifaceted dynamism lacks integrated management approaches. Thus, for the sake of stakeholder welfare, the authorities in state government of West Bengal responsible for management of EKW should come up with an integrated management plan based on the principles of management zoning which will provide a basis for targeted interventions to achieve conservation and wise use of wetlands. The Ramsar framework for the wetland inventory assessment and monitoring, which is a multi-scalar approach, has already been adopted for sustainable management of EKW, but the interconnectivity in the management planning at different hierarchal levels needs to be ensured and maintained for the ecological and economic integrity of this wetland. Approaches with interdisciplinary, participatory, and integrated action planning process should be strictly followed in this wetland complex.

Acknowledgment Authors are indebted to Dr. Sushma Panigrahy, Group Director (Retd.), Space Research Organization, and Indian Space Research Organization India, for her valuable advice in drafting the article. Authors express their gratitude to Mrs. Sourosheni Guha Ray, Dr. Mausumi Pal, Mr. Suman Kumar Dey, and Mrs. Anjana Saha for their technical help during the project survey.

References

Ali SA (2016) Status of solid waste generation and management practice in Kolkata municipal corporation, West Bengal. Int J Environ Sci 6(6):1173–1186

Barnosky AD, Matzke N, Tomiya S et al (2011) Has the Earth's sixth mass extinction already arrived. Nature 471(7336):51–57

Bhattacharya A, Sen S, Roy PK, Majumdar A (2008) A critical study on the status of east Kolkata wetlands with special emphasis on water birds as bio-indicator. In: Sengupta M, Dalwami R (eds) Proceeding of Taal 2007, 12th World Lake Conference, Jaipur, India, 2007

Boyd J, Banzhaf S (2006) What are ecosystem services? The need for standardized environmental accounting units. Ecol Econ 63:616–626

Bunting S, Kundu N, Punch S, Little D (2001) East Kolkata wetlands and livelihoods. https://www.stir.ac.uk

Bunting S, Kundu N, Mukherjee M (2002) Situation analysis of production systems and natural resource in peri-urban Kolkata. https://www.stir.ac.uk. Accessed 7 Jan 2016

Bunting SW, Edward P, Kundu N (2011) Environmental management manual: East Kolkata wetlands. Manak Publishers, New Delhi

CEMPD (2013) Management action plan for East Kolkata Bheries. Final Report. https://www.cempd.com. Accessed 10 Dec 2015

Census of India (2011) Census of India, Census Directorate, New Delhi, India https://www.censusindia.gov.in. Accessed 12 Dec 2015

Chaudhuri SR, Thakur AR (2006) Microbial genetic resource mapping of East Kolkata wetlands. Curr Sci 91:212–217

Chowdhury S, Soren R (2011) Butterfly Lepidoptera: Rhopalocera fauna of east-Calcutta wetlands, West Bengal, India. Check List 7(6):70–73

Costanza R, Daly H (1992) Natural capital and sustainable development. Conserv Biol 6:37–46

Creative Research Group (1997) East Kolkata wetlands and waste recycling region-primary data, base line document for management action plan (As per Ramsar Convention Guidelines), Calcutta Metropolitan Water and Sanitation Authority, West Bengal. https://www.ieswm.org/. Accessed 11 Nov 2015

De M, Bhunia S, Sengupta T (1989) A preliminary account on major wetland fauna of Calcutta and surroundings. Ecology 3(9):5–11

EKWMA and WI (2010) East Kolkata Wetlands http://ekwma.in/ek/. Accessed 11 Nov 2015

Georgalaki MD, Van den Berghe E, Kritikos D et al (2002) Macedocin: a food grade antibiotic produced by *Streptococcus macedonicus* ACA-DC 198. Appl Environ Microbiol 68:5891–5903

Ghosh D (2005) Ecology and traditional wetland practice: lessons from wastewater utilization in the East Calcutta wetlands. Worldview, Kolkata. https://www.ieswm.org/. Accessed 10 Oct 2015

IWMED (2004). Preliminary study on biodiversity of sewage fed fisheries of East Kolkata Wetland Ecosystem https://www.ieswm.org/. Accessed 11 Nov 2015

Klaus-Joerger T, Joerger R, Olsson E et al (2001) Bacteria as workers in the living factory: metal-accumulating bacteria and their potential for material sciences. Trends Biotechnol 19:15–20

Kundu N (2003). The challenges of slum. Global Report on Human Settlements Case Study from India, pp 2013–2014

Kundu N, Pal M, Saha, A (2008) East Kolkata Wetland: a resource recovery system through productive activities. In: Sengupta M, Dalwami R (eds) Proceeding of Taal 2007, 12th World Lake Conference, Jaipur, India, 2007

Kundu N, Pal M, Saha A (2012) East Kolkata wetlands – demographic and livelihood profile. Manak Publishers, New Delhi

Mallick JK (2009) Endemic Marsh Mongoose *Herpestes palustris* (Carnivora: Herpestidae) of East Kolkata Wetlands, India: a status report. J Threat Taxa 1(4):215–220

MEA (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC

Mukherjee DM (1996) Pisciculture and the environment: an economic evaluation of sewage-fed fisheries in East Calcutta. Sci Technol Dev 14(2):73–99

SAC (2011) National wetland atlas, SAC/EPSA/ABHG/NWIA/ATLAS/34/2011, vol 310. Space Applications Centre (ISRO), Ahmedabad

Sayer J, Sunderland T, Ghazoul J, Pfund JL, Sheil D, Meijaard E, Venter M, Boedhihartono AK, Day M, Garcia C, Van Oosten C, Buck LE (2013) Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. Proc Natl Acad Sci 110:8349

Sengupta BK (1980) A salt marsh near Kolkata-a companion and friend, Fish farmers day celebration cum seminar. Available at https://www.ieswm.org/. Accessed 17 Oct 2015

Turner RK, Daily GC (2008) The Ecosystem services framework and natural capital conservation. Environ Resour Econ 39(1):25–35

WISA (2008) Management action plan for East Kolkata Wetlands

WWF (2011) Impact of urbanisation on biodiversity. Case Study from India

WWF (2013) Strategic flood risk management – experience from International Case Studies Consultation. https://www.ieswm.org/. Accessed 10 Oct 2015

People's Dependency on Wetlands: South Asia Perspective with Emphasis on Nepal

21

Pramod Lamsal, Kishor Atreya, Krishna Prasad Pant, and Lalit Kumar

Abstract

Wetland ecosystem is a lifeline for people both in a global and regional scale. Different resources are being provided by this ecosystem for the welfare of humankind since ancient times in the form of food, drinking and irrigation water, fuel wood, timber, medicinal herbs, and non-wood forest products. People's dependency on wetland ecosystems has been increasing in recent years, and South Asia is a good example. However, the booming population and increasing dependency have threatened the wetlands due to unsustainable resource harvesting. Wetlands in Nepal are spatially distributed from lowlands to highlands and are of great value to local people for sustaining their livelihood. However, the degree of their dependency differs with their location. Though the dependency on wetland resources is high in Nepal, people still do not recognize all the ecosystem services of wetlands.

Keywords

Conservation • Nepal • South Asia • Wetland dependency • Wetland resource

P. Lamsal (✉) • L. Kumar
School of Environmental and Rural Science, University of New England, Armidale, NSW 2351, Australia
e-mail: plamsal@myune.edu.au

K. Atreya
Asia Network for Sustainable Agriculture and Bioresources (ANSAB), Kathmandu, Nepal

K.P. Pant
School of Arts, Kathmandu University, Lalitpur, Nepal

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_21

21.1 Wetland and People: An Overview from South Asia

Wetland resources have been used by humans since ancient time, probably from their very origin. Wetlands produce a variety of goods and services essential for sustaining human life on this planet. Food, fiber, timber, medicine, and drinking water are some of the resources that wetland ecosystems provide us, without which our livelihood would not be possible. The dependency, however, constantly increases with a booming population and, as a result, threatens the fragile wetland ecosystems with ongoing unsustainable resource consumption. It is therefore imperative to conserve wetland resources and make sustainable use of these for the welfare of humans.

Based on the hydrological, ecological, and geological characteristics, Cowardin et al. (1979) classified wetlands into marine, estuarine, lacustrine, and palustrine. Similarly, the Ramsar Convention (Article 1.1, 1971) defines most of the natural water bodies such as rivers, lakes, coastal lagoons, mangroves, peat land, coral reefs, and manmade wetlands such as ponds, farm ponds, irrigated fields, sacred groves, salt pans, reservoirs, gravel pits, sewage farms, and canals as wetland ecosystems. These classifications and definitions themselves clearly depict the broader wetland boundary and thus signify its importance. The wetland resources are further significant in the context of developing countries in general and South Asia in particular. South Asia includes eight countries, *viz*., Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka. This region occupies 3.3% of the global land surface, while it is home for over 25% of global population. The majority of people in this region lives in rural areas and depends on natural resources to sustain their livelihood. The region is rich in different types of wetland ecosystems on which rural populations are highly dependent. Around 39,000 ha (1%) of land area is occupied by wetlands in Bhutan. With about 3027 lakes, high-altitude wetlands (HAWs) cover an estimated 0.3% of Bhutan's land area. India has about 757,000 wetlands, covering an area of 15.3 million ha that accounts for 4.7% of the total geographical area. It includes inland wetlands (69%), coastal wetlands (27%), and wetlands smaller than 2.25 ha (4%). Maldives is a group of tiny islands surrounded by the Indian Ocean, where five types of wetlands exist, *viz*., mangroves, marsh lands, inland water bodies, sea grass beds, and coral reefs. Pakistan has more than 225 significant wetlands, covering around 9.7% of land surface. Both natural and manmade wetlands occur throughout Sri Lanka and comprise about 15% of the land area. Around 21 wetlands of potential significance have been documented in Afghanistan; however, the people's dependence on wetland resources is not well documented. Despite the considerable number of wetlands in South Asia, their contribution to people's livelihood is less understood, though considerable amount of resources are harvested from them.

21.2 Major Wetland Resources

The goods and services provided by the wetlands are relevant differently to diverse groups of people in the society depending on the nature of use. Wetland benefits can either be direct harvest from wetlands, functions, or services coming from them and ecosystem-scale attributes (Claridge 1991). The direct harvests include food resources, water for drinking and irrigation, and other wetland resources such as fuel wood, timber, and non-wood forest products (NWFPs) such as fodder and medicinal herbs. The wetland functions include biodiversity conservation, water storage, groundwater replenishment, sediment retention, plant nutrient retention, flood buffering, and carbon sink. Wetlands also provide recreational and water purification services. The ecosystem-scale attributes include cultural uniqueness, wildlife habitat, and biological diversity at a larger scale. This chapter discusses the dependency of South Asian people in general and of Nepal people in particular on the wetland resources to sustain their livelihoods.

21.2.1 Aquatic Food Resources

Aquatic food resources include all the goods that local people consume for meeting the body nutrient needs, such as proteins and vitamins, and those that could be sold in the market for financial returns. Around 13 million people in Bangladesh are dependent on fisheries for sustaining their livelihood, and 80% of them are considered as belonging to the lower-income group (Sultana n.d.). Fishing in wetlands, ponds, and rivers is the only household income source in many rural areas. Inland fisheries in Bangladesh include 260 finfish and 25 shellfish species, major sources of animal protein. Mangrove and salt marsh wetlands are also important for shrimp farming that provides employment to thousands of low-income people from neighboring villages and towns. In the fishing industry in Bangladesh, one million people are full-time employees and 11 million are part-time workers, contributing to 3.3% of the gross domestic product (GDP), earning more than 11% of the total export revenue (Parveen and Islam 2001).

Similarly, in Sri Lanka, 91% of the total fish production was managed by marine fishery in the year 2003, of which 64% was from coastal waters contributing significantly to the local food security. It has been estimated that wetland-based fishery sector provides direct employment to 150,000 people while sustaining at least 1,000,000 people (Atapattu et al. 2010). In Maldives, fish, crabs, and mussels are the major food for people. Similarly, the occupation of 84% people of the Indus Delta in Pakistan is primarily fishing, with estimated catch of fish and shrimps being about 247,000 tonnes per annum.

In India, inland fisheries from wetlands contribute 61% of total production, accounting for more than 5,000,000 t of catch per annum. This sector provides direct and indirect employment to millions of low-income families and supports their livelihood. The Indian Sundarbans mangrove wetlands, in the delta of the Ganga and the Brahmaputra, are vital for people in the West Bengal state. Brackish water fishes, shrimps, crabs, honey, wax, and tannin are some of the resources that cater to both local people and the demands of the metropolitan city. Export of dried fish, shrimps, crabs, and honey brings in substantial foreign exchange, benefiting the local community directly.

Up to 80% of people in Afghanistan are dependent on natural resources for income and sustenance (BW-WG 2008). Hamoun wetland, an inland delta created by the Helmand River, located at the international border between Afghanistan and Iran is an important source of livelihood for the Afghan people living near the delta. It is the source of fishes, medicinal herbs, and other aquatic food resources. The annual fish catch in Hamoun wetland exceeds 5000 kg.

21.2.2 Drinking and Irrigation Water Supply

Water from wetlands has been used for drinking and irrigation since a long time. The case of South Asia is important as it has to feed nearly 25% of the world's population with its limited water resources, and thus freshwater wetlands in particular are significant in this region. In India, human-made wetlands that collect surface runoff during monsoon and then allow water to be used during non-monsoon seasons are important for irrigating large portion of farmland in the northern and southern states. They are also a reliable source of drinking water supply in rural areas. Around 4700 large reservoirs exist in India and they are being used for agricultural irrigation and domestic water supply in villages, towns, and cities across the country (Bassi et al. 2014). Similarly, large lakes, such as Carambolim, Chilika, Dal *Jheel*, Deepor *Beel*, Kabar Tal, Kolleru, Loktak, Nainital, Nal Sarovar, and Vembanad, are traditionally used for agricultural irrigation and domestic water supply (Jain et al. 2007).

Ancient village irrigation water storage tanks and reservoirs are common in Sri Lanka. Over 12,000 tanks and reservoirs exist in the country, covering 4.6% of land surface, and are the major source of water for irrigated agriculture. The Parakrama, Samudraya, and Minneriya tanks are a few examples. Many reservoirs in the country are the source of drinking water to villages, towns, and cities, in addition to being used for irrigation. Some of them include Castlereagh, Norton, Lakshapana, and Mousakelle. The river Mahaweli has been dammed to create a series of multipurpose reservoirs, including Kotmale, Victoria, Randenigala, and Rantambe. Inland freshwater wetlands such as Mahaweli riverine floodplain are also used for drinking and irrigation water supply (IUCN Sri Lanka 2004).

In Bhutan, water from HAW such as glacial lakes and ponds is used for agriculture, mostly to irrigate the downstream paddy field. Apart from irrigation, drinking water supply is also heavily dependent on them.

Hamoun wetland in Afghanistan is channeled for irrigation and covers thousands of hectares of drought-affected agricultural land. Through irrigated agriculture from this wetland, subsistence farmers cultivate a wide range of fruits and vegetables. Kole Hashmat Khan wetland, a shallow freshwater wetland in Kabul, has been used for supplying irrigation and domestic water for a long time. Riverine floodplain basins such as Amu Darya and Helmand are the major sources of water supply for irrigating most of the arable agricultural land in Afghanistan (Boere et al. 2006).

21.2.3 Fuel Wood, Timber, Medicinal Herbs, and NWFPs

The socioeconomic status of South Asian people, especially those living in the rural areas, is low. This has led to more dependency on wetland resources from which they receive livelihood supportive goods. In India, many tribal and indigenous communities live in different states and most of them depend on wetland resources for livelihood. Tribal communities like Boro, Rabha, and Garo in Northeastern India are traditionally wetland dependent for resources such as food, medicinal herb, as well as NWFPs for making handicraft, roofing material, basket, and mat. The mangrove wetlands in the West Bengal Sundarbans are the source of fuel wood for cooking, timber for domestic purposes, and fruits and medicinal herbs for poor income groups.

The Maldives lacks permanent rivers and streams, but brackish ponds/mangroves and freshwater lakes, also called *kulhis*, are available. Maldivian people harvest many freshwater and mangrove wetland goods such as wood for fuel; materials for house posts, fishing gear, and charcoal production; and tannins. They are also the source of food in the form of fish, crabs, and mussels to thousands of local people. Apart from this, diverse medicinal herbs for local healing are obtained from these wetlands, and local production of vinegar and cooking oil from such wetland resources is a well-known economic activity in Maldives.

Sundarbans is an important estuarine mangrove wetland, shared by both Bangladesh and India. Bangladesh occupies 62% of this mangrove ecosystem, which is considered a lifeline for the low-income people of the area. The major dependency is for fuel wood for cooking; timber for boat building; poles for building houses; *Nypa fruticans* leaves for roofing; grass species such as *Cyperus javanicus*, *Imperata cylindrica*, and *Eriochloa procera* for weaving mat; reeds for fencing; and medicinal herbs for local healing. Inland wetlands are used for activities such as extraction of reed and harvesting of edible aquatic vegetation and their products such as medicinal herb in rural areas. Other economic benefits local people derive include agricultural and wild food productions, livestock grazing, timber, fuel wood, fodder, and aquatic fruit harvesting.

Most of the low-income people in Pakistan depend on wetlands for various socioeconomic activities. For example, in Taunsa Barrage, 87% of local people depends on the wetland for fuel wood, livestock grazing, fishing, and collection and trading freshwater turtles. In Indus Delta, local people rely on the floodplain and mangrove wetlands for timber, fuel wood, and NWFPs and for grazing livestock, camels, and other domestic animals. Inland wetlands are equally important as source of staple food, livestock grazing and fodder, and fuel wood and for transport and irrigation and as a significant means of living for low-income people.

Most of the inland freshwater wetlands in Sri Lanka are used by local people for harvesting agricultural products such as rice and leafy vegetables, collection of medicinal herbs for primary healing, and raw materials for small-scale microenterprises (*viz*., making handicrafts and weaving mat). Mangroves and salt marshes are the source of fuel wood for cooking energy, light timber for temporary dwellings, fish traps, and fence posts, while tanbarks are used for tanning sails and nets.

Livestock grazing is a common practice in the Hamoun wetland area of Afghanistan, which is a major source of cash earnings for the dependent people.

21.3 Wetland Dependency: The Case of Nepal

21.3.1 Country Background

Nepal, covering an area of 147,181 km^2, is located in the southern lap of the Himalayas between the latitudes 26°22′ and 30°27′ N and longitudes 80°40′ and 88°12′ E. The elevation ranges from 58 m in the southern Terai lowland to 8848 m in the north at Mt. Everest, the highest peak in the world. This extreme altitudinal gradient has resulted in five broad physiographic regions, *viz*., Terai (<300 m), Siwalik (300–1000 m), Mid Hill (1000–3000 m), Middle Mountain (3000–5000 m), and High Mountain (>5000 m). Physiographic variation has also led to six distinct climatic regions such as tropical, subtropical, temperate, subalpine, alpine, and nival. A land cover mapping during 2010 indicated 39.1% forest land, 29.83% agricultural land, 10.65% barren land, 8.20% snow/glaciers, 7.90% grassland, 3% shrub land, 0.60% water body, and 0.32% built-up area (Uddin et al. 2015). About 83% of the total area consists of mountain and hilly regions, while the remaining consists of Terai low land. The total population of the country, based on 2011 census, stood at 26.5 million. Terai lowland accommodates almost 60% of the total population. Four major river systems, originating from the High Himalayan zone draining 70% of the country, are Koshi in the eastern region, Narayani in the central region, Karnali in the western region, and Mahakali in the far-western region. Apart from these, several medium-sized rivers originate in the Mid Hills (Rapti, Bagmati, Kamala, Kankai, Tinau, etc.), whereas small rivers, mostly seasonal in character, originate from the Siwalik (Churia) ranges and dissect the Terai lowland. Nepal is primarily an agricultural country, and its economy is mostly dependent on the use of available natural resources. Agriculture depends heavily on rainfall, groundwater recharge, and wetlands. The geography is dotted with farmlands, snow lands, and small freshwater wetlands such as rivers, lakes, ponds, marshes, swampy lands, irrigation canals, fishponds, and reservoirs.

21.3.2 Status of Wetlands

Nepal has four decades of history of wetland conservation. The first wetland enlisted as a Ramsar site was Koshi Tappu wetland, an important habitat for the last surviving species of wild water buffalo (*Bubalus arnee* Kerr, 1792). The wetlands in the country attracted attention only after the Department of National Parks and Wildlife

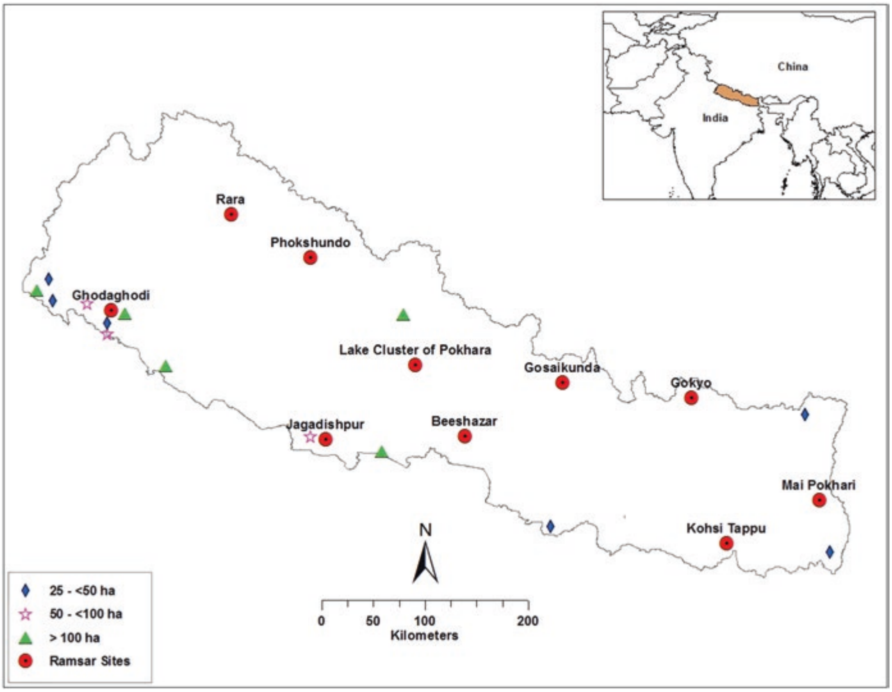


Fig. 21.1 Spatial distribution of Ramsar and other important wetlands in Nepal

Conservation succeeded in listing Koshi Tappu as a Wetland of International Importance in 1988. So far, ten wetlands, covering an area of 60,561 ha, are listed in the Ramsar Site of International Importance (Fig. 21.1).

Out of the ten Ramsar wetlands, four are located in the Terai lowland, two in Mid Hill, while four are in high-altitude region. Terai lowland region being highly populous, the wetlands here support the livelihood of large populations through their provisional goods. One Ramsar wetland in Mid Hill bears great religious-cultural values, while the other provides economic, recreational, and religious-cultural values. The HAWs are important for maintaining ecological functions and services that sustain livelihood of both upstream and downstream populations.

In addition to ten Ramsar sites, there are several other wetlands (about 5000 lakes, 1380 reservoirs, and 5183 village ponds) in Nepal. Around 3252 glaciers and 2323 glacial lakes are identified in the high-altitude regions of the country. Other wetland categories include irrigated paddy fields, rivers, and swamps (Table 21.1), which bear significance in terms of livelihood support to the local people. The wetlands of Nepal, including Ramsar sites, occupy 5.6% of the total land surface, of which rivers and irrigated paddy fields hold the major proportion (i.e., 97%).

Table 21.1 Wetland types and their estimated areas in Nepal

SN	Wetland types	Estimated area (ha)	%
1	Irrigated paddy fields	398,000	48.58
2	Rivers	395,000	48.21
3	Marginal swamps	12,500	1.53
4	Ponds	7277	0.89
5	Lakes	5000	0.61
6	Reservoirs	1500	0.18
	Total	819,277	100.00

Source: Directorate of Fisheries Development, Kathmandu, Nepal (DoFD 2012)

21.3.3 Wetland Dependence of Local People

Like other South Asian neighboring countries, wetland ecosystems in Nepal support many local people, mainly low-income rural groups, for sustaining their livelihood. As mentioned earlier, the wetlands of Nepal are geographically categorized as high-altitude, Mid Hill, and Terai lowland wetlands and people's dependency on those wetlands differs accordingly.

21.3.3.1 High-Altitude Wetlands (HAWs)

Rara, Phokshundo, Gosainkunda, and Gokyo are the Ramsar listed wetlands of high-altitude regions. All of them support tourism and are important sources of income generation for the local people. These HAWs are the source of drinking and irrigation water supply to the downstream communities. The major river basins in Nepal and even for India and Bangladesh originate from these HAWs and Himalayan glaciers on which water-based livelihood of millions of people depends. Livestock grazing is a common practice in all HAWs catchment and people in these areas rear cows and sheep for milk and meat as a means of livelihood. Apart from the Ramsar sites, numerous other wetlands bear equal significance for sustaining livelihood at local level. Some such wetlands are Panch Pokhari, Khaptad Daha, Kyangjing, Parbati Kunda, Singjema, Thulo Pokhari, Timbung, and Warmi. High-altitude wetlands bear religious-cultural significance to Hindu and Buddhist communities as thousands of devotees visit the HAW in different seasons of the year. They are considered sacred in Hindu mythology, and in *Janai Purnima*, a religious festival, thousands of people visit these wetlands to perform rituals. The catchment of HAW is a source of various medicinal herbs, and among them, yarsagumba (*Ophiocordyceps sinensis)* is economically important. During summer season, thousands of low-income people of western Nepal flock to the High Himalayan region for harvesting this herb, which is in high demand and fetches good price in national and international markets. Shrestha and Bawa (2014) reported that yarsagumba is the second largest economic contributor to the people of Western Nepal after farm income, accounting for more than 21% of the household income and 53% of the total cash income.

21.3.3.2 Mid Hill Wetlands (MHWs)

Mai Pokhari was the lone wetland of eastern Mid Hills listed as a Ramsar site. Lake Cluster of Pokhara Valley of western Mid Hills is the latest addition to this list in early 2016. In Mai Pokhari, local people depend for irrigation and drinking water on this wetland and its catchment. People from the adjoining villages collect fuel wood, fodder, timber, leaf litter, wild mushroom, and diverse medicinal herbs from the lake complex. Tourism is a major industry of the lake complex; both national and international tourists visit the area round the year. Tourism has promoted employment opportunities to the people of this area.

Lake Cluster of Pokhara Valley consists of series of nine different lakes, located within a close proximity of Pokhara city in Kaski district of western Mid Hill Nepal, with Phewa being the largest one. Begnas Lake is a source of fuel wood and fodder collection, timber harvesting, livestock grazing, bathing, and commercial cage fish culture. The water from the lake has been diverted and used for irrigating downstream agriculture land parcels. Tourism in the area employs many local people, making them economically stable. In Rupa Lake, around 15,000 local ethnic low-income people residing in the catchment area are fully dependent on fisheries and other provisional resources to sustain their households. The ethnic Pode, Bote, and Majhi are traditional fishing communities living in the Mid Hill of Western Nepal, whose livelihood is based entirely on the wetland fisheries. Gurung et al. (2012) reported that each household of Pode community generates around US$ 635 per annum from capture and cage culture fisheries at the Phewa Lake. Fishery activities have been a significant income-generating and employment opportunity for these ethnic communities for a long time. Cage fish culture and capture fisheries are popular economic activities in most of the MHWs. For example, in Phewa Lake, Rupa Lake, Begnas Lake, and Kulekhani reservoir catchment area, it is thought that fishery shares over 75% of the total gross annual income of low-income group fisher households (Wagle et al. 2012). Similarly, wetland-related tourism plays an important role for both rural and urban people of MHWs. For instance, economic activities of people in the vicinity of Phewa, Rara, and Rupa Lakes mostly revolve around the flux of national and international tourists the year round.

21.3.3.3 Lowland Wetlands (LWs)

Ghodaghodi, Jagdishpur, Beeshazar, and Koshi Tappu are the four Ramsar sites located in the Terai lowland. Multiple resource extraction is a common practice in most of the lowland wetlands. For instance, local people in Ghodaghodi Lake Complex have collected fuel wood, timber, fodder, and fruits for generations. Many plant species of the complex bear medicinal properties and are good sources for curing diseases locally. Fisheries, snails (*Helix* sp.), sal (*Shorea robusta*) leaf, and lotus (*Nelumbo nucifera*) leaf collection are other important sources of economic activities in the complex. Wetland resources at Ghodaghodi Lake Complex contribute 12.4% of the total gross annual income of the local wetland-dependent people (Lamsal et al. 2015). The wetland water is also used for irrigating agricultural fields in the southern side of the lake during summer and winter seasons.

Table 21.2 Tangible uses of wetlands in the Terai lowland of Nepal

Uses	No. of wetlands under the specific use	% of resource users
Fishing	153	94
Grazing	113	70
Irrigation	112	69
Plant harvest[a]	96	59
Domestic use[b]	52	32
Fuel wood	32	20
Wildlife use	20	13
Religious use	18	11
Other uses[c]	23	14

Source: IUCN Nepal (1996)
[a]Thatch grass, timber, aquatic crops, fodder
[b]Washing clothes and kitchenware, bathing
[c]Travel routes, waste disposal

The livelihood of more than 100,000 people of the buffer/catchment zone of Koshi Tappu Riverine wetland depends on its resources. Livestock rearing, rice paddy cultivation, fishery, firewood and driftwood collection, mat weaving, and selling edible wild vegetable plants are routine activities of these people, thus making wetland resources a reliable source of income. An ethnic fishing community, *Malaha*, fully depends on fishery at Koshi Tappu. Apart from fishery, they also utilize wetland plant *Typha elephantina* for weaving mats and other nonusable wetland plant species for bio-briquette and compost that fetch good money in the local markets. Of the 103 ethnic groups, 20 are wetland dependent, most of which live in the Terai lowland (IUCN Nepal 2004). Some such ethnic groups are Sunuha, Mallah, Kewat, Bote, Musahar, Gongi, Darai, Kumal, Dasuhad, Sahani, Bantar, Danuwars, Barthamus, Majhis, Tharus, and Kushar. Jagdishpur reservoir, another Ramsar site, was originally created for irrigation and is said to irrigate more than 6000 ha of agricultural land during lean periods. Apart from irrigation, local people depend on this reservoir for fishing, livestock grazing, fuel wood, and fodder. More than 40 species of fish exist in this reservoir and are the main source of income for poor. Bishazari Lake, located in Central Nepal, has been used as a source of irrigation water. Apart from irrigation, local people extract resources such as fuel wood, fodder, timber, medicinal herb, and fish from the wetland. Livestock grazing at the dyke and buffalo wallowing in lake water are the other common activities in the area. Local ethnic *Tharu* community collects NWFPs for making mat, rope, and carpet as an alternative source of income and snails as food supplement.

IUCN Nepal (1996) portrayed the most common nine uses of the wetlands in the Terai lowland (Table 21.2) that shows fishing as the most important economic activity of the local people.

Apart from Ramsar sites, there are numerous other wetlands in Terai lowland that bear equal significance for sustaining livelihood, such as Bedkot Tal, Paderni Tal, Deukhuria Tal, Rampur Tal, Badhaiya Tal, and Gaindahawa Tal. People use all the wetlands in Terai lowland for carrying out Hindu religious-cultural activities.

Table 21.3 Major uses of wetland in Nepal

Wetland types	Wetland uses					
	Aquatic food	Drinking and irrigation	Fuel wood, timber, medicinal, NWFPs	Tourism	Livestock grazing	Religious and cultural
HAWs	+	+	++	+++	+	+++
MHWs	++	++	+++	++	++	+++
LWs	+++	+++	+++	+	+++	+++

+++ high, ++ medium, + low

Popular Chhat and Maghi festivals in Terai lowland are celebrated along rivers, ponds, and lakes.

Thus, it is clear that in Nepal, local people depend on wetlands to sustain their livelihood like other South Asian countries. However, the degree of dependency on wetlands varies with geographic location (Table 21.3).

Overall, it can be said that people nearby HAWs mainly use wetlands for tourism-related activities, performing religious-cultural practices, and collecting medicinal herbs and NWFPs. People nearby MHWs mainly collect fuel wood, timber, and NWFPs, worship wetlands as a religious practice, and, in some areas, harvest fishes either by capture or by cage fishery. On the other hand, people nearby LWs are more dependent on wetland resources compared to the people nearby HAWs and MHWs. They use them for collecting aquatic food such as fishes and crabs, drinking and irrigation water supply, fuel wood and NWFPs, livestock grazing, and religious practices. Wetland uses are classified into four types: provisioning, regulating, cultural, and supporting (MEA 2005). Provisioning service, due to its tangible nature, is only considered as wetland use by common people in Nepal. Though regulating, cultural, and supporting services are equally important for human society, it is generally not considered explicitly due to its intangible nature.

21.4 Conclusion

A large number of people in South Asian region, particularly low-income groups, are dependent on wetland resources to sustain their livelihood. Though the way of using wetlands is diverse based on locality and culture, major uses are harvesting wetland resources and using the wetlands in situ. Wetland ecosystem has been a major provider of food resources, drinking and irrigation water, as well as fuel wood, timber, medicinal herbs, and NWFPs to this region for a long time. Wetlands are also used for recreation and tourism. Therefore, conservation, sustainable management, and wise use of the wetland ecosystems are critical for realizing long-term benefits to the local people. Though the local communities depend heavily on wetland resources in South Asia, they still do not recognize the full ecosystem services of wetlands. Highlighting the importance of the wetland's goods and services to their livelihood can help motivate them to support conservation of wetlands. Recognizing the importance of wetland resources to their livelihood can help in effective policy making for the conservation of the wetlands and sustainable use of wetland resources.

References

Atapattu SS, De Silva S, Senaratna SS (2010) Wetland and agriculture: a case for integrated water resource management in Sri Lanka. International Water Management Institute. Available via http://publications.iwmi.org/pdf/H042855.pdf. Accessed 20 Dec 2015

Bassi N, Kumar MD, Sharma A et al (2014) Status of wetlands in India: a review of extent, ecosystem benefits, threats and management strategies. J Hydrol Reg Stud 2:1–19

Boere GC, Galbraith CA, Stroud DA (eds) (2006) Waterbirds around the world. The Stationery Office, Edinburgh, p 960

BW-WG (2008) Biodiversity and wetlands working group. Final Technical Report of NCSA and NAPA projects, p 52

Claridge GF (1991) An overview of wetland values: a necessary preliminary to wise use. PHPA/AWB Sumatra Wetland Project Reports No 7, AWB Bogor

Cowardin LM, Carter V, Golet FC et al (1979) Classification of wetlands and deepwater habitats of the United States. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC

DoFD (2012) Country profile – Nepal 2011/2012, fisheries sub-sector. Directorate of Fisheries Development (DoFD), Kathmandu

Gurung R, Glaser M, Hofmann AM et al (2012) Resource use and dependency on wetlands: a study of the Jalari fishing community of Phewa Lake, Nepal. In: Shrestha MK, Pant J (eds) Small-scale aquaculture for rural livelihoods: proceedings of the national symposium on small-scale aquaculture for increasing resilience of rural livelihoods in Nepal. Institute of Agriculture and Animal Science, Tribhuvan University, Nepal, and the World Fish Center, Penang, p 191

IUCN Nepal (1996) An inventory of Nepal's wetlands. IUCN-Nepal, Kathmandu

IUCN Nepal (2004) A review of the status and threats to wetlands in Nepal: IUCN wetland and water resources programme. IUCN, the World Conservation Union

IUCN Sri Lanka (2004) Wetland conservation in Sri Lanka. Proceedings of the National Symposium on Wetland Conservation and Management. Sri Lanka, p 75

Jain SK, Agarwal PK, Singh VP (2007) Hydrology and water resources of India. Springer, Dordrecht

Lamsal P, Pant KP, Kumar L et al (2015) Sustainable livelihoods through conservation of wetland resources: a case of economic benefits from Ghodaghodi Lake, western Nepal. Ecol Soc 20(1):10. http://dx.doi.org/10.5751/ES-07172-200110

MEA (2005) Ecosystems and human well-being: synthesis, Millennium Ecosystem Assessment. Island Press, Washington, DC

Parveen S, Islam MF (2001) Fisheries in Bangladesh: a critical review, Environment and Development Series No. 08/2002. North South University, Dhaka

Shrestha UB, Bawa KS (2014) Economic contribution of Chinese caterpillar fungus to the livelihoods of mountain communities in Nepal. Biol Conserv 177:194–202

Sultana P (n.d.) Improving livelihoods of wetland users: MACH lessons. Policy Brief 4: 4. Available via http://www.nishorgo.org/tbltd/upload/pdf/0.76065300%201357812118_Improving%20Livelihoods%20of%20Wetland%20Users.pdf. Accessed 06 Aug 2015

Uddin K, Shrestha HL, Murthy MSR et al (2015) Development of 2010 national land cover database for Nepal. J Environ Manag 148:82–90

Wagle SK, Shrestha HK, Bista JD et al (2012). Cage fish culture and capture fishery as dominant livelihood sources for fisher community in Pokhara Valley, Nepal: A socio-economic update. In: Shrestha MK, Pant J (eds) Small-scale aquaculture for rural livelihoods: proceedings of the national symposium on small-scale aquaculture for increasing resilience of rural livelihoods in Nepal. Institute of Agriculture and Animal Science, Tribhuvan University, Nepal and the World Fish Center, Penang, p 191

Part VI

Mapping and Modeling Wetlands

Mapping of Wetlands using Satellite Remote Sensing Data: Indian Experience

22

Sushma Panigrahy

Abstract

India harbors diverse types of wetlands spread over inland, coastal, marine, and high mountains. The diversity and distribution pattern over the large geographic region of India makes wetlands inventory a challenging and time-consuming activity. Satellite remote sensing, particularly the multispectral optical sensors, has been found useful for this purpose. IRS LISS III sensors with 23.5 m spatial resolution that provide multispectral images in green, red, NIR, and SWIR region were used to develop a methodology for wetland mapping. Various combinations of spectral indices, *viz*., NDWI, MNDWI, NDVI, and NDPI, were found suitable for wetland mapping. Besides wetland boundary, it was feasible to map three wetland structural components, *viz*., extent of water, aquatic vegetation, and water turbidity. Among the aquatic vegetation types, emergent and to some extent floating types could be mapped. Water quality was expressed in terms of three qualitative ratings. It was found essential to use two date data pertaining to wet and dry seasons to improve accuracy of classification and derive hydrological behavior of wetlands. The procedure was used to map wetlands of entire India at 1:50,000 scale using LISS III images of 2006–2007. LISS III image enabled mapping of wetlands of >2.25 ha. Smaller than this size were mapped as points. This chapter highlights the procedure used and the advantages and limitations of remote sensing technology for wetland mapping.

Keywords

Mapping of wetlands • Multispectral optical sensors • Remote sensing technology • Satellite image classification • Wetlands

S. Panigrahy (✉)
Space Applications Centre, Ahmedabad, India
e-mail: sushmasac@yahoo.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_22

22.1 Introduction

Wetlands are one of the most productive ecosystems in the world (Ghermandi et al. 2010). The wetland ecosystem encompasses a variety of classes, primarily caused by regional and local differences in soils, topography, and climate that influences the hydrology. These variations lead to variations in factors like water chemistry, flora, fauna, etc. Hydrology being the controlling factor of any wetland, they may be permanent or seasonal in nature. As per genesis, wetlands are normally associated with five major systems: (a) marine (coastal wetlands including rock shores and coral reefs), (b) estuarine (including deltas, tidal marshes, and mangrove swamps), (c) lacustrine (wetlands associated with lakes), (d) riverine (wetlands along rivers and streams), and (e) palustrine (marshes, swamps, and bogs). Depending on the type of wetland, it may be filled mostly with water, water-saturated soil, grasses, shrubs, moss, trees, or an amalgam of many of these. Utility-wise, wetlands directly and indirectly support millions of people by providing services such as food, fiber and raw materials, storm and flood control, clean water supply, scenic beauty, and educational and recreational benefits. The Millennium Ecosystem Assessment (MEA) estimates conservatively that wetlands cover 7% of the Earth's surface and deliver 45% of the world's natural productivity and ecosystem services of which the benefits are estimated at US$ 20 trillion a year (www.millenniumassessment.org). These resources, particularly the natural ones, have been subjected to unplanned anthropogenic exploitation that has led to degeneration and disappearance of many wetland types. Since the 1980s, consolidated international efforts are made to develop strategies for conservation and preservation of this resource. Inventory of wetlands is the first requirement for planning and management. Inventory essentially is maps that relate a feature to any given geographical location and have a strong visual impact. The basic purpose of wetland mapping is to provide a list of all the wetlands of an area, the type-wise distribution, the status of wetland structural components, and the occurrence and distribution of important taxa such as vegetation, birds, and fish. Standards of mapping need to be worked out well in advance, so that it supports updating required for improvement of map content as well as monitoring for change detection over time. Wetland mapping standard across the world was spearheaded by a number of international organizations, notably the WWF (World Wide Fund for Nature), IUCN (International Union for Conservation of Nature), and Wetland International. Wetland inventory is carried out at different scales, each one having a definite purpose. In general, five terminologies are used to denote the purpose of scale:

- Global – to show distribution of dominant wetlands in specific continents and islands
- Continental – to show distribution of regions within continents or islands dominated by wetlands
- Regional – predominance of specific wetland types
- Local – all wetlands (types and sizes)
- Site specific – variability within wetlands

In general, the map information differs as per the scale. The site-specific and local scales contain detailed information of wetland features. As the scale becomes coarser from regional to global, the information content gets limited. Three scales within a hierarchical approach were used for wetland inventory in Australia (Finlayson et al. 1999). The scales recommended for this purpose were (1) wetland at continent level with maps at a scale of 1:5,000,000, (2) wetland aggregations within each region with maps at a scale of 1:250,000, and (3) wetland sites within each aggregation with maps at a scale of 1:50,000 or 1:25,000. A Global Review of Wetland Resources and Priorities for Wetland Inventory (GRoWI) was undertaken in 1998 by the Wetland International and the Environmental Research Institute on behalf of the Bureau of the Ramsar Convention on Wetlands (Finlayson et al. 1999). The study provided an overview of international, regional, and national status on wetland inventories. The final purpose of the review was to identify ways for creating and updating wetland inventories in all countries. In most countries, wetland inventory has been based on ground surveys that are mostly at local level. During the 1990s, ground survey was supported by false-color infrared aerial photographs, mainly in developed countries like the USA. Such methods resulted in the collection of detailed information on the location, size, and biophysical features of wetlands (Wilen and Bates 1995). However, its usefulness has been limited by the availability and cost of the photography, particularly when large areas are involved. After the launch of the first land survey remote sensing satellite Landsat-1 by the USA in 1972, remote sensing images were widely explored to prepare wetland inventories. The US Fish and Wildlife Services has been using satellite remote sensing data for wetland mapping since the 1980s. Over the years, many more countries started using remote sensing data for natural resource survey and monitoring. Satellite remote sensing technology is now recommended as a cost-effective way to produce timely maps of wetlands with good accuracy. This chapter highlights the utility of satellite remote sensing technology for wetland mapping.

22.1.1 Satellite Remote Sensing Technology

From a general perspective, remote sensing is the science of acquiring and analyzing information about objects or phenomena from a distance (Lillesand and Keifer 1987). Remote sensing sensors having the capability to utilize the full electromagnetic spectrum increase the ability to gather additional information about the physical properties of a target compared to the traditional visual survey. This has led to the use of various devices to sense and record the reflected or emitted energy at a particular spectrum. These devices are known as sensors that are flown in satellites. Today, satellite remote sensing is defined as the use of sensors flown in satellites to observe, measure, and record the electromagnetic radiation (EMR) reflected or emitted by the Earth and its environment for subsequent analysis and extraction of information. The EMR to be sensed includes ultraviolet, visible light, near infrared (NIR), middle infrared (MIR), short-wave infrared (SWIR), and far infrared

Table 22.1 The spectral regions commonly used in satellite remote sensing sensors

EMR region	Wavelength	Property
Visible	0.4–0.7 μm	Reflectance
Reflective infrared	0.7–3.0 μm	Reflectance
Thermal infrared	3.0–15 μm	Radiative temperature
Microwave	0.1–30 cm	Brightness temperature (passive), backscattering (active)

(thermal), microwave, and long-wave radio energy. A brief description of the concept of satellite remote sensing is given here.

22.1.2 Remote Sensing Imaging Elements

The first requirement for remote sensing is to have an energy source, which illuminates or provides electromagnetic energy to the target of interest. Most of the sensors use the Sun as the source of energy for imaging and are known as passive sensors. These sensors are popularly known by the EMR region they sense like optical, thermal, microwave, and so on. As the energy travels from its source to the target, it comes in contact and interacts with the atmosphere it passes through. This interaction may take place a second time as the energy travels from the target to the sensor. Once the energy makes its way to the target through the atmosphere, it interacts with the target depending on the properties of both the target and the radiation. After the energy has been scattered by or emitted from the target, the EMR is collected and recorded in a sensor (mounted on a satellite, orbiting in space). This recorded signal from the sensor is transmitted, often in electronic form, to a receiving and processing station on Earth where the data are processed and stored in digital form. This data is processed and used by subject experts to derive required information.

22.1.3 Advantage of Remote Sensing for Wetland Mapping

Remote sensing technology provides many advantages over the traditional methods in wetland study due to (a) capability to achieve a synoptic view with wide area coverage, (b) potential to map at different scales, (c) capability to carry out survey during desired period, and (d) low cost. Specific advantage of remote sensing data is the spectral, spatial, and temporal spatial resolution.

Spectral resolution refers to the width or range of each spectral band being recorded. We know that each target affects different wavelengths of incident energy differently: they are absorbed, reflected, or transmitted in different proportions. Information collected from each spectral band from a sensor contains unique data, which otherwise is not amenable from the human eye. Table 22.1 highlights the spectral region and its property. The sensors are known by the nature of their

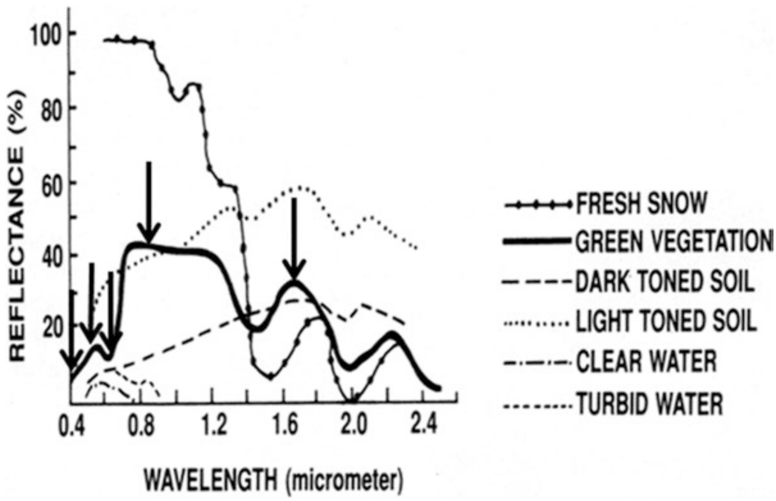


Fig. 22.1 Typical spectral reflectance of water and other targets in visible and reflective near-infrared (NIR) region. The *arrows* indicate the band positions commonly used in multispectral optical remote sensing sensors

spectral capability like optical, thermal, microwave, etc. We focus here on the optical remote sensing that is being used for mapping of natural resources including wetlands.

Optical remote sensing satellites carry sensors that make use of visible, NIR, and SWIR region to form images of the Earth's surface. These sensors are classified depending on the number of spectral bands used for imaging like multispectral, hyperspectral, etc. The most commonly used sensor for mapping of resources is the multispectral imaging. As the name suggests, these sensors provide images from multiple broad spectral bands (5–15 μm width). Such multispectral sensors generate multilayer spectral images that contain both the brightness and spectral (color) information. Each band gives a definite spectral signature of targets due to their difference in radiation, absorption, and reflectance properties. Examples of some of the advanced multispectral systems are the US Landsat Thematic Mapper (TM), the French Systeme Probatoire d' Observation de la Terra (SPOT), the High-Resolution Visible Sensor (HRVS), and the Linear Imaging Self Scanning (LISS) sensors (III, IV) of the Indian Remote Sensing (IRS) satellite. These sensors provide data in four or more spectral bands, which have been found optimum for various features like vegetation, water, soil, snow, etc. The most common spectral bands used fall in the blue, green, red, NIR, and SWIR region. The typical spectral signatures of water in relation to vegetation, soil, and position of spectral bands commonly used in multispectral sensors are shown in Fig. 22.1. The standard practice of visualization of spectral response of targets in remote sensing image makes use of the red, green, and NIR bands to assign them basic colors (blue, green, and red) for visualization. Such an image is known as false-color composite (FCC), in which vegetation appears in different shades of red.

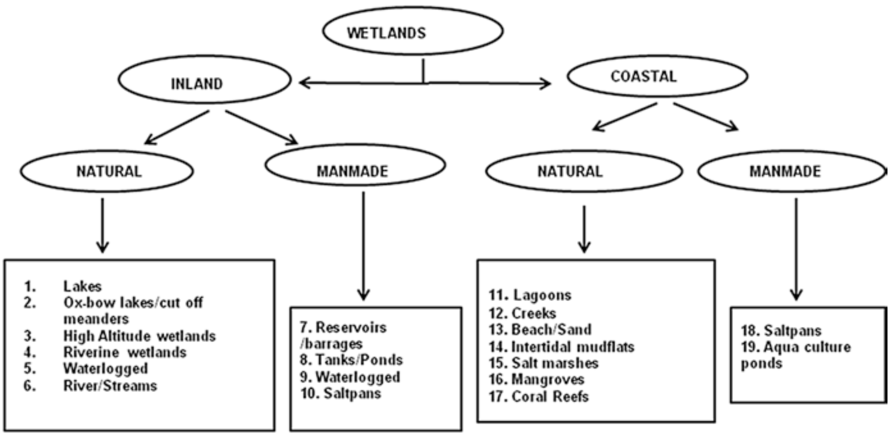


Fig. 22.2 Hierarchical grouping of the 19 wetland types found in India

Another advantage of multispectral sensors is the capability of providing data in different spatial resolution from the same satellite platform. Spatial resolution refers to the discernible detail in the image and is directly related to scale of mapping; finer resolution gives details for local area studies, while coarser ones are preferred for regional/global studies. For example, the three sensors on board the IRS Resourcesat-1/IRS Resourcesat-2 satellite provide images of spatial resolution of 5.8 m (LISS IV), 23.5 m (LISS III), and 50.0 m (Advance Wide Field Sensors, AWiFS). LISS IV image is found suitable for 1:25,000 scale mapping, while LISS III image is suitable for 1:50,000 scale and AWiFS for 1:250,000 scale. As the resolution becomes finer, the area coverage becomes smaller that increases the data load (Fig. 22.2). Variable spatial resolution data from the same satellite platform is of particular advantage for mapping wetlands at national to local scale at the same time frame.

Temporal resolution is the capability of acquiring images of any given area repeatedly over a time span. This is the revisit capability of a remote sensing satellite over a given area. Most of the optical remote sensing satellites used for mapping have a temporal resolution ranging from 15 to 25 days. Sometimes multiple satellites are placed in orbit in such a way that it increases the frequency of repeat cycle. This capability is of particular advantage for wetland mapping due to the dynamics of wetland features. One has to select proper date of acquisition for true representation of hydrology. The temporal resolution also helps in monitoring the seasonal, annual, and long-term changes.

The wide swath of remote sensing image is of particular advantage to model wetland ecology. Catchment hydrology is the most important factor that affects wetlands. The wide swath images facilitate catchment level studies, which is of immense use for wetlands nestled in difficult terrain setups like high mountains and coastal swamps (Murthy et al. 2013).

22.2 Mapping of Wetlands

Mapping of wetlands using satellite images use various pattern recognition techniques to identify and discriminate various features. The fundamental of the remote sensing data interpretation is that every surface object has its own unique pattern of reflected, emitted, and absorbed radiation across the spectra bands. Thus, techniques that enhance this difference of the target of study from its surrounding are developed. Various statistical classifiers use different measures to discriminate the difference (Lillesand and Keifer 1987). Most commonly used classifiers are supervised and unsupervised ones. There are other advanced classifiers such as fuzzy, neural network, and decision tree. However, it is now well established that a lot of efforts are required to develop classification methodology that suits the final objective of any thematic mapping (Sohn and Rebello 2002). Detection of water bodies is achieved with high accuracy using optical remote sensing data due to the very distinct spectral signature of water in NIR band. Detection of water bodies is one of the earliest applications of remote sensing data (Jensen et al. 1986). However, spectral signatures of wetlands are complex as most of the wetlands are a mosaic of varied components such as open water, dry soil, wet soil, sand, macrophytes, and trees. Even in the case of water, the spectral signature varies significantly due to depth, suspended sediments, coloration, etc. In addition, certain land classes like burnt land, urban clusters, and shadow areas are often misclassified as open water. Thus, the classification algorithm for wetland mapping needs fine-tuning depending upon the wetland characteristic of the study area. Some of these problems are overcome by selecting an optimum data acquisition period and spectral bands. The classification/interpretation methods for wetland mapping have evolved and improved over the years to keep pace with the advanced sensors. Lulla (1983) reviewed the use of Landsat MSS satellite imagery for surveying wetlands, coastal ecosystems, and aquatic environments. A review of classification and inventory of wetlands at global level using satellite images is given by Scott and Jones (1995). Use of remote sensing data from various platforms, including aerial photography and satellite images for wetland mapping, is reviewed by Hardisky et al. (1986), Lee and Lunetta (1996), Prigent et al. (2001), Griffith (2002), Stacy and Marvin (2002), and Elhadi et al. (2010). The advantages and limitations of various methodologies for wetland classification are given by Finlayson et al. (2001).

To summarize, the wetland extraction techniques using optical imagery that are used operationally can be categorized into the following four basic types: (a) statistical pattern recognition techniques including supervised and unsupervised classification methods, (b) linear unmixing, (c) single-band thresholding, and (d) spectral indices. Among these, the most commonly used one is the spectral index (Ji et al. 2015). The spectral index is a single number derived from an arithmetic operation (e.g., ratio, difference, and normalized difference) of two or more spectral bands. The arithmetic operation not only enhances the spectral signals by contrasting the reflectance between different wavelengths but also cancels out a large portion of the noise components that are common in different wavelength regions (Lei et al. 2009). Such a concept was first applied to study vegetations. As the typical reflectance pattern for a healthy vegetation shows high absorption due to chlorophyll, at 650 nm (red region) and high reflection due to leaf internal structure, at 750 nm (NIR region), this differential response has been used to develop different vegetation indices. Normalized Difference Vegetation Index (NDVI) is the most commonly used index for such purpose (Townshend and Justice 1986). A similar concept has been used to develop spectral water indices because water absorbs energy at NIR and SWIR wavelengths. An appropriate threshold of the index is then established to separate water bodies from other land cover features. McFeeters (1996) developed the NDWI using the reflectance of the green and near-infrared band. Xu (2006) revised and developed the modified NDWI (MNDWI) in which the SWIR band was used to replace the NIR. This index was developed to overcome the inseparability of built up areas with water bodies. Xu (2006) also recommended a manual adjustment of the threshold based on site characteristics to achieve a more accurate delineation of water. Lacaux et al. (2007) developed a Normalized Difference Pond Index (NDPI) using green and SWIR bands that performed well to detect ponds in Africa.

22.3 Wetlands in India

The geographic spread of India, lying between 8° 4′ and 37° 6′ north latitude and 68° 7′ and 97° 25′ east longitude, is 3.28 million km^2. The country is surrounded by ocean in three sides, the Bay of Bengal on the east, the Arabian Sea on the west, and the Indian Ocean to the south. The mighty Himalayan range adorns the northern side. The country receives rains with the onset of the southwest monsoon in June that continues until the middle of September. Broadly, there are five physical units: the Great Mountains of the North, the North Indian Plain, the Peninsular Plateau, the Coastal Plains, and the Islands. The diverse physical setup harbors a wide variety of freshwater, saline, and marine wetlands (MoEF 2012). Around 19 distinct wetland types have been identified and mapped in India (Panigrahy et al. 2012). These wetlands in turn support a wide range of biodiversity (Prasad et al. 2002). India has a number of mighty river systems like the Ganges Brahmaputra, Indus, and Godavari. These systems give rise to a number of natural wetlands like lakes, oxbow lakes, meanders, and man-made wetlands like reservoirs, barrages, check dams, tanks, waterlogged areas, etc. The long coastline of more than 7500 km supports many coastal and marine wetlands. Two unique wetland types found in the coastal area are the mangrove swamps and coral reefs. Mangrove swamp is an association of halophytic trees, shrubs, and other plants growing in brackish to saline tidal waters in the Indian coast and islands. India shelters the Sundarbans, the largest mangroves region in the world and habitat of the Royal Bengal Tiger. Coral reefs are shallow water, tropical marine ecosystems characterized by remarkably high biomass production and rich biodiversity. All the three major reef types (atoll, fringing, and barrier) occur in India. The High Altitude Wetlands (HAWs) are another unique type of wetland nestled in higher reaches of the Himalayas. HAW is a generic term to include wetlands like lakes, swamp, and marshy meadows found at an altitude higher than 3000 m, above mean sea level (amsl). These HAWs play a key role in the hydrology and ecology of Himalayan Rivers like the Ganges, Brahmaputra, Indus, and Teesta. They also support unique biodiversity, wildlife habitat, and socio-economics of local inhabitants. Some of these unique wetlands are reported to be more vulnerable to climate change (Patel et al. 2009).

Estimation of wetland area of India is a challenging task due to the large geographic spread of the country, diversity of wetlands, and occurrence of some of the unique wetlands in not-so-accessible environment. There is wide variation in estimates of wetland area of India mainly due to different methods used and wetland criteria followed. An early estimate reported around 58.2 m ha area under wetlands in India (Woistencroft et al. 1989; Anon 1993). This estimate excluded rivers but included the lowland rice fields that occupied around 71% of total estimate. The Ministry of Environment and Forests (MoEF 1995) estimated an area of about 4.1 m ha excluding the mangrove swamps. Estimate obtained from 1:250,000 scale maps using satellite images of the 1992–1993 period was 8.26 million ha (Garg et al. 1998). These estimates did not include rice fields, rivers, and canals. The most recent wetland mapping at 1:50,000 scale using satellite images carried out by Space Applications Centre (SAC) reported 15.26 million ha area under wetlands including the rivers (SAC 2011; Panigrahy et al. 2012).

22.3.1 Satellite Remote Sensing Application

Mapping and monitoring of natural resources using satellite remote sensing in India developed systematically with the launch of the first land resource satellite IRS 1A in 1988. This satellite, provided data from two sensors, LISS I with 72.5 m spatial resolution and LISS II with 36.25 m resolution. Since then, India has launched a series of satellites (IRS 1B, 1C, 1D, P4, P6, and Resourcesat-2) carrying a number of multispectral optical sensors that provided data in varied spectral, spatial, and temporal resolution. The indigenous sensors accelerated the use of remote sensing technology for thematic mapping of natural resources. Mapping of wetlands was initially focused on important types like mangroves and coral reefs. Mapping of mangrove cover using RS data is now done regularly by Forest Survey of India (fsi.nic.in/cover_2013). The first mapping of all the wetlands using RS data was taken up during 1992–1996 by SAC under the NWM project on the behest of MoEF. Mapping was done at 1:250,000 scale using IRS LISS II data acquired during the 1992–1993 period (Garg et al. 1998). Visual interpretation of geocoded photographic prints of the FCC was made with the standard spectral band combination (red, green, and NIR). Though this exercise generated the first wetland maps of the country, the need for further improvement in terms of wetland parameters was explored with time. Launch of Resourcesat-1 satellite with the capability of providing multispectral data in three spatial resolutions from LISS IV, LISS III, and AWiFS facilitated further research on wetland study. Finer spatial resolution of LISS III/IV improved the accuracy of extraction of wetland features such as water spread and aquatic vegetation. Progress in satellite data products, image processing software, and computer hardware improved timeliness and accuracy of thematic mapping. The GIS enabled integration of ancillary data from other sources to improve the information content of maps. Such integrated digital database facilitated the development of Wetland Information System to facilitate retrieval, query, and viewing of data (Patel et al. 2015).

22.3.2 Classification of Wetland Types

The prerequisite of wetland inventory is to finalize the wetland types to be mapped and devise a classification system as per the requirement of the country. For devising a suitable wetland classification system, it is essential that it should follow certain definition of wetland. The first wetland classification system popularly used in the world was based on hydrological, ecological, and geological characteristics (Cowardin et al. 1979). It categorized wetlands into marine (coastal wetlands), estuarine (including deltas, tidal marshes, and mangrove swamps), lacustrine (lakes), riverine (along rivers and streams), and palustrine ("marshy" – marshes, swamps, and bogs). At present, it has been agreed upon by most of the nations to follow the definition as per the Ramsar Convention on Wetlands, which is an international treaty signed in 1971 for national action and international cooperation for conservation and wise use of wetlands and their resources (www.ramsar.org). Accordingly, a nation is required to identify areas and make a list of wetlands that satisfy these criteria. Some of the important features of that classification system are that it should be simple, convenient to use by decision makers, and amenable to digital database structure. Such a classification system was first developed and used for wetland mapping under the NWM project in 1992–1993 (Garg et al. 1998). All the wetlands were assigned into 24 types. This classification system was further modified under the National Wetland Inventory and Assessment (NWIA) project for mapping at 1:50,000 scale (SAC 2011). The modification was based on the similarity in utility value as well as unambiguous identification in remote sensing image. For example, the ash pond and abandoned quarries (water) were merged with "man-made pond." The other types that were suitably merged included "playas," "estuaries," "backwater," and "rocky coast." On the other hand, "river/stream" that was not included in the earlier scheme was included. The modified classification system had 19 wetland types that were arranged under a Level III hierarchical system. Level I had two wetland classes, inland and coastal, each of these further bifurcated into two subclasses, natural and man-made. The 19 wetland types were suitably placed under these two subclasses (Fig. 22.3). A total of six wetland types fall under inland-natural level, four under inland-man-made, seven under coastal-natural, and two under coastal-man-made level, respectively. Details on definition of each wetland type can be viewed from the "National Wetland Atlas: India" (SAC 2011). All the 19 types were distinctly identified in remote sensing images. Many of the wetland types occurred in associations. For example, the riverine types, oxbow lakes, and waterlogged areas were found in the same landscape in the major river plains. The inland saltpan was found in association with some of the lakes. In the coastal areas also, association of mudflats, mangroves, salt marshes, and saltpans were found. In

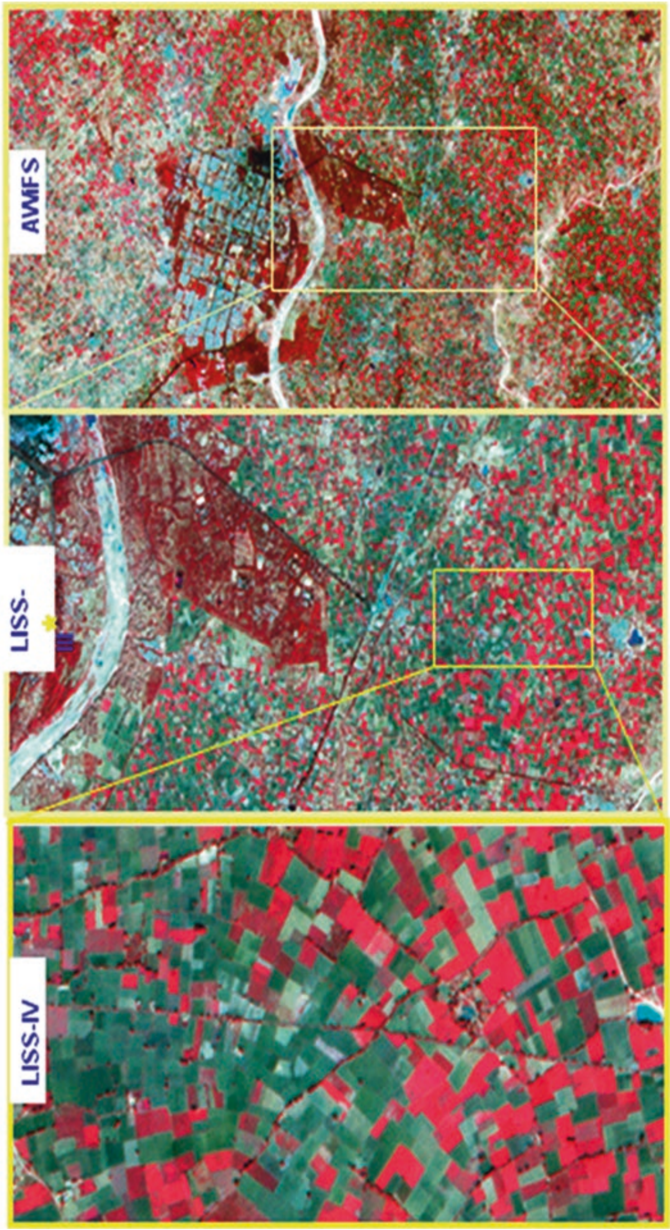


Fig. 22.3 The concept of imaging at different spatial resolutions suitable for resource mapping at variable scales as seen in FCC of AWiFS, LISS III, and LISS IV sensors over an area. The *rectangle* in the image highlights the reduction in area coverage as the spatial resolution increases

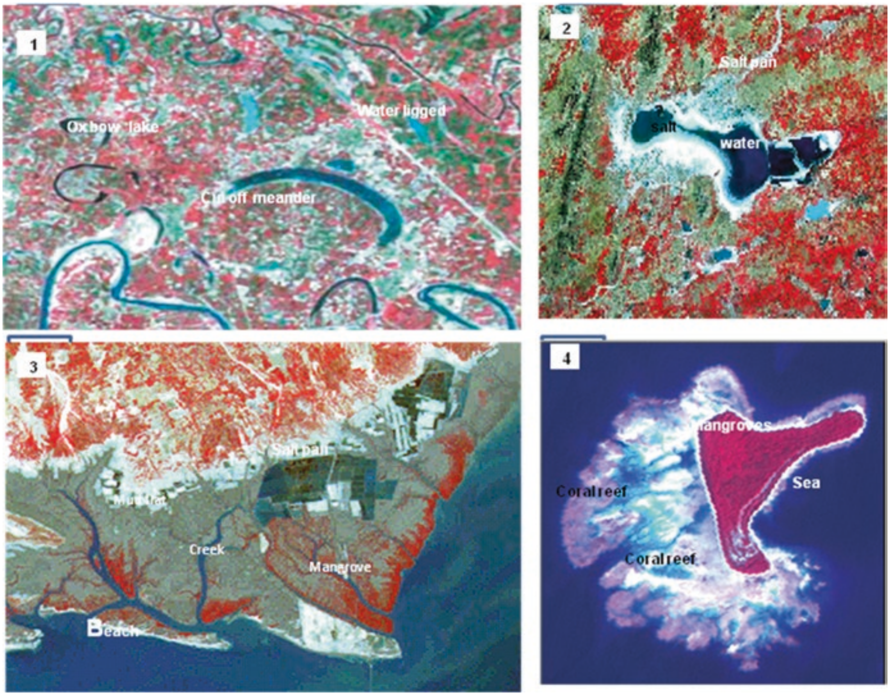


Fig. 22.4 Co-occurrence of wetland types as seen in LISS III FCC: (1) valley plains, (2) inland saltpans around the salt lake, (3) coastal landscape, and (4) island systems

islands, association of various types of coral reefs with mangroves was observed. Examples of such co-occurrence of different wetland types in the inland, coastal, and islands as observed in LISS III FCC are shown in Fig. 22.4.

22.3.3 Mapping Wetland Features

Wetland maps need to contain information that reflects its hydrological and biological characteristics. Water spread and water quality are some of the hydrological features that are needed for modeling the hydrological status. Wetlands in India support a diversity of biota mainly macrophytes. It is estimated that more than 1200 plant species are found in Indian wetlands (Gopal and Sah 1995). This aquatic vegetation apart from their ecological role is a valuable source of food, shelter, breeding, and nesting sites of indigenous and migratory birds. They also play an important role in supporting the fish diversity. Remote sensing images differentiate some of these features very distinctly. Many of the wetland features like water, wet soil/mud, aquatic vegetation, and turbidity of water have distinct spectral signatures. Spectral response of various wetland features as observed in LISS III FCC is

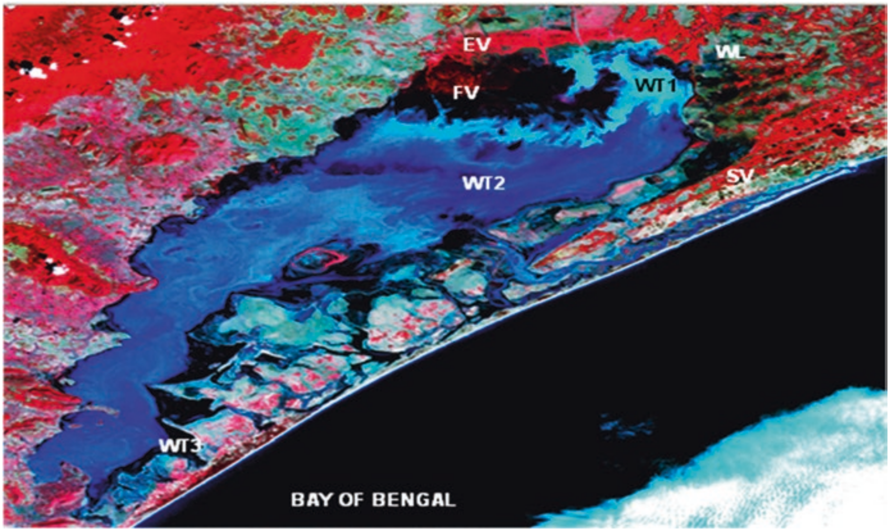


Fig. 22.5 LISS III FCC of a lagoon in the east coast of India showing the spectral appearance of wetland components, *viz*., emergent aquatic vegetation, floating vegetation, waterlogged area, shore vegetation, and qualitative turbidity of water; high (WT3), moderate (WT2), and low (WT3)

shown in Fig. 22.5. Some of the wetland features delineated by techniques developed using multispectral remote sensing image are given below:

1. Wetland boundary
   Wetland boundary essentially denotes the spatial spread/extent of wetland area. Identifying the boundary of wetlands is a complex task, as wetlands encompass a number of covers like open water and aquatic vegetation, particularly floating and emergent, mud/soil, etc. The areas under these types of covers vary seasonally and annually. The maximum spread of these components forms the boundary of wetland. Temporal images are now used to obtain the maximum spread and delineate the boundary as a single layer.
2. Water spread area
   It refers to the area under standing water with in the boundary of a wetland. It includes open water (with or without submerged vegetation) and with floating vegetation. Since water spread area of a wetland varies with season, multi-date images are used to understand the nature of hydrological regime of wetlands.
3. Aquatic vegetation spread
   The presence of vegetation in wetlands provides information about its trophic condition. The wetlands, in general, support four types of aquatic vegetation, *viz*., benthic, submerged, floating, and emergent. It is feasible to delineate the last two types of vegetation using multispectral optical remote sensing data.
4. Turbidity of open water

Water quality of wetlands can be represented by turbidity status. It is feasible to generate turbidity status of open water with a qualitative rating (high, medium, and low). This layer is particularly relevant for inland wetlands like lakes, reservoirs, and rivers.

22.3.4 Image Analysis for Wetland Feature Extraction

LISS III data with 23.5 m spatial resolution is used for mapping 1:50,000 scale of all natural resources in India. LISS III data is available on board the Resourcesat-1/Resourcesat-2 satellites. LISS III sensor provides data in four spectral bands: (i) 0.52–0.59 (green), (ii) 0.62–0.68 (red), (iii) 0.77–0.8 (NIR), and (iv) 1.55–1.70 μm (SWIR). Images have a swath of 141 km. The revisit capability of the satellite offers the scope of selecting images of any area at an interval of 24 days. Thus, one can select optimum data acquisition period as per the requirement of the study area. In general, two dates pertaining to wet and dry season were recommended, as they represent two extreme hydrological statuses, for wetland mapping in India. Remote sensing images bring out these seasonal changes in water spread, vegetation spread, and surrounding land use very clearly. Seasonal changes were observed in all physiographic regions, though more prominent in case of inland wetlands like reservoirs, lakes, and tanks (Fig. 22.6). In case of high altitude lakes, seasonal changes were manifested as freezing and melting. Wet season data acquired during September–October and dry season data during April–May were found optimum as they represented maximum and minimum hydrological phase of wetlands. It was also important to use data pertaining to a normal monsoon year for wetland identification, since deficit rainfall strongly influenced wetland characteristics particularly in arid and semiarid regions of the country.

There are certain preprocessing steps and other supporting activities that need to be done before carrying out analysis of images for thematic mapping. The standard procedure of preprocessing involving geocoding, orthorectification, multi-date image registration, etc., was done before proceeding to image analysis. Another aspect of mapping, particularly at the national level, is to follow a standard spatial framework that sets standards for geographic accuracy (datum, projection, etc.), so that maps can be generated accurately for various administrative units like district and state. India has developed a well-defined National Spatial Framework (NSF) to facilitate digital mapping and database (NNRMS 2005). It is in use for mapping various natural resources at 1:250,000 and 1:50,000 scales. For 1:50,000 scale, the country gets covered by 5112 grids of 38.1 × 38.1 cm size with well-defined four-corner coordinates for each grid. The images are required to be registered with respective grids. Thus, grid level map becomes the basic unit. This facilitates compiling the maps for various administrative units like district and state. Remote sensing image analysis also requires field data collection that is used to train the classification algorithm and verify the accuracy of results. There is a standard method of collecting this information using global positioning system (GPS),

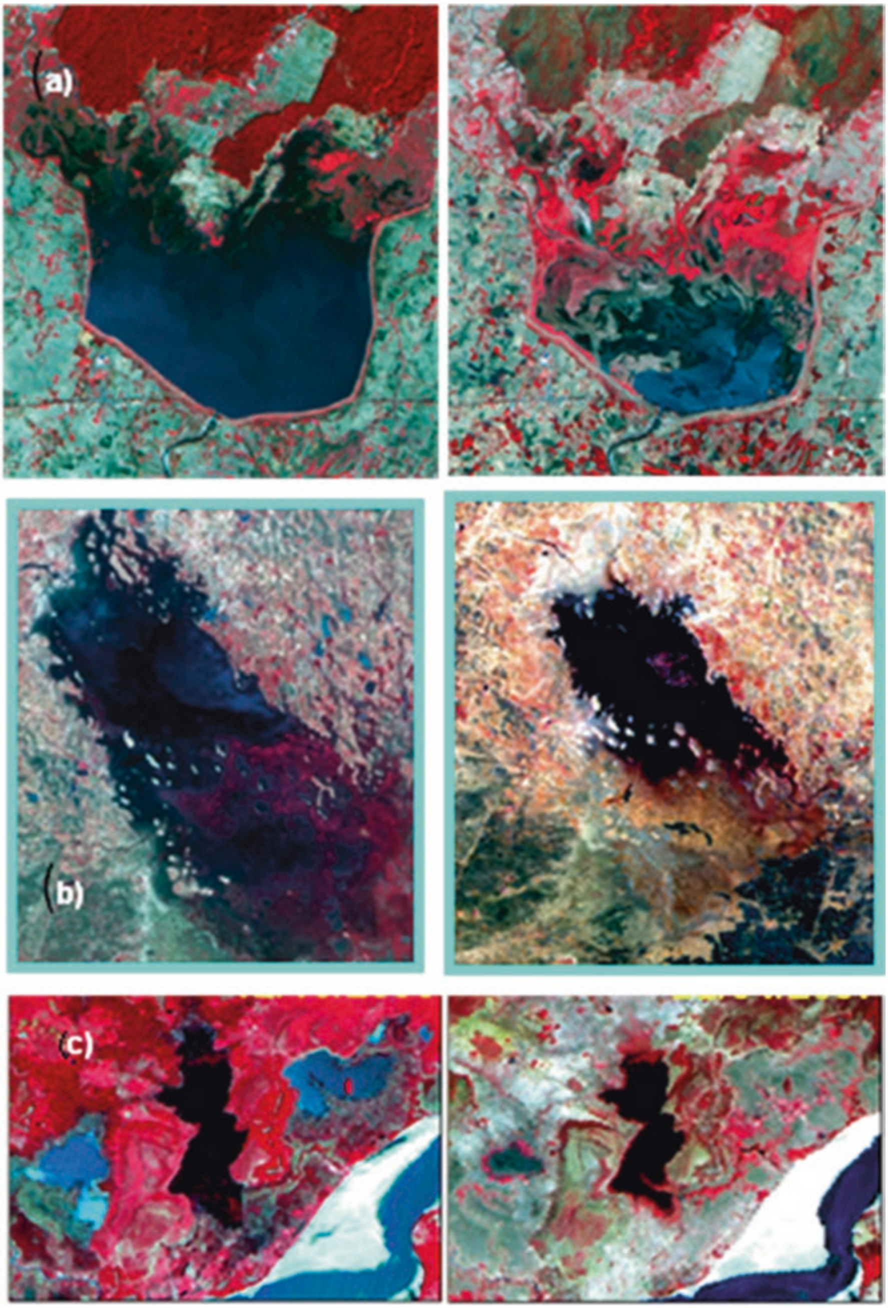


Fig. 22.6 Seasonal changes in wetland features acquired during wet season (left) and dry season (right) as seen in LISS III FCC: (**a**) a reservoir in the Himalayan region, (**b**) an inland lake in semi-arid western region, (**c**) a freshwater lake in the eastern region

digital photograph, and satellite image of the study area. The field data also forms the benchmark for subsequent monitoring and change analysis.

Image analysis for feature extraction is done using various classification algorithms. Spectral index-based approach has been evaluated and found to be the optimum method for wetland detection. The above spectral indices were generated from the individual bands of LISS III data using standard image processing software and stacked as layers or bands for further use. The following indices were found to enhance different wetland features.

(i) Normalized Difference Water Index (NDWI) = (Green-NIR)/(Green + NIR)
(ii) Modified Normalized Difference Water Index (MNDWI) = (Green-SWIR)/(Green + SWIR)
(iii) Normalized Difference Vegetation Index (NDVI) = (NIR – Red)/(NIR + Red)
(iv) Normalized Difference Pond Index (NDPI) = (SWIR – Green)/(SWIR + Green)
(v) Normalized Difference Turbidity Index (NDTI) = (Red – Green)/(Red + Green)

Instead of using any single index, combinations of two or three indices were found to perform better to extract different wetland features. The indices were used to generate a false-color composite (FCC) that highlights the areas under open water, wet soil/mud, aquatic vegetation, shore vegetation, etc., for viewing. Field information collected is used to decide a proper hierarchical threshold for feature delineation. The following combinations of indices were found suitable for extraction of different wetland features:

- Wetland boundary: combinations of NDWI, NDPI, and NDTI were used to extract the wetland boundary through suitable hierarchical thresholds.
- Open water: MNDWI was used to delineate the open water spread within the wetland mask.
- Aquatic vegetation: a combination of NDPI and NDVI was used to generate the aquatic vegetation layer within a wetland.
- Turbidity level: MNDWI was used to generate three qualitative turbidity levels (high, moderate, and low) based on standard deviation thresholds.

The spectral response of an inland lake in four bands of LISS III and four spectral indices is shown in Fig. 22.7a. The performance of combinations of indices in delineating wetland features of an inland-natural lake is shown in Fig. 22.7b.

Spatial resolution of LISS III data supported minimum mapping unit of 2.25 ha. Smaller wetlands (<2.5 m area) that could be detected were marked as point features. After image classification, assignment of type of wetland was done by the wetland experts as per the classification code.

To generate maps and create GIS database of wetlands, the thematic layers need to be imported to GIS environment using standard procedure. The GIS facilitates integration of ancillary data like administrative boundaries to generate maps and

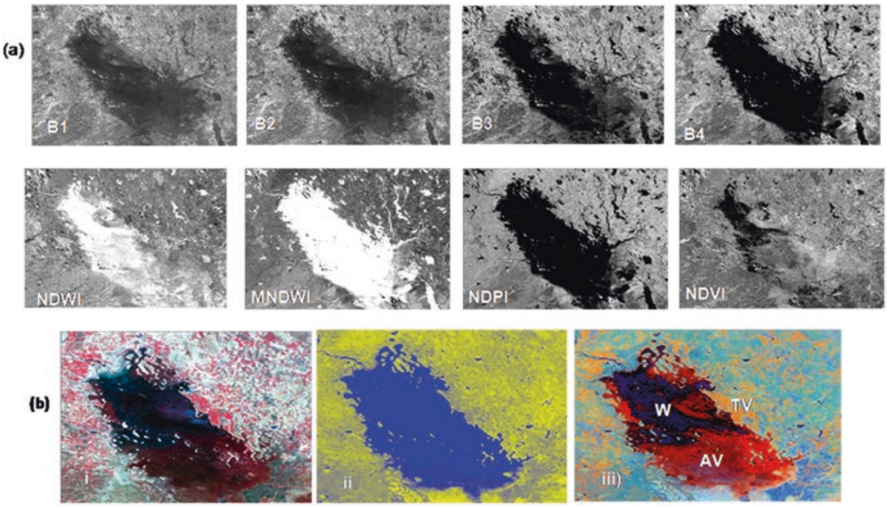


Fig. 22.7 (**a**) Images of the four LISS III spectral bands (B1–B4) of an inland-natural lake, four spectral indices used to delineate wetland features, and (**b**) performance of combination of indices in delineating wetland features, (i) LISS III FCC; (ii) FCC of NDWI, NDPI, and NDTI enhancing the wetland boundary; and (iii) FCC of MNDWI, NDPI, and NDVI enhancing open water and vegetation

statistics at the level of various administrative units (district, state, country). Elevation contours are needed to delineate the wetlands above 3000 m amsl designated as HAWs.

The above procedure was tested over different regions in India and was found to perform well. The method was used to map the wetlands of entire India at 1:50,000 scale under the NWIA project (www.moef.nic.in, SAC 2011). A total of 712 LISS III scenes pertaining to two seasons (2006–2007) were used to produce wetland maps showing distribution pattern and seasonal status of 19 types of wetlands. The following section analyzes the wetland scenario in India based on NWIA findings.

22.4 Wetland Scenario in India

22.4.1 Extent of Wetland Types

The total estimated area under 19 types of wetlands was 14.71 M ha. Inland wetlands occupied 10.562 M ha area, compared to 4.142 M ha area under coastal wetlands. Rivers/streams occupied the largest area (35.75%). Reservoir/barrages and intertidal mudflats were the other two major types covering 16.87% and 16.4% of the area, respectively. The remaining types of wetland occupied less than 5% area each. Inland wetlands play a crucial role in hydrology and water resources of terrestrial area. Notwithstanding the importance of the rivers, the seven wetland types were of high importance to freshwater hydrology, biodiversity, and socio-economy.

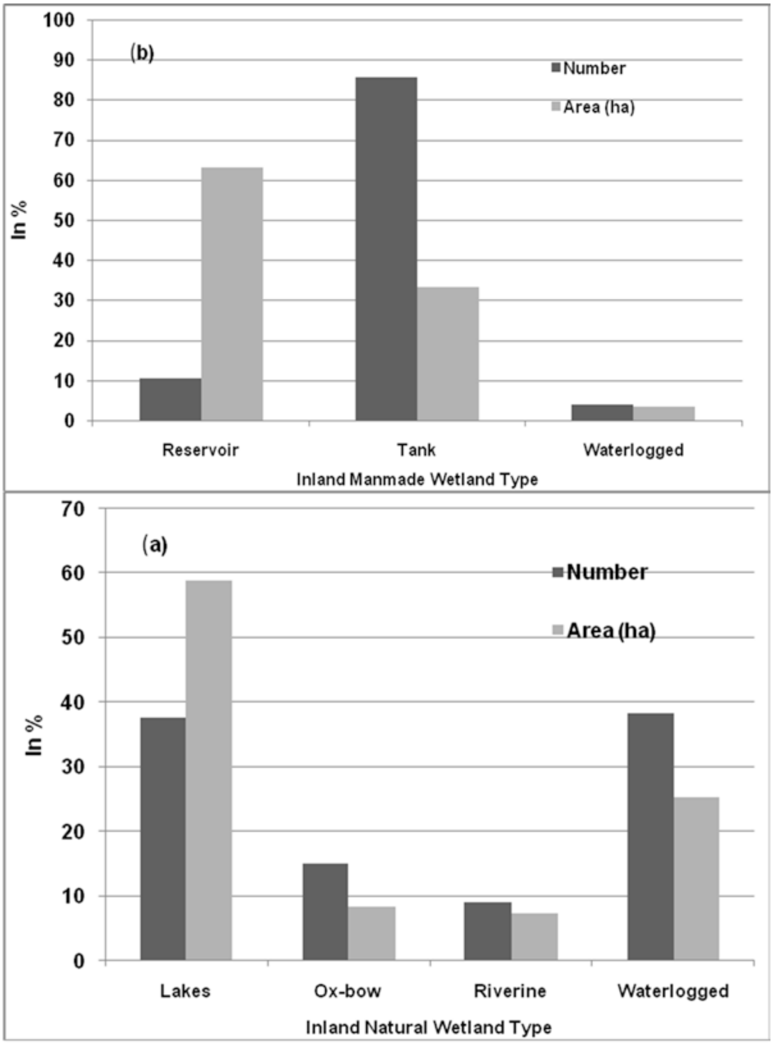


Fig. 22.8 Number and area under (**a**) three man-made freshwater wetland types, (**b**) four freshwater natural wetland types

Four of these were natural (lakes/pond, oxbow lakes/cutoff meanders, riverine, and waterlogged) and three man-made types (reservoir/barrage, tank/pond, and waterlogged). Analysis of data of these seven wetland types was done to understand their comparative contribution and status. These seven types of wetlands occupied 51,68,563 ha area, distributed in 1,73,960 units/patches. Man-made wetlands were the major one; spread over an area of 39,28,134 ha, they accounted for 76.0% of the total area. Among the man-made types, reservoirs/barrages were the major one with 63.18% share of area. Though number-wise tanks/ponds were the highest, they occupied only 33.0% area due to their small sizes (Fig.22.8a). Among the four natural wetland types, lake/pond was the major one with 58.81% share of area. A total of 11,740 lakes were mapped with an extent of 7,29,532 ha area. Waterlogged was the second major one occupying 25.4% area, followed by oxbow lakes/cutoff meanders (Fig. 22.8b).

22.4.1.1 Small Wetlands

A large number of wetlands were mapped as points due to their small size (<2.25 ha). A total of 5,55,557 small wetlands were mapped, which were assigned 1 ha nominal area. Taking this into account, the total area under wetlands estimated was 15.26 M ha, which is around 4.64% of the geographical area of the country. As observed in the satellite image, most of these were village ponds, particularly in the mainland. The eastern Indian region showed high concentration of these small village ponds (Fig. 22.9). The state of West Bengal had the highest number of these small ponds (1,38,707 ha). In the case of the Himalayan region, most of the small wetlands were high altitude lakes.

22.4.1.2 High Altitude Wetlands (HAW)

Mapping HAWs is one of the most difficult tasks due to the inaccessible terrain and harsh environment of the region. Around 56.4% area of the Indian Himalayan region is above the altitude of 3000 m. Rivers, marshes, and lakes constituted HAW. The high altitude rivers being of low width due to steep gradient could be mapped as line features at 1:50,000 scale. The rivers showed seasonal change in state of water (liquid and frozen), with banks devoid of woody vegetation. Lakes known as high altitude lakes (HALs) were the most dominate wetland at this altitude. Based on their origin, mostly five types were found: salt lakes, glacial lakes, structural lakes, remnant lakes, and natural dam lakes. A total of 4699 HALs were mapped including 1966 very small ones marked as points (Panigrahy et al. 2013). Small lakes of <10 ha areas were highest in number (84%). Altitudinal distribution showed that maximum numbers of lakes (56.2%) were located in the elevation range of 4000–5000 m. Large lakes of >500 ha area were also observed in this elevation range. In total 734 lakes were identified in the altitude range of >5000 m elevation. HALs undergo freezing and melting cycles in a year, which were clearly observed from RS images (Fig. 22.10). Images acquired during full liquid phase of the lakes were found suitable for mapping the HAL. The catchment of these lakes were mainly rocky, snow-clad mountains, with small patches of marshy vegetation, sometimes even salt-encrusted surrounding. These features were clearly distinguished in remote sensing image (Fig. 22.11). Marshes were found in the catchments of large lakes. These are habitat to some of the unique fauna. Chushul Marsh, one of the large marshes in the Western Himalaya, was observed at an altitude of 4150 m amsl.

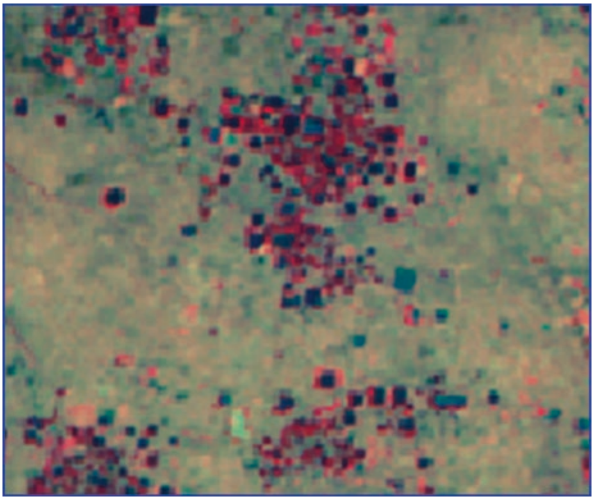


Fig. 22.9 LISS III FCC of an area in West Bengal showing abundance of small (<2.0 ha) man-made ponds mapped as point features

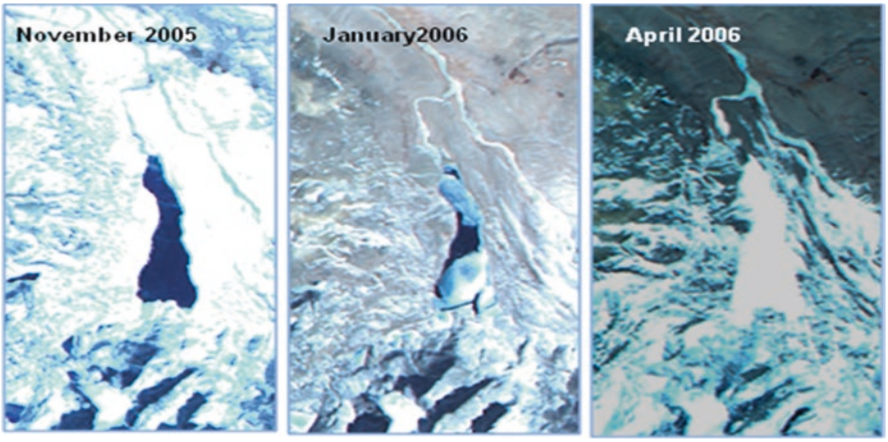


Fig. 22.10 Temporal LISS III FCC showing the change in state of water of a HAL located at 5090 m altitude

22.4.2 Status of Wetlands

Status of most of the wetlands in terms of water spread, vegetation, and water turbidity showed significant seasonal change. In general, the water spread area was higher during post-monsoon, while vegetation area was higher during pre-monsoon. The turbidity of water was medium to low in both the seasons. However, turbidity of water in many of reservoirs was high during post-monsoon. Total area under vegetation was higher during dry season compared to wet season. Aquatic vegetation was more in the case of lake/pond, riverine wetland, oxbow lake, and tank/pond (Panigrahy et al. 2012).

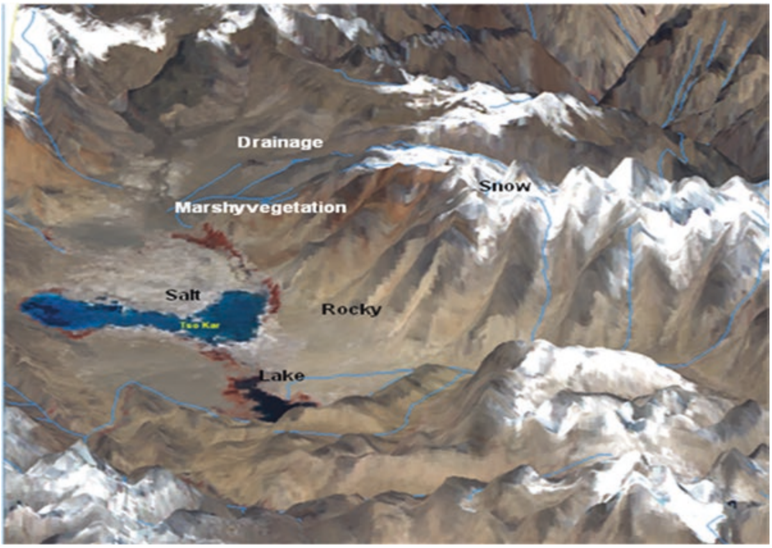


Fig. 22.11 LISS III FCC showing the perspective view of a high altitude lake and its surrounding landscape

In order to understand the hydrology of freshwater wetlands that play a crucial role in water resources, analysis of important inland wetlands was carried out. Thus, four natural wetlands (lakes, riverine, ox bow/cutoff meanders, and waterlogged) and three man-made wetlands (reservoirs/barrages, tank/pond, and waterlogged) were considered. Among the inland-natural wetlands, maximum change was observed in case of lakes/ponds. Water spread in lakes/ponds occupied around 62.3% of lake area in post-monsoon, which reduced to 27.0% in pre-monsoon. Area under vegetation increased from 34.8% to 62.6% (Fig. 22.12a, b). The increase in vegetation in lake was also mainly due to proliferation of invasive plants like water hyacinth in the shallow water areas and emergent vegetation in the muddy areas. Agricultural practice was also observed inside many lakes during the dry season. The other three types of natural wetlands also showed reduction of both water spread and vegetation area during dry season. In the case of inland-man-made wetland types, reservoirs/barrages showed least vegetation area during post-monsoon (4.8%), while waterlogged area was around 32.0%. Increase in vegetation area during pre-monsoon was observed in all types of wetlands except waterlogged areas (Fig. 22.13a, b).

22.5 Conclusion

India harbors diverse types of wetlands. Inventory of wetlands is one of the prime requirements to develop a comprehensive framework for the conservation policy/planning of these resources. Making inventory of wetlands is a challenging task as they include a diverse type of systems spread over the vast stretch of the Indian

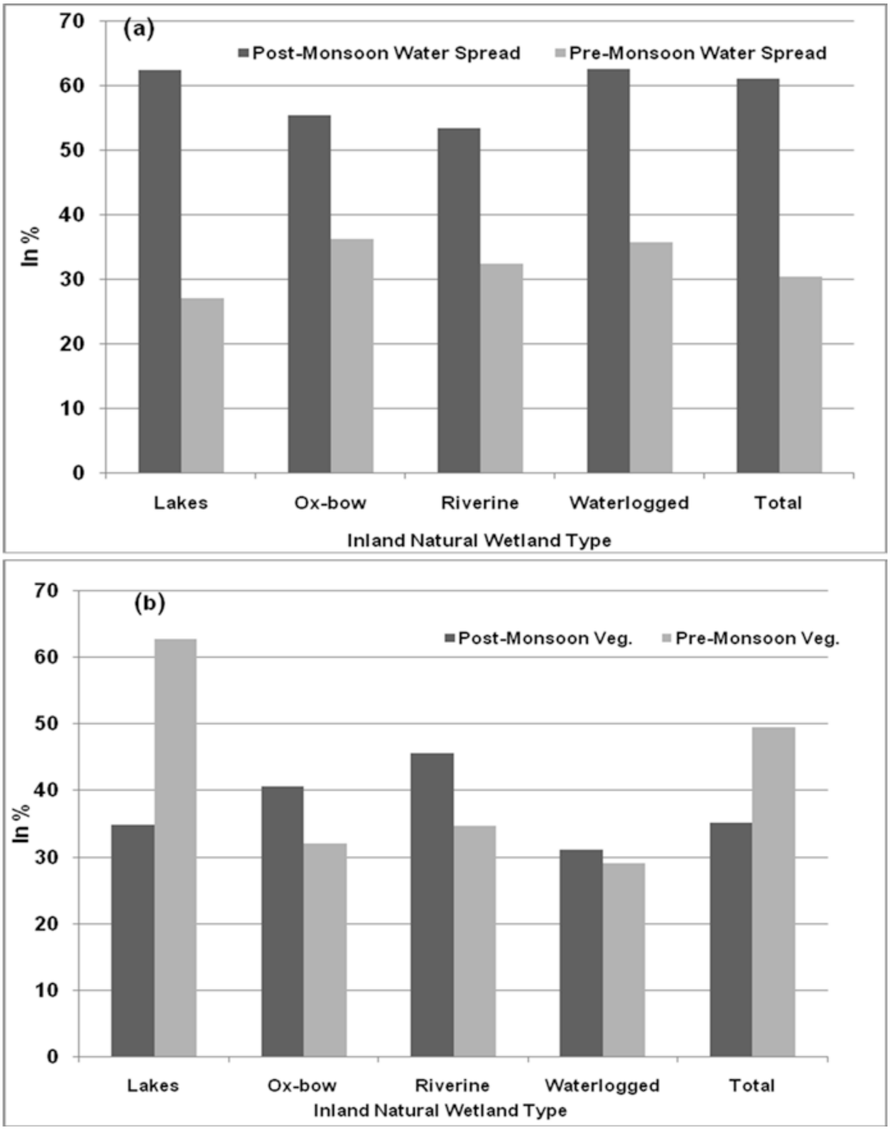


Fig. 22.12 Post- and pre-monsoon changes in (**a**) water spread area and (**b**) aquatic vegetation in four freshwater natural wetland types

landmass. Each wetland type is a complex system composed of water, vegetation, soil, mud, etc. Satellite remote sensing technology is of particular use in obtaining accurate and timely information on these ecosystems. The multispectral and multi-spatial resolution remote sensing images from the three sensors (AWiFS, LISS III, IV) from IRS satellite Resorcesat-1/Resorcesat-2 facilitate mapping wetlands at different scales. Four band images in visible and reflective infrared region gave distinct

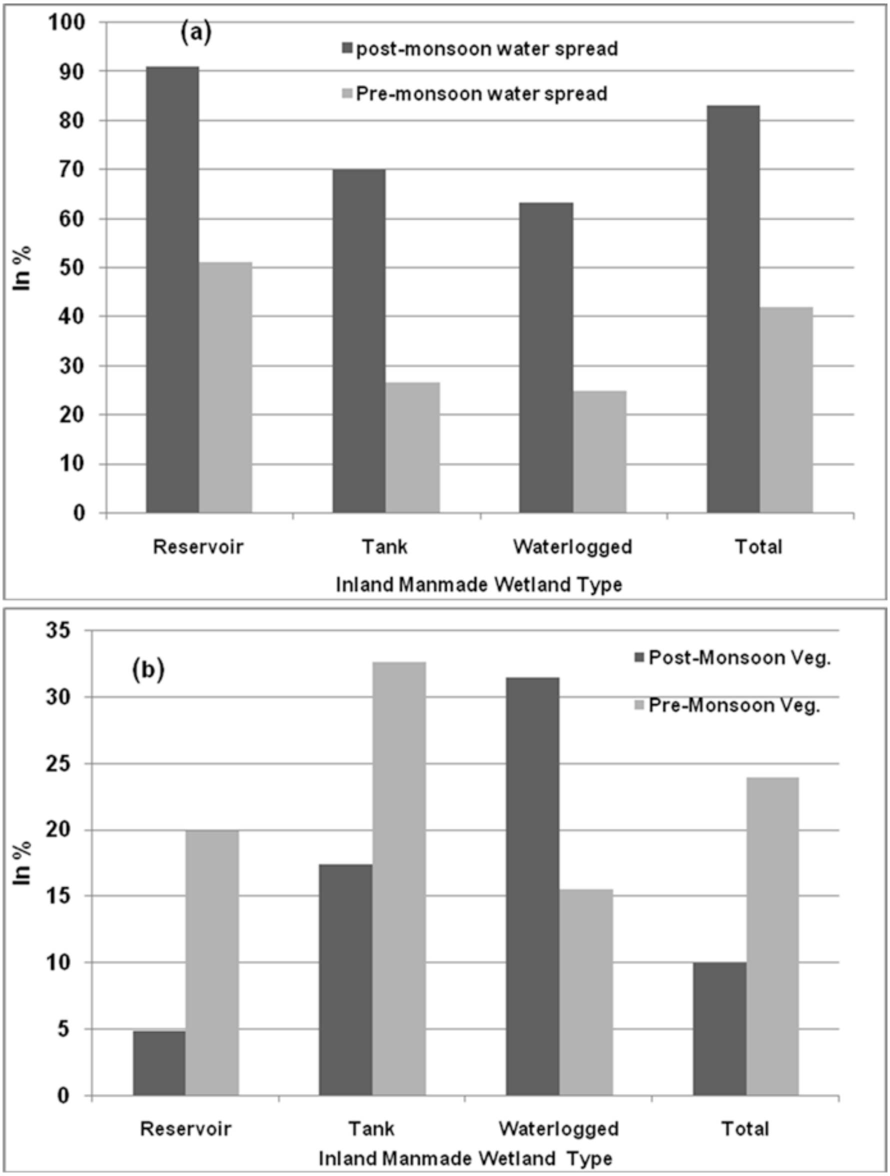


Fig. 22.13 Post- and pre-monsoon changes in (**a**) water spread area and (**b**) aquatic vegetation in three freshwater man-made wetland types

spectral signatures to indentify different wetland types found in India. Various combinations of spectral indices, *viz*., NDWI, MNDWI, and NDPI, were found to delineate features like boundary, water spread, spread of aquatic vegetation, and qualitative turbidity of water. Two-season data representing the wet season and dry season were found essential for mapping, as wetland hydrology is strongly influenced by monsoon. This procedure was used to map wetlands of the country at 1:50,000 scale using LISS III data 2006–2007. The results showed that an area of 14.27 M ha is under 19 types of wetlands. The water spread area of wetlands, particularly the inland types like lakes, reservoirs, and tanks, reduced significantly in dry season. On the other hand, the area under aquatic vegetation increased. This was mainly due to growth of emergent vegetation in the wet soils, proliferation of invasive weeds like water hyacinth in shallow waters, and, to some extent, agriculture.

Remote sensing is now accepted as a fast and cost-effective technology for wetland mapping, suitable for large countries like India. Digital analysis of satellite data results in easy integration of map into a GIS, with other ancillary data for complete wetland information. The technology is best suited for monitoring change at regular time intervals to assess the efficacy of conservation measures taken. The use of remote sensing data for wetland mapping requires certain understanding regarding the selection of data required, when to acquire, and how many repeat cycle data are needed as per the characteristics of study area. It also requires certain preparatory activities to standardize spatial framework, image analysis procedure, and field data collection that need to be understood well to get the desired result. The present procedure based on multispectral remote sensing has certain limitations for site-specific studies that require quantification of wetland parameters like depth, water quality, aquatic vegetation, etc. The advanced sensors like hyperspectral, microwave, and thermal are being explored for this. However, the current state of the art of remote sensing technology is of great use for reconnaissance survey of wetlands at different scales to obtain baseline data such as type-wise distribution, catchment characteristics and seasonal changes. The remote sensing images augment scientific planning for field data collection for site-level studies at reduced cost, time, and efforts.

References

Anon (1993) Directory of Indian wetlands, WWF India, New Delhi and AWB Kuala Limpur, xvi, p 264

Cowardin LM, Carter V, Golet FC, LaRoe ET (1979) Classification of wetlands and deepwater habitats of the United States. U S Department of Fish and Wildlife Service, Washington, DC

Elhadi A, Onisimo M, Denis R (2010) Multispectral and hyperspectral remote sensing for identification and mapping of wetland vegetation: a review. Wetl Ecol Manag 18:281–296

Finlayson CM, Davidson NC, Spiers AG, Stevenson NJ (1999) Global wetland inventory status and priorities. Mar Freshw Res 50:717–727

Finlayson CM, Davidson NC and Stevenson NJ (eds) (2001) Wetland inventory, assessment and monitoring: practical techniques and identification of major issues. In: Proceedings of Workshop 4, 2nd International Conference on Wetlands and Development, Dakar, Senegal, 8.14 1998, Supervising Scientist Report 161, Supervising Scientist, Darwin

Garg JK, Singh TS and Murthy TVR (1998) Wetlands of India, Project Report, RSAM/SAC/RESA/PR/01/98, p 240, Space Applications Centre, Ahmedabad

Ghermandi A, van den Bergh JCJM, Brander LM, de Groo HLF, Nunes P (2010) Values of natural and human-made wetlands: a meta-analysis. Water Resour Res 46:1–12

Gopal B, Sah M (1995) Inventory and classification of wetlands in India. Vegetatio 118:39–48
Griffith JA (2002) Geographic techniques and recent applications of remote sensing to landscape-water quality studies. Water Air Soil Pollut 138:181–197
Hardisky MA, Gross MF, Klemas V (1986) Remote sensing of coastal wetlands. Bioscience 36:453–460
Jensen JR, Hodgson ME, Christensen E, Halkard E, Mackey J, Tinney LR, Shartiz R (1986) Remote sensing inland wetlands: a multispectral approach. Photogramm Eng Remote Sens 52:87–100
Ji L, Geng X, Sun K, Zhao Y, Gong P (2015) Target detection method for water mapping using landsat 8 OLI/TIRS imagery. Water 7:794–817
Lacaux JP, Tourre YM, Vignolles C, Ndione JA, Lafaye M (2007) Classification of ponds from high-spatial resolution remote sensing: application to Rift valley fever epidemics in Senegal. Remote Sens Environ 106:66–74
Lee KH, Lunetta RS (1996) Wetland detection methods. In: Lyon JG, McCarthy J (eds) Wetland and environmental applications of GIS. Lewis Publishers, New York, pp 249–284
Lei J, Zhang L, Wylie B (2009) Analysis of dynamic thresholds for the normalised difference water index. Photogramm Eng Remote Sens 75:1307–1317
Lillesand TM, Keifer RW (1987) Remote sensing and image interpretation. Wiley, New York
Lulla K (1983) The Landsat satellites and selected aspects of physical geography. Prog Phys Geogr 7:1–45
McFeeters SK (1996) The use of Normalised Difference Water Index (NDWI) in the delineation of open water features. Int J Remote Sens 17:1425–1432
MoEF (1995) Wetlands of India: a directory. ministry of environment and forests. Government of India, New Delhi
MoEF (2012) Wetlands of India: a directory. Ministry of environment and forests. Government of India, New Delhi
Murthy TVR, Patel JG, Panigrahy S and Parihar JS (eds) (2013) National Wetland Atlas: wetlands of International Importance under Ramsar Convention, Space Applications Centre (ISRO), Ahmedabad, p 230, ISBN:978-93-82760-00-9.
NNRMS (2005) NNRMS Standards: a national standard for EO images, Thematic and Cartographic Maps, GIS Databases and Spatial Outputs, ISRO Bangalore publication, p 201
Panigrahy S, Murthy TVR, Patel JG, Singh TS (2012) Wetlands of India: inventory and assessment at 1: 50,000 scale using geospatial techniques. Curr Sci 102:852–856
Panigrahy S, Patel JG, Parihar JS (eds) (2013) National Wetland Atlas: high altitude lakes of India. Space Applications Centre, ISRO, Ahmedabad, p 108 ISBN:978-93-82760-00-9
Patel JG, Murthy TVR, Singh TS, Panigrahy S (2009) Analysis of the distribution pattern of wetlands in India in relation to climate change. ISPRS Archives XXXVIII-8/W3 Workshop Proceedings: Impact of Climate Change on Agriculture, pp 282–287
Patel JG, Panigrahy S, Parihar JS (2015) National wetland database and information system: a step towards integrated planning for conservation of wetlands in India. J Geomatics 9:184–192
Prasad SN, Ramachandra TV, Ahalya N, Sengupta T, Kumar A, Tiwari AK, Vijayan VS, Vijayan L (2002) Conservation of wetlands of India – a review. Trop Ecol 43:173–186
Prigent C, Matthews E, Aires F, Rossow WB (2001) Remote sensing of global wetland dynamics with multiple satellite datasets. Geophys Res Lett 28:4631–4634
SAC (2011) National Wetland Atlas, India, SAC/EPSA/ABHG/NWIA/ATLAS/34/2011, Space Applications Centre (ISRO), Ahmedabad, p 306
Scott DA, Jones TA (1995) Classification and inventory of wetlands: a global overview. Vegetatio 118:3–16
Sohn Y, Rebello NS (2002) Supervised and unsupervised spectral angle classifiers. Photogramm Eng Remote Sens 68:127–128
Stacy LO, Marvin EB (2002) Satellite remote sensing of wetlands. Wetl Ecol Manag 10:381–402
Townshend JR, Justice CO (1986) Analysis of dynamics of African vegetation using the normalised difference vegetation index. Int J Remote Sens 7:1435–1445

Wilen BO, Bates MK (1995) The US fish and wildlife service's wetland inventory project. Vegetatio 118:153–169

Woistencroft JA, Hussain SA, Varshney CK (1989) India: introduction. In: Scott DA (ed) A directory of Asian Wetlands. IUCN, World Conservation Union, Switzerland, pp 367–505

www.fsi.nic.in/cover_2013

www.millenniumassessment.org

www.moef.nic.in

www.ramsar.org

Xu H (2006) Modification of Normalised Difference Water Index (NDWI) to enhance open water features in remotely sensed imagery. Int J Remote Sens 27:3025–3033

Habitat Level Mapping of Coral Reefs at Different Scales: Case Study on Andaman and Nicobar Islands

23

Nandini Ray Chaudhury

Abstract

Tropical coral reefs represent a major coastal or marine wetland type. This chapter highlights the global distribution of tropical coral reefs, their ecosystem services and major threats. The concept of coral reef habitat mapping has been discussed in detail. Coral reef habitat mapping at different scales have been described with respect to space-based inputs like aerial photographs and satellite imageries available at different resolutions. Major global and regional scale reef mapping projects using aerial photographs and multispectral satellite imageries have been discussed here. The chapter also highlights different habitat mapping methods based on different image processing techniques. Habitat mapping of Andaman and Nicobar Islands as a subset of Indian Ocean reefs with Indian Remote Sensing data and its current constraints have been illustrated as a case. Future directions of this field have also been mentioned in brief.

Keywords

Andaman and Nicobar • Coral reefs • Habitat mapping • Aerial photographs • Satellite images

N. Ray Chaudhury (✉)
Environment & Hydrology Division, Space Applications Centre, Indian Space Research Organisation, Ahmedabad 380015, India
e-mail: nandinirc@sac.isro.gov.in

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_23

23.1 Coral Reefs: A Critical Eco-resource

Coastal wetlands represent a zone of critical trade-offs between human interests in ecology and economics. The global coastal zone including small islands contributes 4% of the earth's total land area but supports more than a third of the world's population (Barbier et al. 2008). Coastal population density is increasing exponentially with high proportion of urbanisation (McGranahan et al. 2007). Long-term sustainability of this population depends on coastal wetland ecosystems and the services they provide, like shoreline protection, fisheries production and improved water quality. The past three decades have experienced increasing degradation and loss of major coastal wetland habitats like salt marshes (50%), mangroves (35%) and coral reefs (30%) despite their ecological services (Barbier et al. 2008).

Coral reefs are one of the major types of wetlands based on the wetland classification by the Ramsar Convention (Ramsar Convention Secretariat 2010). Coral reef ecosystems are found within the tropical belt of 30° N and 30° S latitudes on the earth where winter temperatures remain 18–20 °C. The global distribution of coral reefs is shown in Fig. 23.1. Percentage area occupied by coral reefs in different oceanic regions is summarised in Table 23.1. Indo-Pacific region occupies the largest area (91.90%), while Atlantic and Caribbean regions cover 7.60% area followed by the Eastern Pacific with only 0.50% area (Spalding et al. 2001). Among the subregions, Southeast Asia leads with 40.80% followed by the Indian Ocean with 32.30% area. The reef building or hermatypic corals are confined to the photic zone where sufficient sunlight penetrates to facilitate photosynthesis by their endosymbiont dinoflagellate algae, zooxanthellae. As a keystone ecosystem on earth, coral reefs are characterised by high biological productivity and environmental complexities.

As a major coastal or near-shore marine ecosystem, tropical coral reefs provide critical habitat to one-fourth of the known marine organisms, including some of the

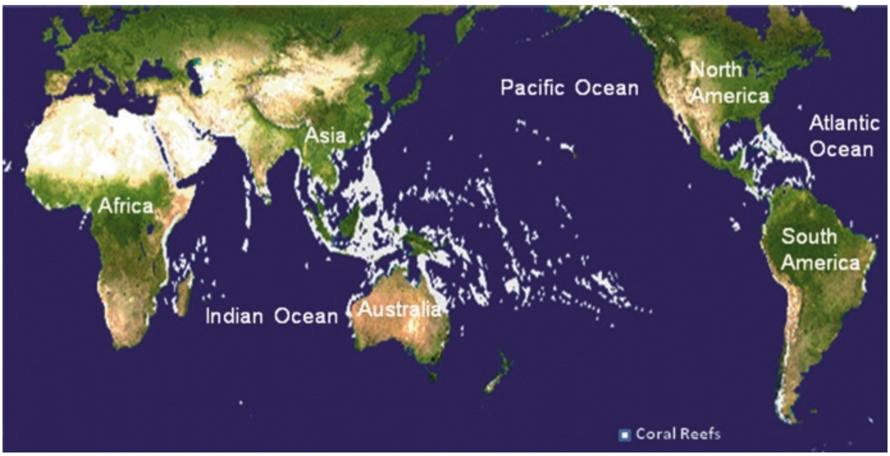


Fig. 23.1 Global distribution of coral reef ecosystems (Source: www.reefbase.org)

Table 23.1 Coral reef area (%) in different oceanic regions

Oceanic regions	Area (in % of world total)
Indo-Pacific Region	91.90
Southeast Asia	40.80
Indian Ocean	32.30
Red Sea and Gulf of Aden	6.10
Arabian Gulf	1.50
Arabian Sea	11.30
Atlantic and Caribbean	7.60
Caribbean	7.00
Atlantic	0.60
Eastern Pacific	0.50

Source: Spalding et al. (2001)

rare avifauna (Buddemeier et al. 2004) while occupying only 0.09% area of global oceans (Spalding et al. 2001). It has been estimated that more than 275 million people live within 30 km of coral reefs whose life and livelihood directly depend on the reefs (Burke et al. 2011). This is true for most of the developing countries and a number of island nations whose physical foundation itself is formed by coral reefs. Wave buffering; coastline protection against erosion, storm surges, tsunamis and flooding; sediment stabilisation and control on beach and island formation; and control on reef and lagoon circulation are considered as major regulating services extended by coral reefs (Kench et al. 2009). Cultural services include spiritual identity for indigenous communities, contribution to scientific knowledge, education and research interests and recreation and aesthetic values. Coral reefs harbour potential economic interests in terms of tourism and marine sports in many tropical countries. More than 100 countries benefit from coral reef tourism, which contributes more than 30% of export earnings of 20 or more such countries (Burke et al. 2011). Nutrient cycling, carbon and nitrogen fixation in oligotrophic environment, biogenic calcium carbonate production and associated coastal ecosystem protection like seagrass meadows and mangroves are the key supporting services offered by coral reefs. The annual value of a hectare of coral reef has been estimated to be US$ 129,000 which makes it the most economically valuable coastal ecosystem (Silvestri and Kershaw 2010).

Unfortunately, the most valuable coastal ecosystem is the most vulnerable too. Worldwide tropical coral reefs are either experiencing, or at risk from, overexploitation of reef resources including destructive fishing practices like beam drawling, dynamite and cyanide fishing, coastal development, sedimentation and pollution. Parallel to these anthropogenic impacts, there are biological and ecological threats like coral diseases, trophic level disturbances and invasive species. However, coral reefs' sensitivity towards climate change stresses (warming and acidic oceans, intense tropical storms) has surpassed its responses towards ecological disturbances and anthropogenic impacts (Lesser 2011). Broad-scale global assessments have argued that the world has 'effectively lost' 19% of original coral reef area since 1950, 15% is in ‘critical state’ while another 20% seriously threatened (Wilkinson 2008).

For a fast depleting natural resource like tropical coral reefs, inventory and spatial documentation in the form of habitat maps thus have become an urgent need for effective resource planning and management. Benthic habitat maps present spatial documentation of location of coral reefs, geomorphological zones and benthic categories and potentially depict the overall health of the ecosystem and thus become important tools for coral reef management. These maps not only serve as base maps to examine the physical reef structure and resource inventory but also allow estimation of biodiversity and ecological functions.

23.2 Coral Reef Habitat Mapping: A Way of Resource Documentation

Habitat mapping essentially upholds the essence of old science of landscape ecology (Franklin 2010). Coral reef habitat mapping demonstrates the application of landscape ecology into marine environment or seascape. The seascape is described here through quantitative metrics recognising attribute (or feature) patterns in a spatial context. Coral reefs, seagrass beds, mangroves and salt marshes have been the most targeted natural coastal wetlands or ecosystems where the concept of habitat mapping has been widely applied and accepted. In common parlance, the term habitat means the natural home or environment of an organism. However, in the context of habitat mapping, the term habitat embodies species assemblages and associated substrata (Mumby et al. 1997). The classic approaches perceive coral reefs as landforms of biological origin and accordingly define them with respect to two major attributes, its geomorphological structure and benthic cover.

Coral reef mapping has evolved considerably from its original form of navigational feature charting since the early eighteenth century to the global-scale Millennium Coral Reef Mapping Project (MCRMP, Andréfouët et al. 2006) in the twenty-first century. Coral reef mapping has advanced with improving hydrographic and remote sensing technologies providing a wide array of mapping techniques. However, the choice of technique essentially depends on the purpose, the end product or map, scale of the work and availability of resources (Spalding et al. 2001). The confluence of sophisticated sea-floor mapping technologies, Global Positioning System (GPS) and Geographical Information System (GIS) especially after the 1990s provided the foundation for mapping coral reefs across the globe (Franklin 2010) that otherwise happened to be a ‘remote’ target. Shallow water coral reef habitat mapping is best accomplished with airborne and satellite remote sensing. The initial step for coral reef habitat delineation and classification defines a finite domain for each coral reef unit or system and allows physical accounting of the reef area and diversity of habitat types (Franklin 2010).

Effective ecosystem management of coral reefs or for that matter any other wetlands depends on linked inputs from a progression of knowledge through mapping, measurement, monitoring and modelling (Phinn et al. 2006; Yamano 2013).

Mapping provides baseline surveys or inventories. Mapping makes way for measurements of different mapped variables in terms of their spatial (area) and absolute quantities. Monitoring involves the time domain and allows comparison of baseline maps or data with updated information. This leads to change detection and calculation of rate of changes with respect to time. Modelling includes data integration towards building empirical, statistical or physics-based relations between environmental variables and coral reef processes enabling prediction of ecosystem response to a single or a set of environmental parameters.

23.3 Habitat Level Mapping of Coral Reefs at Different Scales

Coral reef habitat mapping is a major example of thematic mapping. The scale of a map is a measure of proportionate representation of size dimension(s) of feature(s) on map as that on ground or earth's surface. Choice of map scale essentially depends on the purpose of the map and the total coverage area to be represented. Thus, coral reef habitat maps encompass the wide array of ecosystem level organisations (i.e. biogeographic regions, reef systems, unit reefs, community and colony) and portray particular thematic attributes ranging from reef locations to coral bleaching locations (CRTR Remote Sensing Working Group 2010) at best-suited scales. Scale of the map is dependent on the spatial resolution of photographs (both digital and aerial) and satellite imageries, the key inputs to benthic habitat mapping. For a sensor, spatial resolution refers to its resolving capability to image or record two closely spaced objects on the earth's surface as two separate objects and is commonly represented in terms of the minimum distance between the two. For an image, however, resolution connotes the level of (feature) details and is represented in terms of pixel size. The spatial and spectral resolution (location, bandwidth and total number of spectral channels) of the sensor controls the 'descriptive resolution' (Mumby et al. 1997) or the classification system used for mapping. Thus, the classification system is always linked to the scale of the map. Descriptive resolution is hierarchical in nature. The level of information content represented through the classification system gets generalised as one moves from large to small scale. The hierarchical structure of classification scheme generally takes care of different user needs, technical expertise and remote sensing data sources.

Aerial photography with its longest history in coral reef remote sensing applications offers unparalleled usefulness towards baseline mapping and monitoring habitat and ecosystem level changes over time (Cochran 2013). Low and high altitude aerial photographs (astronauts' photographs from spacecraft like the Space Shuttle and International Space Station) have played a considerable role in studying earth's coral reefs. High-resolution mapping of shallow water coral reefs can well be achieved through an aerial flight at a height of 1,000 m or less (Spalding et al. 2001). As on date low altitude aerial photography remains one of the most successful remote sensing methods for providing synoptic data on live coral cover and coral colonies (Green et al. 2000; Mumby et al. 2004), and an altitude of 914 m has been considered optimal for the same (Green et al. 2000).

Coral reefs of Florida Keys, USA, have been mapped at a scale of 1:51,500 using natural colour aerial photographs acquired by the National Oceanic and Atmospheric Administration (NOAA) during 1991–1992 (FMRI 2000). The benthic habitat classification scheme for this study was developed with expert knowledge in ecology and local knowledge of the Florida Keys. This habitat classification scheme recognises 24 classes of benthic communities in four major habitat categories: corals, seagrasses, hard bottom and bare substrates. Benthic habitat mapping of the main Hawaiian Islands was also carried out with aerial photographs (supported with hyperspectral imageries) acquired by NOAA in 2000 at a scale of 1:24,000 (Coyne et al. 2003). The classification system developed for this study recognised a 'zone/habitat' approach and defined the benthic communities based on two major attributes, 'zones' and 'habitats' (Coyne et al. 2003). Zone refers to the location of the benthic community, while habitat indicates the substrate and/or cover type. Thus, each mapped polygon will have a habitat (i.e. the benthic community composition) within a zone (its location within a reef). This classification system included 11 mutually exclusive zones, four broad habitat classes and a number of subcategories, yielding 27 nonoverlapping, distinct habitat types (Coyne et al. 2003). This scheme remains flexible for users to expand or collapse the thematic detail to suit their mapping needs. In a more recent attempt, mapping of shallow water habitats and coral reef community characterisation has been carried out with aerial imageries acquired during March 2013 (Walker and Klug 2014). LiDAR bathymetry supported aerial imageries were analysed on GIS software to map the benthic habitats at 1:1,000 scale. The hierarchical classification scheme used in this study considered four broad habitat classes (coral reef and colonised hard bottom, unconsolidated sediment, seagrass and other delineations) and 12 subtypes.

Second to aerial photographs, multispectral satellite imageries have immensely contributed to reef habitat mapping at various scales for the past 40 years. Initially with the medium resolution (in tens of metres) multispectral sensors on-board Landsat series, SPOT and Indian Remote Sensing (IRS) series of satellites, coral reef habitat mapping flourished in the classical realms of reef geomorphology and community mapping at local to regional scales addressing diverse science and management issues. The year 1999 ushered in a new era of high-resolution, multispectral sensors with the launch of IKONOS multispectral sensor (4 m spatial resolution), while the launch of Landsat 7 Enhanced Thematic Mapper (ETM+) in the same year ensured an acquisition schedule specifically targeting coral reefs of the world (Yamano 2013). The new-generation, high-resolution sensors allow more detailed reef-scale mapping with high classification accuracy (Andréfouët et al. 2003). Coral reef habitat maps have gone much beyond the simplistic application of resource inventory. Today, these maps serve as a potential product for species-habitat correlation with more number of studies reporting correlation with reef fish parameters (Yamano 2013).

The largest-scale, global coverage coral reef habitat maps are currently available as digital products from the MCRMP of the US National Aeronautics and Space Administration (NASA). This project, launched in 2001, initiated a global compilation of Landsat 7 Enhanced Thematic Mapper (ETM+) (30 m resolution) satellite images of the global coral reefs. The MCRMP came up with a five-level hierarchical classification system for coral reef mapping solely based on coral reef geomorphology. The MCRMP classification system recognises coral reefs as continental or oceanic reefs as level 1, reef typology as level 2, gross reef-scale structure as level 3, geomorphological units (like fore reef, reef flat and enclosed lagoon) discernible on Landsat-7 ETM+ imageries as level 4 and level 5 combines the levels 1–4 attributes to give a final, combinatorial typology (Andréfouët et al. 2006; Hamylton and Andréfouët 2013). As a policy, MCRMP does not recognise any ecological or habitat classes in the five-level classification scheme due to high cost involvement for field data collection (Andréfouët et al. 2006).

23.4 Habitat Mapping Methods

Reef mapping approaches have co-evolved with the availability of airborne and space-borne sensors and imageries. Systematic visual interpretation of aerial photographs and fine-to-moderate spatial resolution satellite images remains one of the most successfully applied and widely validated reef mapping techniques until date (Phinn et al. 2012). Since the early 1970s, reef remote sensing in the digital domain has followed a conventional, 'sensor-down' approach where scene-specific image statistics guide the image classification (unsupervised and supervised) and interpretation (Hochberg et al. 2003). This sensor-down approach has been quite successful in characterising reef geomorphology and at times benthic community mapping which are mostly semi-quantitative in nature. Community scale mapping on the other hand has explored the potential of an alternate, deterministic 'reef-up' approach where the image classifier statistics are defined independently of an image dataset by the virtue of *in situ* spectral cataloguing. The benthic cover of the reef pixel is discerned through matching the spectral reflectance features as recorded in the field. This reef-up approach has been playing a strong, complementary role towards strengthening per-pixel classification and mapping potential from airborne and space-borne hyperspectral image datasets. However, with the application of hyperspectral image as an input for reef mapping, the scale changes from habitat to finer substrates or benthic covers/communities. Spectral analysis and radiative transfer modelling depend on a physics-based approach towards habitat mapping. This approach too produces fine-scale substrate or benthic cover map rather than habitat map. The major sources of calibration and validation data for reef habitat mapping remain GPS-tagged point or spot check data and photo and video transects together with field knowledge.

Object-based image analysis or OBIA approach (Blaschke 2010) is becoming popular in the domain of reef habitat mapping. This technique combines the visual interpretation cues with image segmentation rules and the classification process and produce output based on the multi-scale, environment-specific, expert knowledge. This technique provides a multi-scale or multilayer map of the reef environment where each layer corresponds to a specific feature scale (like geomorphic zones, benthic community, benthic patch or biotope) (Phinn et al. 2012).

Coral reef habitat maps are considered as *discrete maps* (Roelfsema and Phinn 2013) whose accuracies are generally derived through an error matrix. The error matrix tabulates the level of agreement for a pixel pertaining to a thematic class in the image-based map and the same location in the reference data. *Overall accuracy* is the most common accuracy measure that accompanies the habitat maps.

23.5 Reef Habitat Mapping of Andaman and Nicobar Islands: A Case Example

As a subset of Indian Ocean coral reefs, reefs of Andaman and Nicobar showed significant signs of change in the last decade. The episodic events of Indian Ocean earthquake and tsunami in 2004 interrupted the reef recovery process since the mass coral bleaching (MCB) event of 1998 (Tamelander and Rajasuriya 2008).

The Andaman and Nicobar Islands (ANIs) of India represent an island ecosystem characterised by unique coexistence of three distinct and diverse biomes of the earth, tropical rainforests, mangroves and coral reefs. Located in the southeast Bay of Bengal, within the limits of 6–14° north latitudes and 91–94° east longitudes, ANIs mark the southeastern limit of the Indian territory in the Indian Ocean. The north-south-oriented chain of the ANIs is considered as the surface expression of the submerged mountain range of Myanmar: the Arakan Yoma. The two distinct island groups, Andaman district in the north and Nicobar district in the south, are separated by a deep oceanic ridge located at 10° N latitude and the 160 km wide Ten Degree Channel. The ANIs consist of 572 islands, some of which are volcanic. Proximity to the equator, climatic characteristics and edaphic factors have proved ideal for flourishing rich natural ecosystems of terrestrial rainforests, coastal mangroves and coral reefs in this island group. Biogeographical proximity to insular Southeast Asia, holding one of the biodiversity hot spots in the world, has contributed to a significant biodiversity of these island ecosystems.

The Space Applications Centre (SAC) of the Indian Space Research Organisation (ISRO) has kept an eye on these critical marine habitats of India from the space right from the 1980s. Reef and reef habitat mapping has been carried out in routine priority for environmental conservation plans at different scales and levels (country level, regional level, etc.) using different remote sensing techniques and data processing methods (Nayak and Bahuguna 1997; Navalgund et al. 2010; Ajai et al. 2012; Bahuguna et al. 2013). The coral reefs of Andaman and Nicobar were initially mapped at 1:50,000 scale with IRS-1A Linear Imaging Self-Scanner (LISS) II, Landsat TM and SPOT MLA data for the period 1988–1991. SPOT MLA data was preferred for delineating the intra-reef zones with benthic (coral, macroalgae or seaweeds and seagrass) cover. The coral reefs were mapped on broad geomorphological classes as observed in the satellite data. The classification system was up to level 3 which included coral reef as level 1, reef geomorphological zones as level 2, and intra-reef zones with some signatures of benthic or litho-substrates, as identified on the image, as level 3. Accuracy of the maps varied between 79% and 89%

(at 90% confidence level). The total reef area as computed for ANI was 959.30 km^2 (Nayak and Bahuguna 1997).

After the Indian Ocean tsunami of 26 December 2004, coral reef habitats of ANI were again mapped as a subset of Central Indian Ocean reefs using Resourcesat-1 LISS III and LISS IV-MX sensor data pertaining to 2005–2006 period (Navalgund et al. 2010; Bahuguna et al. 2013). Selected Resourcesat-1 AWiFS and LISS scenes from 2004 depict their corresponding pre-tsunami condition. Following a comprehensive, four-level, eco-geomorphological classification system, each reef habitat map represents the reef typology (level 1), intra-reef geomorphic zones and subzones (levels 2 and 3) and ecological categories (level 4) (Navalgund et al. 2010; Bahuguna et al. 2013) in the form of an annotated, satellite image. The image interpretation followed a hybrid approach by combining image interpretation methods based on decision rules or interpretation keys developed for discerning the reef geomorphology elements, while benthic zones or ecological categories were understood with the additional help of spectral signature sets. The mapping was carried out at 1:50,000 scale with subsets digitally zoomed maximum up to 1:25,000 scale. The mapping method followed image segmentation and image interpretation approach for individual coral reefs, an approach similar to that of NASA's MCRMP. The reef unit is thematically interpreted essentially within the limits of seaward reef boundary and the landward high tide line (HTL). Associated coastal zone categories like island, beach, mudflat, mangrove and jetty are also indicated on the reef habitat maps. For 23 selected Andaman and seven Nicobar reef cases, the atlas depicted the reef-scale changes after tsunami with multi-sensor, multi-temporal data from Resourcesat-1. The total area occupied by the coral reefs in the ANI, as computed using Resourcesat-1 satellite data (2004–2006), is 998.6 and 53 km^2, respectively. These reefs are in a vulnerable condition (Navalgund et al. 2010; Bahuguna et al. 2013). A detailed appraisal on the ecological status of the Andaman and Nicobar coral reefs as mapped from 2004 to 2006 data is available in Bahuguna et al. (2013).

The Andaman and Nicobar reefs, as classic case of narrow, fringing reefs in coastal settings, pose a significant challenge to the viewing capabilities of space-borne passive sensors. Synchronisation of low-tide reef exposures (especially for coastal reefs) with optimal solar illumination under cloud-free conditions adds on to the natural constraints of reef imaging. The structural configuration of this reef type too contributes to this problem. The reef area viewed by the space-borne sensors is the two-dimensional surface area of the reef, exposed at the time of image capture. The third dimension (i.e. the underwater depth of the reef structure) is partially represented in the detectable reef slope area. However, on the planar surface, the reef slope also becomes a part of the two-dimensional reef habitat map.

If the objective of reef habitat mapping essentially remains identification and delineation of intra-reef geomorphic features and ecological categories, then along with reef area, the structural characteristics of reef type also needs to be considered. Fringing and atoll types of reefs are challenged with inherent property of 'constriction' or narrowness. For fringing reefs, the width (breadth) dimension becomes more important than its length for displaying intra-reef zonation. A wide fringing

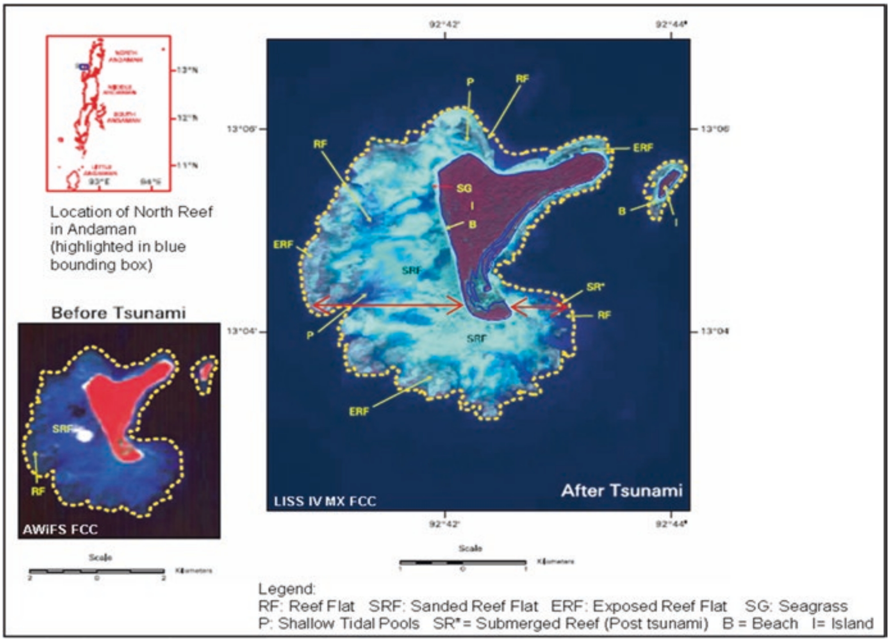


Fig. 23.2 Post-tsunami changes observed in the North Reef Island, Andaman, India (pre-tsunami image is Resourcesat-1 AWiFS FCC of 16 December 2004, post-tsunami image is LISS-IVMX FCC of 2 February 2005). The *red lines* indicate different widths of reef exposure on western and eastern sides of the reef

reef is expected to display more number of intra-reef geomorphic zones than a narrow fringing reef of the same length. This is illustrated in Fig. 23.2, the habitat map for the North Reef Island of Andaman. The relative width of this fringing reef is greater in the west than in the east. Accordingly, the number of reef zones identified with visual clarity is also more in the western part than on the east.

23.6 Habitat Mapping: Future Directions

Coral reef habitat mapping is an evolving field. Planning and management needs will continuously demand customised reef habitat maps at specified spatial scales. Till date, multispectral sensors remain one of the major operational remote sensing options to continuously provide habitat level mapping and monitoring capability over a long time (i.e. more than 40 years) and space (i.e. from reef scale to global coverage). With evolution of sensors, image processing and analysis techniques will also co-evolve and improve.

In the past four decades, conventional reef sensing has matured from simple detection and visual interpretation of reef features to complex reef habitat mapping using OBIA techniques. This approach has a continuous demand of high-(spatial) resolution, digital imaging with preferably high radiometry from different generations of passive, opto-imaging systems working in the visible and NIR (near infrared) part of the spectrum. The last decade has seen potential development and applicability of hyperspectral imaging and data analysis techniques to calibrate and validate the high-resolution, digitally enhanced and classified reef substrate maps with higher thematic accuracy. Space- and airborne hyperspectral remote (top-down) sensing and *in situ* (reef-up) sensing of coral reefs are strengthening the physics-based, optical algorithms to detect benthic substrates or assemblages with higher accuracy and comment on their physiological properties from remotely sensed data. Active in-water acoustic systems like single and multibeam echo sounders and side-scan SONAR (Sound Navigation and Ranging) are becoming popular as AGDS (Acoustic Ground Discrimination Systems) that will eventually fill the existing gap of reef-scale, shallow water bathymetry where passive, optical data often gets challenged with depth of sunlight penetration and water transparency issues. AGDS provide precise bathymetry as well as ground discrimination capability. Active, airborne, laser-based imaging systems like LiDAR (Light Detection and Ranging) and sounding systems like LADS (Laser Airborne Depth Sounder) are complementing high-resolution optical reef imaging with reef bathymetry and rugosity (surface roughness) information. Reef habitat mapping will continuously improve and evolve with synergistic use of these advanced imaging and sounding techniques in the future.

Acknowledgements The author thanks Director of the Space Applications Centre (SAC), ISRO and the Deputy Director of the Earth, Ocean, Atmosphere, Planetary Sciences and Applications Area (EPSA) for their overall guidance, encouragement and support to study coral reef ecosystems through various earth observation mission programmes. The author thanks the Group Head of the Biological and Planetary Sciences and Applications Group (BPSG)/EPSA for the encouragement and fruitful discussions. Head of the Environment and Hydrology Division (EHD)/BPSG is thanked for the support and encouragement. The author acknowledges with thanks Dr. Sushma Panigrahy, former Group Director, Agriculture, Terrestrial Biosphere and Hydrology Group, EPSA, SAC for inviting to contribute this chapter.

References

Ajai Nayak S, Tamilarasan V, Chauhan HB, Bahuguna A, Gupta C et al (2012) Coastal zones of India. Space Applications Centre (ISRO), Ahmedabad, p 597

Andréfouët S, Kramer P, Torres-Pulliza D, Joyce KE, Hochberg EJ, Garza-Pérez R et al (2003) Multi-site evaluation of IKONOS data for classification of tropical coral reef environments. Remote Sens Environ 88:128–143

Andréfouët S, Muller-Karger FE, Robinson JA, Kranenburg CJ, Torres-Pulliza D, Spraggins SA et al (2006) Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space. In: Proceedings of 10th International Coral Reef Symposium, Okinawa, Japan, 1732–1745

Bahuguna A, Ray Chaudhury N, Bhattji N, Ajaiand Navalgund RR (2013) Spatial inventory and ecological status of coral reefs of the Central Indian Ocean using Resourcesat-1. Ind J Mar Sci 42:684–696

Barbier EB, Koch EW, Silliman BR, Hacker SD, Wolanski E, Primavera J et al (2008) Coastal ecosystem-based management with nonlinear ecological functions and values. Science 319:321–323

Blaschke T (2010) Object based image analysis for remote sensing. J Photogramm Remote Sens 65:2–16

Buddemeier RW, Kleypas JA, Aronson RB (2004) Coral reefs and global climate change. Pew Center Global Climate Change Report, p 42

Burke L, Reyter K, Spalding M, Perry A (2011) Reefs at risk revisited. World Resources Institute, Washington, DC, p 114

Cochran SA (2013) Photography applications. In: Goodman JA, Purkis JS, Phinn SR (eds) Coral reef remote sensing. Springer, Dordrecht, pp 29–49

Coyne MS, Battista TA, Anderson M, Waddell J, Smith W, Jokiel P et al (2003) Benthic habitats of the main Hawaiian islands. NOAA, Silver Spring, p 48

CRTR Remote Sensing Working Group (2010) Directory of remote sensing applications for coral reef management. The University of Queensland, St Lucia, p 31

FMRI (2000) Benthic habitats of the Florida Keys. FMRI Technical Report 4, Florida Marine Research Institute, p 53

Franklin EC (2010) Marine landscape ecology of coral reefs emerges from developments in seafloor mapping, GPS and GIS. In: Joe Bremen (ed) Ocean globe, ESRI Press, Redlands, pp 193–204

Green EP, Mumby PJ, Edwards AJ, Clark CD (2000) Remote sensing handbook for tropical coastal management. Coastal management sourcebooks 3. UNESCO, Paris, p x+316

Hamylton S, Andréfouët S (2013) An appraisal of the extent and geomorphological diversity of the coral reefs of the United Kingdom dependent territories. In: Sheppard CRC (ed) Coral reefs of the United Kingdom overseas territories. Springer, Dordrecht, pp 1–11

Hochberg EJ, Atkinson MJ, Andréfouët S (2003) Spectral reflectance of coral reef bottom-types worldwide and implications for coral reef remote sensing. Remote Sens Environ 85:159–173

Kench P, Perry C, Spencer T (2009) Coral reefs. In: Slaymaker O, Spencer T, Embleton-Hamann C (eds) Geomorphology and global environmental change. Cambridge University Press, Cambridge, pp 180–213

Lesser MP (2011) Coral bleaching: causes and mechanisms. In: Dubinsky Z, Stambler N (eds) Coral reefs: an ecosystem in transition. Springer, Dordrecht, pp 405–419

McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environment and urbanization. Int Inst Environ Dev 19:17–37. doi:10.1177/0356247807076960

Mumby PJ, Green EP, Edwards AJ, Clark CD (1997) Coral reef habitat mapping: how much detail can remote sensing provide? Mar Biol 130:193–202

Mumby PJ, Hedley JD, Chisholm JRM, Clark CD, Jaubert J (2004) The cover of living and dead corals using airborne remote sensing. Coral Reefs 23:171–183

Navalgund RR, Ajai Bahuguna A, Ray Chaudhury N, Bhattji NS, Madhupriya N (2010) Coral reef atlas of the world, vol 1 Central Indian Ocean. Space Applications Centre (ISRO), Ahmedabad, p 282

Nayak SR, Bahuguna A (1997) Coral reef atlas of India. Space Applications Centre (ISRO), Ahmedabad, p 96

Phinn S, Joyce K, Scarth P, Roelfsema C (2006) The role of integrated information acquisition and management in the analysis of coastal ecosystem change. In: Richardson LL, LeDrew EF (eds) Remote sensing of aquatic coastal ecosystem processes. Springer, Dordrecht, pp 217–247

Phinn SR, Roelfsema CM, Mumby PJ (2012) Multi-scale, object-based image analysis for mapping geomorphic and ecological zones on coral reefs. Int J Remote Sens 33:3768–3797

Ramsar Convention Secretariat (2010) Wetlands inventory: a Ramsar framework for wetland inventory and ecological character description. Ramsar handbooks for the wise use of wetlands, 4th edn, vol 15. Gland, Switzerland

Roelfsema CM, Phinn SR (2013) Validation. In: Goodman JA, Purkis JS, Phinn SR (eds) Coral reef remote sensing. Springer, Dordrecht, pp 375–401

Silvestri S, Kershaw F (2010) Framing the flow: innovative approaches to understand, protect and value ecosystem services across linked habitats. UNEP World Conservation Monitoring Centre, Cambridge, p 62DEW/1243/CA

Spalding MD, Ravilious C, Green EP (2001) World atlas of coral reefs. University of California Press, Berkeley, p 424

Tamelander J, Rajasuriya A (2008) Status of coral reefs in South Asia: Bangladesh, Chagos, India, Maldives and Sri Lanka. In: Wilkinson C (ed) Status of coral reefs of the world: 2008. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, pp 119–130

Walker BK, Klug K (2014) South-east Florida shallow-water habitat mapping and coral reef community characterization. Florida DEP Coral Reef Conservation Program report, Miami Beach, p 83

Wilkinson C (ed) (2008) Status of coral reefs of the world: 2008. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, p 296

Yamano H (2013) Multispectral applications. In: Goodman JA, Purkis JS, Phinn SR (eds) Coral reef remote sensing. Springer, Dordrecht, pp 51–78

24 Modeling Systems and Processes in Wetlands: A Case Study of Engineered Bioremediation of BTEX-Contaminated Water in Treatment Wetlands

Shreejita Basu, Brijesh Kumar Yadav, and Shashi Mathur

Abstract

A number of pollutants are released to the soil-water systems due to various anthropogenic activities. One of the most environmentally benign treatment options of such pollutants is bioremediation. Since natural bioremediation is quite slow, engineered bioremediation techniques like bio-stimulation and bio-augmentation could be used in treatment wetlands (TWs) for hastening the cleaning process. In this chapter, the enhanced bioremediation techniques and the role of plants in the treatment wetlands are discussed. The empirical equations used to evaluate the wetland performance are described next. Subsequently, the governing mass balance equations and the relevant degradation kinetics used for mechanistic modeling of the fate and transport of these contaminants in the rhizosphere zone are discussed. At the end, case studies of batch experiments and pot-scale treatment wetlands are included for practical understanding of the engineered bioremediation process using treatment wetlands.

Keywords

BTEX degradation • Engineered bioremediation • Mechanistic modeling • Polluted soil-water resources • Treatment wetlands

S. Basu (✉) • S. Mathur
Department of Civil Engineering, IIT Delhi, New Delhi, India
e-mail: shreejita.basu@gmail.com

B.K. Yadav
Department of Hydrology, IIT Roorkee, Roorkee, India

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_24

24.1 Soil-Water Pollution

Over several decades, a huge number of polluting chemicals such as total petroleum hydrocarbons (TPH), polychlorinated biphenyl (PCBs), polycyclic aromatic hydrocarbons (PAHs), heavy metals, and pesticides, which pose potential threats to human health, are released in the environment. As a result, the major constituents of the hydrological system (soil, surface, and groundwater) are the ultimate sinks for such toxic pollutants. This is due to the various anthropogenic activities like accidental spillage in industries, leaks from underground storage tanks, agricultural practices, and poor waste disposal in landfills. Consequently, chemical, biological, and physical properties of these natural resources have been altered, resulting in the continuous loss of soil-water functions in sustaining living organisms. Large-scale production, transport, use, and disposal of petroleum have made it as one of the leading contaminants in the subsurface. The petroleum products are typically multicomponent organic mixtures composed of chemicals with varying degrees of water solubility. It is of significant concern since these contaminants exist in separate phases in soil-water systems that pose a long-term threat to the down-gradient receptors. When small volumes of these contaminants are released, it may be entirely trapped in the vadose zone. If a greater volume is released, it may move through the unsaturated zone and develop a "smear zone" near the capillary fringe (Lahvis et al. 1999). The constituents can dissolve into groundwater, adsorb onto aquifer sediments, volatilize and diffuse through the unsaturated zone, or undergo natural bioremediation.

In order to treat polluted soil-water resources, many in situ and ex situ remediation techniques have been developed. Out of these techniques, bioremediation is the most cost-effective and feasible under a broad range of environmental conditions (Yadav and Hassanizadeh 2011). The new emergent bioremediation is "enhanced bioremediation" which is achieved by either addition of nutrients or bacterial strain to the polluted site. Also in recent years, enhanced bioremediation in the presence of plants using treatment wetlands has shown promising results. A plant-enhanced bioremediation technique that combines the remediation potential of plants and their associated microorganisms is the natural or constructed treatment wetland. The problem with natural wetlands is large variability in functional components, whereas constructed or treatment wetlands can be built with a higher order of control. Treatment wetlands (TWs) are widely used for secondary treatment of wastewater containing organic pollutants using different plant species and flow patterns. The TWs can be designed as shallow ecosystems to mobilize biological, chemical, and physical processes that can treat contaminated soil-water.

24.2 Remediation Techniques

Remediation techniques degrade xenobiotic compounds depending upon their properties. The most common organic contaminants in groundwater include aromatic hydrocarbons, pesticides, and chlorinated compounds (Alvarez and Illman 2006).

Table 24.1 Physicochemical properties of BTEX compounds

Properties	Benzene	Toluene	Ethylbenzene	o,m,p-xylene
Molecular weight (g/mol)	78	92	106	106
Water solubility (mg/L) at 25 °C	1780	535	152	175, 135, 198
Liquid density(g/cm^3) at 20 °C	0.88	0.87	0.87	0.88, 0.88, 0.86
Henry's constant at 25 °C	0.2219	0.2428	0.345	0.2084, 0.3139, 0.3139
Log (K_{ow})	2.15	2.80	3.26	3.12, 3.37, 3.29

Heavy metals are transformed to other species by physical, chemical, or biological means and unlike organic compounds cannot be degraded or destroyed. Petroleum hydrocarbons are classified as light and dense nonaqueous phase liquids (LNAPL and DNAPL, respectively) as per their relative density. An example of LNAPL is BTEX (benzene, toluene, ethylbenzene, xylene), a common contaminant in the environment. Some of the physicochemical properties of BTEX compounds are given in Table 24.1. Though BTEX are immiscible with water, their solubility is several orders of magnitude higher than the permissible level for drinking water. The maximum permissible levels for these mono-aromatic compounds in potable water are 0.05, 1, 0.7, and 10 ppm for benzene, toluene, ethylbenzene, and isomers of xylenes, respectively (USEPA 2006). Owing to the harmful health effects of BTEX compounds even at low levels of concentration, it is inevitable to look for environment-friendly remediation options.

The removal of BTEX from soil-water systems can be done by chemical methods like use of dispersants, chemical oxidation, and photocatalysis (Mascolo et al. 2008). Physical techniques like physical containment, booming and skimming, mechanical removal, water flushing and sediment relocation, electro-remediation, air sparging, carbon adsorption, filtration, and adsorption by zeolites are also used (Zhu et al. 2004). The physical and chemical treatment of these hydrocarbons is usually expensive and harmful to the indigenous biota. The other promising and environmentally benign technique is bioremediation that causes no harm to the contaminated ecosystem. Bioremediation has been applied to clean up spills of petroleum products under a broad range of environmental conditions, soil and groundwater systems, marine shorelines, and surface water. Since the natural attenuation of these compounds is quite slow, the microbial population and their environmental conditions are technically modified for hastening the process of biodegradation.

24.2.1 Bio-stimulation and Bio-augmentation

The bio-stimulation is accomplished by addition of nutrients, electron acceptors, and other compounds to the contaminated soil-water system, which affects the metabolic activities of the relevant degraders. The bio-augmentation is another technique for improving the capacity of a contaminated matrix by addition of specialized microbial cultures, which are grown separately under well-defined conditions.

Depending on the site conditions, the responses of bio-stimulation and bio-augmentation toward degradation of hydrocarbons are a mix of success and failure. It has been shown by researchers that bio-augmentation in the field is not a convincing method to enhance the biodegradation of oil in open environment (Zhu et al. 2004). The relationship of the inoculated microorganism with its new biotic and abiotic environments, in terms of survival, activity, and migration, can be decisive in the outcome of any bio-augmentation strategy (El Fantroussi and Agathos 2005).

On the other hand, bio-stimulation is a more robust technique for aerobic degradation of hydrocarbons in polluted sites (Venosa et al. 2002). In most situations, the spilled petroleum hydrocarbons at a site provide a substantial carbon source for the native microbial population, but sometimes nutrients like nitrogen and phosphorus become limiting. In such cases, bio-stimulation can accelerate the degradation rate (Nikolopoulou and Kalogerakis 2009). Many studies have compared the performance of bio-augmentation and bio-stimulation and found that nutrient addition alone is more effective than adding microbial strains (Jobson et al. 1974). For many applications, it becomes difficult to determine whether bio-augmentation has a significant edge over bio-stimulation or vice versa. Thus, there is a need for site-specific studies on bioremediation at a hastened rate using bio-augmentation and bio-stimulation either separately or together. Many hydrocarbons in soil-water have been remediated using plants as natural stimulants. Research has proven that the use of plants can provide a multi-synchronous environment for enhanced bioremediation of organic contaminants in soil-water systems. Some of these articles have documented various processes on the role of plants in remediating and restoring contaminated soil and groundwater (Shimp et al. 1993; Schnoor et al. 1995; Yadav et al. 2013).

24.2.2 Plant-Enhanced Bioremediation

Plants play an important role when it comes to cost-effective remediation technique (Yadav and Hassanizadeh 2011). Plants can take up pollutants in their roots, which get accumulated, metabolized, or volatilized, or the rhizosphere microflora around the plant roots may accelerate the biodegradation of the pollutant (Basu et al. 2015). Yadav et al. (2011) verified the fact that the rhizospheric zone is a suitable location with diverse group of microorganisms, to have significantly large number of microorganisms as compared to unplanted soils. Jordahl et al. (1997) found that the populations of benzene-, toluene-, and xylene-degrading microorganisms in the rhizosphere of *Populus* trees were five times more than that observed in barren contaminated soil. In addition, roots increase diffusion of oxygen that ultimately enhance the biodegradation of BTEX-polluted root zone system. The microbial consortia present in the rhizospheric zone degrade a part of the contaminants before taken up by roots. Thus, the rhizospheric zone acts as an active and relatively favorable in situ bioreactor for the growth of microbes, which transform the contaminants into nontoxic daughter products. The plants promote microbial degradation by providing optimum conditions and basic nutrients, using root exudates like

Table 24.2 Some examples of remediation potential of hydrocarbons by plants

Plants	Xenobiotic	Removal process	References
Phragmites australis	Benzene	Vertical flow CW	Tang et al. (2009)
Salix sp., *Phragmites* sp., *Scirpus* sp., *Juncus* sp., *Cornus* sp.	BTEX	Pilot system upward flow, CW sand/gravel	Bedessem et al. (2007)
Scirpus cyperinus, *Juncus effusus*, *Carex lurida*, *Typha latifolia*	BTEX	Constructed wetland	Niell and Nzengung (2004)
Hybrid *Populus* trees	12 organics including BTEX	Hydroponic system	Burken and Schnoor (1999)
Alfalfa	Toluene	Laboratory chamber with two U-shaped channels	Narayanan et al. (1998a)
Salix babylonica	Ethanol and benzene	Hydroponic system	Corseuil and Moreno (2001)

short-chain organic acids, amino acids, and sugars which support a variety of aerobic and anaerobic microorganisms (Williams 2002). Plants also control the infiltration of contaminants from surface leakages and their movement into groundwater aquifers.

Thus, plants can be used in treatment wetlands to degrade contaminant loads. Table 24.2 gives some examples from the literature where various plant species have been used in different types of wetlands to remediate hydrocarbons. The organic contaminant load undergoes several elimination pathways in a treatment wetland. The main processes as listed by Kadlec (1992) are volatilization, photochemical oxidation, biodegradation, sedimentation, and sorption. Salmon et al. (1998), Wemple and Hendricks (2000), Ji et al. (2002), Omari et al. (2003), and Gessner et al. (2005) reported petroleum hydrocarbon removal by constructed wetland. The efficiency of phytoremediation depends on the type of plant species and soil and water properties along with the physical and chemical properties of the contaminant. Ranieri et al. (2013) used different macrophytes like *Phragmites australis* and *Typha latifolia* to remove BTEX using constructed wetlands (CWs). They found the average removal using *P. australis* was 5% higher than *T. latifolia* and 23% higher than unplanted field. Field studies done by Moore et al. (2002) revealed that natural attenuation of BTEX in wetland is by processes like sorption, aerobic and anaerobic biodegradation, and volatilization. Researchers have used *Canna generalis* for phytoextraction of Pb and removal of Cd from soil (Prasad and Freitas 2003). *Canna indica* has been used in CWs to absorb Cd, Zn, and Ni from sludge (Lin et al. 2010) and 30% of total nitrogen (Cui et al. 2010). *Canna* hybrid “Yellow King Humbert” has the capability to remediate pesticide triazophos (Cheng et al. 2007). In wetlands, oxygen is produced through photosynthesis and is transferred from the leaves to the roots of plants by processes of diffusion and convection (Armstrong and Armstrong 1991; Grosse et al. 1991; Ottová et al. 1997). This forms an aerobic microenvironment, which in turn supports the decomposition reactions of root microorganisms. The bioremediation potential in the wetlands results from the rhizospheric and endophytic microorganisms associated with the plants.

24.3 Treatment Wetlands (TWs): Principles and Types

The TWs are traditionally seen as black boxes where the contaminated water enters and treated water leaves the system. However, in recent years, emphasis is given to understand the different physical, biological, and chemical processes occurring in the wetlands. These TWs comprise of water, solutes, plants, and various microbes that create optimum conditions for removing the pollutants. The bioremediation potential in the wetlands results from rhizospheric and endophytic microorganisms associated with the plants. These microbes use the contaminant as a carbon source or energy source for growth and secondary substrate in co-metabolic pathways. The plants promote microbial degradation by providing suitable conditions and root exudates like short-chain organic acids, amino acids, and sugars that support a variety of aerobic and anaerobic microorganisms (Williams 2002). The basic classification of wetlands is based on the type of macrophytic (plants) growth and further bifurcated based on the water flow regime. The type of wetlands with plants includes free-floating, floating-leaved, emergent, and submerged plants like common reed (*P. australis*), cattail (*Typha* sp.), or soft rush (*Juncus* sp.) growing on gravel, on sediment, or in hydroponic solution. The TWs are mainly divided into surface flow (SF) and subsurface flow (SSF) wetlands. The SF wetlands have water usually less than 0.4 m depth and are densely vegetated. These wetlands are further subdivided into horizontal flow (HF) and vertical flow (VF) types based on the direction of the water flow through the porous media (Langergraber 2008). The polluted water flows horizontally (i.e., the inlet and outlet placed horizontally opposite) through the artificial filter bed of porous media, which usually consists of a matrix of sand or gravel and the aquatic macrophytes, roots, and rhizomes. In VF type, water is added intermittently to prevent flooding. The water infiltrates into the substrate and then gradually drains down vertically before collecting in a drainage network at the base (Langergraber and Haberl 2001).

24.3.1 Surface Flow (SF) System

These wetlands mimic the natural wetlands and are known as the free water surface (FWS) wetlands. It usually consists of a shallow basin or channel with a barrier to prevent the seepage or other media to support the roots of emergent plant species. In this type, the water is flooded from the top and infiltrates through the soil surface or exposed for evaporation. The SF wetlands are like ponds or lagoons with dense vegetation (Vymazal 2005) where mostly anaerobic processes dominate at deeper sites. Surface autotrophic zone is dominated by planktonic or filamentous algae or by floating or submerged aquatic macrophytes in such types of wetlands (Kadlec 2000).

24.3.2 Subsurface Flow System

The SSF wetland technology was suggested by Seidel (1967). It uses a bed of gravel or soil. In SSF wetlands, the wastewater flows through constructed media bed planted with wetland plants (USEPA 1993). Here the contaminated water enters through an inlet and passes below ground surface, through the root and shoot zone of plants until it meets the outlet collection system. An SSF wetland combines aerobic, anoxic, and anaerobic zones. In SSF wetlands, the energy losses by evaporation and convection are minimized, as the water is not exposed during the treatment. SSF wetlands have better treatment efficiencies over a smaller land area as compared to SF wetlands.

The two types of SSF wetlands have similar removal mechanisms but different hydraulics. The schematic diagram in Figs. 24.1 and 24.2 shows the two types. The horizontal flow wetlands are made in such a way that the water flows in a horizontal direction with the inlet at one end and the outlet at the opposite end. These wetlands are commonly sealed with an impervious liner to prevent seepage and to ensure the controlled outflow. In the VF wetlands, water surface floods to a depth of several centimeters then slowly percolates downwards through the porous media collected by a drainage network at the bottom. The bed drains completely, which allows air to refill the bed. This enables oxygen to enter the wetland. The VF wetlands have gained more popularity than HF systems as they have higher oxygen transfer and good nitrification over a smaller area (Cooper 1999; USEPA 2000). In addition, there are variations of the VF wetlands like with upflow or downflow. The hybrid system consists of combinations of different horizontal or vertical flow wetlands.

The major pathways for the removal of hydrocarbons via CWs are volatilization and microbial degradation; others are photochemical oxidation, sedimentation,

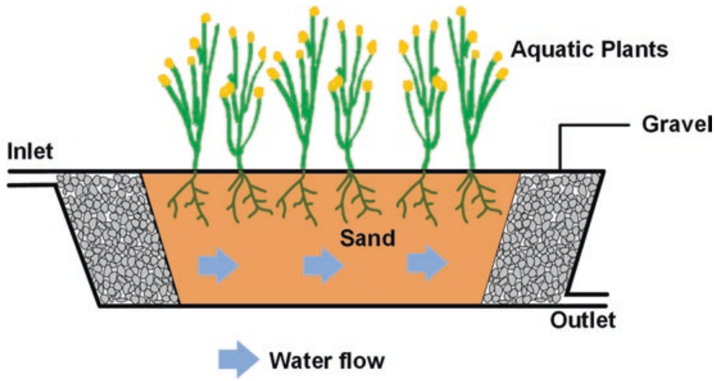


Fig. 24.1 Schematic representation of horizontal flow (*HF*) constructed wetland

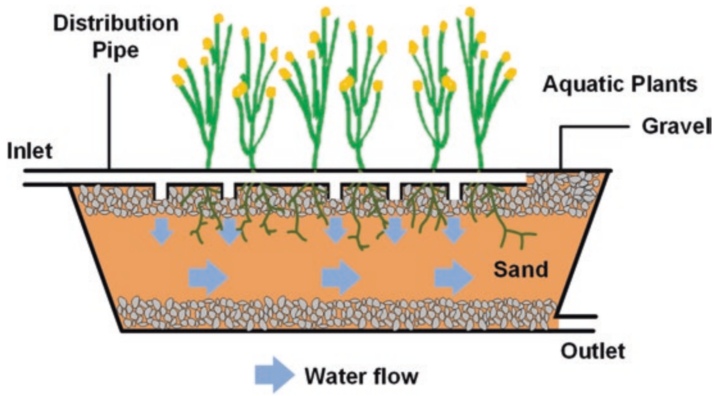


Fig. 24.2 Schematic representation of vertical flow (*VF*) constructed wetland

sorption, chemical precipitation, and filtration. Petroleum wastewater is documented to degrade in natural wetland systems (Wemple and Hendricks 2000; Wallace and Knight 2006). Since the rates of degradation of hydrocarbons are more rapid in the aerobic environments, CWs with maximum oxygen transfer capacity will be the most suitable for treatment.

Although there is a vast literature on construction and operation of constructed and treatment wetlands, it is still difficult to evaluate their performance. This is because the degradation of contaminants occurs through a series of complex physical, chemical, and biological processes simultaneously. This problem can be solved by identifying the major removal processes and validating the results with the help of numerical modeling (Llorens et al. 2011a, b).

24.4 Removal Processes in Treatment Wetland

Organic contaminants like hydrocarbons are often broken down into daughter products or mineralized into carbon dioxide and water. The beneficial effects of the vegetation in treatment wetlands for remediating recalcitrant hydrocarbons like BTEX are many. The contaminant load undergoes several removal processes in the treatment wetland as shown in Fig. 24.3. The main processes are listed below:

- *Phytodegradation*: Plant enzymes break down organic pollutants via phytodegradation or phytotransformation.
- *Phytoextraction*: Removed pollutants are accumulated in tissues and harvested from aboveground plant biomass such as shoots.
- *Phytovolatilization*: Transforms pollutants into volatile forms which are released to the atmosphere.

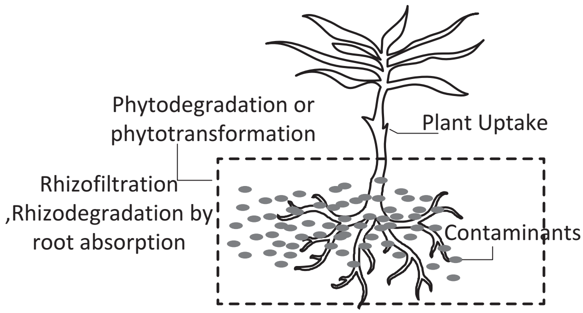


Fig. 24.3 Schematic diagram showing the plant-assisted bioremediation mechanisms

- *Rhizodegradation/phytostimulation*: Refers to the breakdown of pollutants by using plant-microbe interactions in which root exudates play an important role in stimulating microbial communities or specific enzymes.

One of the important parameters to predict the uptake in plants from soil-water systems is octanol-water partition coefficient (*Kow*), usually expressed in the log scale (Cunningham and Berti 1993). Hydrophobic compounds with *log(Kow)* values between 1.0 and 3.5 can translocate from roots to shoots effectively (Schnoor et al. 1995). BTEX compounds have *log(Kow)* values varying between 2.13 and 3.20 (Table 24.1). The uptake of BTEX by plants can be quantified using the relationship developed for translocation into roots and shoots (Briggs et al. 1982). The uptake is rapid until the system reaches equilibrium. The root concentration factor (RCF) is applied to analyze the comparative solute mass in root biomass to the growing solution that is expressed as Eq. 24.1:

$$RCF = \frac{\text{Concentration in roots}\left(mg\,/\,\mathrm{L}\right)}{\text{Concentration in solution}\left(mg\,/\,\mathrm{L}\right)} \tag{24.1}$$

Similarly, the transpiration concentration stream factor (TCSF) is popularly used to quantify the solute mass in shoot biomass as compared to roots (Trapp 2000) (Eq. 24.2):

$$\mathrm{TCSF} = \frac{\text{Amount in shoots}\left(mg\,/\,\mathrm{L}\right)}{\text{Conc.in solution}\left(mg\,/\,\mathrm{L}\right) * \text{Transpired vol.of water}\left(\mathrm{L}\right)} \tag{24.2}$$

The two broad categories of models to describe the solute uptake by plant root biomass are (1) empirical and (2) mechanistic. The empirical approach correlates the solute concentration in media with that in plant biomass using plant uptake factor (Yerokun and Christenson 1990). In such models, the contaminant concentration in plant biomass and soil is assumed to be at equilibrium without considering the exposure time. Further, such a relationship is only valid for a narrow range of contaminant concentration (Carlson and Bazzaz 1977), and thus the empirical approach does not represent contaminant behavior under site-specific conditions. Mechanistic approach simulates solute uptake using uptake kinetics by roots. Based on the solute uptake parameters considered, these methods can be further subdivided (Mathur and Yadav 2009) into (1) active and (2) passive uptakes. Most of the organic contaminants follow a passive diffusive process at low concentrations (Bromilow and Chamberlain 1995).

24.5 Models Used for Treatment Wetlands

The modeling techniques are mostly used for understanding and evaluating the various processes involved in treatment of pollutants in wetlands. Most of the models developed for CWs are relevant to HF CWs and refer to simple first-order decay models. These models depend on the data of input and output concentrations (Rousseau et al. 2004), and the treatment process is treated as if in a black box (Fig. 24.4) because interactions among soil, vegetation, water, and microorganisms are not separately considered in simulations (Toscano et al. 2006). The mechanistic or process-based models are complicated and describe any one or in combination of (1) hydraulic behavior and single solute transport models, (2) reactive transport in saturated conditions, and (3) reactive transport models for variably saturated conditions.

The first class of models are analytical with closed form equations. The derivation is based on laws governing water flow and solute transport. Let us consider the contaminant mass balance in an elementary root zone layer of Δz thickness shown in Fig. 24.5. The contaminant influx into the layer is denoted by $J(z)$ (mg per unit area per unit time) [$ML^{-2}S^{-1}$] and outflux from the layer is $J(z+\Delta z)$. SC is the sink term denoting amount of solute taken up by plant roots and degradation of contaminant by microbial biomass [$ML^{-3}S^{-1}$]. Then, the change in total contaminant concentration Ct over time t can be written as

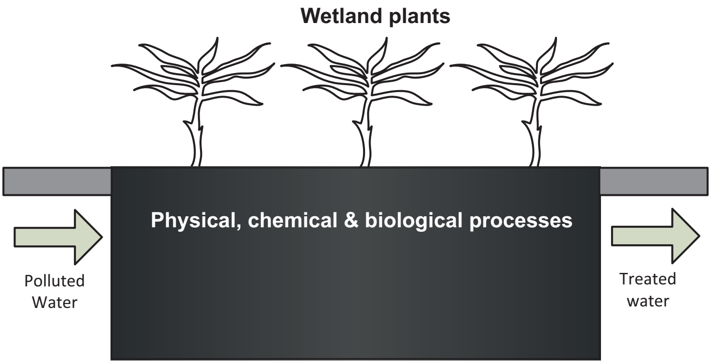


Fig. 24.4 Schematic representation of constructed wetland used for deducing empirical equations based on observed input and output concentration of the target pollutant

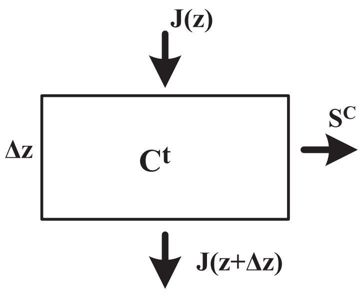


Fig. 24.5 Diagram showing contaminant flux

$$\frac{\partial C^T}{\partial t} = \frac{J(z) - J(z + \Delta z)}{\Delta z} - S_C \tag{24.3}$$

Expressing Eq. 24.3 as partial derivatives, we can write Eq. 24.4:

$$\frac{\partial C^T}{\partial t} = -\frac{\partial J}{\partial z} - S_C \tag{24.4}$$

Here, the total contaminant concentration in soil volume (*Ct*) is the sum of contaminant in the soil solution and the contaminant adsorbed on porous media and expressed as

$$C^T = \theta . C + \rho_S S_D \tag{24.5}$$

Here, *C* is the contaminant concentration in the soil solution (mg per unit volume of soil solution) [ML^{-3}], θ is the volumetric moisture content [L^3L^{-3}], ρS is the bulk density of the porous media [ML^{-3}], and *SD* is the contaminant adsorbed to the porous media [MM^{-1}].

The total flux J in Eq. 24.3 includes the change in the contaminant concentration due to advection, dispersion, and diffusion and is as given below:

$$J = J_{adv} + J_{dis} + J_{\text{diff}} \tag{24.6}$$

where *Jadv*, *Jdis*, and *Jdiff* are the advective, dispersive, and diffusive fluxes, respectively.

Advective Flux Advection causes the contaminant to move due to the velocity of the flow and hence the advective flux is given as

$$J_{adv} = v\theta C = qC \tag{24.7}$$

where *v* is the pore water velocity [LT^{-1}], *q* is the soil-water flux [LT^{-1}], and θ is the volumetric moisture content.

Diffusive Flux Diffusion is mathematically described by Fick's law that states that the net rate of contaminant transport is proportional to the negative gradient of its concentration and can be modified for unsaturated porous medium as

$$J_{\text{diff}} = -\tau D_O \theta \frac{\partial c}{\partial z} = -D_m \theta \frac{\partial c}{\partial z} \quad (24.8)$$

where τ is the tortuosity factor (dimensionless) which accounts for the increased distance of transport due to tortuous path of the solute particle in a porous media. *Do* and *Dm* are the free water diffusivity and molecular diffusion coefficients, respectively [L^2T^{-1}].

Dispersive Flux The dispersion at a microscopic scale occurs due to the variation of velocity within the pores and due to the tortuous movement of the fluid around the soil grains. Macroscopic dispersion refers to the dispersion resulting from the interfingering of materials of different permeability. Mechanical dispersion is mathematically described in the same way as molecular diffusion by using the Fick's law as

$$J_{dis} = -\alpha_L v \frac{\partial C}{\partial z} = -\alpha_L \frac{q}{\theta} \frac{\partial C}{\partial z} \quad (24.9)$$

where αL is the longitudinal dispersivity of the porous media in the direction of flow [L] and v is the pore velocity.

Now by adding all the abovementioned fluxes, we get the resultant flux as in Eq. 24.10:

$$J = J_{adv} + J_{dis} + J_{diff} = qC - D\theta \frac{\partial C}{\partial z} \quad (24.10)$$

where $D = \tau D_O + \alpha_L \frac{q}{\theta} = \tau D_O + \alpha_L v$

Here, D is the diffusion-dispersion or hydrodynamic dispersion coefficient, which is the pore water velocity-dependent function [L^2T^{-1}].

The modified form of advection-dispersion (Eq. 24.11) is obtained by substituting Eqs. 24.4 and 24.5 into Eq. 24.10:

$$\frac{\partial\left(\theta c + \rho_b s\right)}{\partial t} = -\frac{\partial}{\partial z}\left(qC - \theta D \frac{\partial C}{\partial z}\right) - S_C \quad (24.11)$$

Different degradation kinetic models can be used to determine the rate of degradation of hydrocarbons like BTEX. These can be constant or zero-order, linear or first-order, and Monod or Michaelis-Menten. In zero-order kinetics, the rate of depletion of contaminant is taken as a constant irrespective of the contaminant concentration in soil-water at a particular time. The first-order or linear kinetic model assumes the rate of contaminant degradation proportional to the BTEX concentration at a particular time. This kinetics is often appropriate for simulating NAPL biodegradation in aquifers (Seagren et al. 1994) due to mass transfer limitation during contaminant diffusion from soil-water to microbes that are mostly attached to the aquifer solids (Alvarez and Illman 2006). The most popular kinetics for characterizing BTEX biodegradation is the hyperbolic equation proposed by Monod

(1949) and referred as Monod or Michaelis-Menten kinetics. The Monod kinetics can describe degradation rates ranging from zero-order to the first-order kinetics with respect to the target contaminant concentration. Therefore, it is also termed as a biphasic kinetic model. A general expression of hydrocarbon depletion in soil, in which only microbial densities and the contaminant concentration determine the degradation kinetics, can be written as (Lyman et al. 1992)

$$-\frac{\partial C}{\partial t} = \mu_{\max} C \frac{\left(C_O + X_O - C\right)}{\left(K_S + C\right)} \tag{24.12}$$

where $\mu_{\max}$ is the maximum growth rate, C is the contaminant concentration at time t, $C0$ is the initial contaminant concentration, $X0$ corresponds to the contaminant required to produce initial microbial density, and Ks is the half-saturation constant also known as growth-limiting concentration. The above equation reflects a linear relationship of changes in microbial density as well as nonlinear relationship of changes in contaminant concentration on the rate of contaminant degradation. Furthermore, different simplified degradation kinetic models can be approximated considering extreme ratios of initial contaminant concentration ($C0$) to Ks or initial microbial densities ($X0$) to $C0$ in Eq. 24.12 and are listed in Table 24.3 (Yadav et al. 2011).

The drawback in simple transport and first-order decay models is that the validity of the results is limited to situations where the underlying assumptions hold. Such models are generally not suitable to model reactive and degradation processes in wetlands (Kadlec 2003), and simplified models are often useful tools for evaluating water flow and transport of inert solutes. Rousseau et al. (2004) gave a comprehensive and critical review of the first-order rate constants for horizontal subsurface flow (HSSF) constructed treatment wetlands. Thus, mechanistic models consider the hydrodynamic and the biodegradation processes occurring in CW systems and, at the same time, account for a larger range of sources of wastewater.

Of the simple empirical models, regression analysis provides useful information about relationships between input and output concentrations but the equations are valid only for the data used to model them (Kumar and Zhao 2011). It is known that

Table 24.3 Various kinetic models for degradation of BTEX compounds in soil-water systems

Kinetic model	Condition	Equation	Rate constant
Zero order	$X_0 \gg C_0, C_0 \gg K_S$	$-\frac{\partial C}{\partial t} = k_0$	$k_0 = \mu_{\max} X_0$
First order	$X_0 \gg C_0, K_S \gg C_0$	$-\frac{\partial C}{\partial t} = k_1 C$	$k_1 = \mu_{\max} \frac{X_0}{K_S}$
Monod or Michaelis-Menten	$X_0 \gg C_0$	$-\frac{\partial C}{\partial t} = k_m C\left(K_S + C\right)$	$k_m = \mu_{\max} X_0$

the initial concentration in the wetland is assumed constant in most first-order modeling efforts. However, in reality, the initial concentrations in the wetland may exhibit spatial variability (Uddameri 2010). Tank-in-series model (TISM) partitions the wetland into smaller reactors, which causes distribution of detention times. The number of tanks in the TISM shows the degree of mixing. A high value of N means a small degree of dispersion and therefore indicates a plug flow reactor. If $N = 1$, then a single combined stirred-tank reactor (CSTR) is defined. The biphasic Monod model represents the transition from first to zero order, and the degradation rates of the pollutants are limited by their availability at relatively low pollutant concentration and saturated at relatively high concentration (Mitchell and McNevin 2001). The retardation model is the best to design CWs since it allows a steady-state decrease in the components (Kumar and Zhao 2011). There are many reaction rate constants reported in the literature for different types of CWs and different experimental setups and conditions. Thus, it is difficult to conclude a unique "k" value from the data. Thus, there numerical models with more complexities are required to help in understanding the process in CWs. This can be done using process-based models that give a holistic insight into the "black box."

Process-based models such as FITOVERT are used for VSSF-CW in saturated and unsaturated conditions. HYDRUS is a software tool in which CW2D module has been added to model the transport and reactions of pollutants (Toscano et al. 2006). More mathematics-based software STELLA is used for nonlinear dynamic systems in CWs. A new module for an existing coupled flow and reactive transport code PHWAT was implemented. To evaluate the relative contribution of various microbial reactions to remove organic matter in HSSF-CW, Ojeda et al. (2008) used a two-dimensional (2D) mechanistic mathematical model. Langergraber et al. (2009) gave a general biokinetic model to predict biochemical transformation and degradation processes for nitrogen and organic matter in SSF CWs. Constructed wetland model no. 1 (CWM1) utilizes the biokinetic processes in HF- and VF-CWs, and the main objective is to simulate the effluent concentration. Thus, while the black box category models fail to explain the internal process mechanisms, the process-based numerical models like FITOVERT, CW2D, STELLA PHWAT, 2D mechanistic model, and CWM1 modeling software's/simulation tool can be used to explain the processes' equations in a better way. Tables 24.4 and 24.5 summarize all the current CW models.

Statistical modeling techniques like multiple regression models, clustering tree diagrams, regression trees (CHAID), and redundancy analysis (RDA) have been applied by Hijosa-Valsero et al. (2011) to study the removal of organic matter and pharmaceuticals in urban wastewater by means of CWs. Also Stein et al. (2006) applied two statistical techniques known as Levenberg-Marquardt method and nonlinear mixed effects to fit the k-C* model to data set consisting of 192 time series COD concentrations measured from batch-loaded SSF wetlands. Sun and Saeed (2009) examined the accuracy of four design approaches including Monod kinetics, first-order kinetics, CSTR, and plug flow (PF) patterns using three statistical parameters (coefficient of determination, relative root mean square, and model efficiency)

Table 24.4 Summary of the empirical models used in treatment wetlands

No.	Types	Equation	References
1.	Regression	$C_{out} = aC_{in}^{b} q^{c}$	Stone et al. (2002)
2.	First order	$\frac{C_{out}}{C_{in}} = e^{\frac{k_A}{q}}$	Kadlec (2000)
3.	Time-dependent retardation	$k_v = \frac{K_O}{b\tau + 1}$	Shepherd et al. (2001)
4.	Tank-in-series	$\frac{C_{out}}{C_{in}} = \frac{1}{(1 + k_{VRC} t / N)^N}$	Kadlec (2003)
5.	Monod	$r = k_{o,v} V \frac{C}{K_{HSC} + C}$	Mitchell and McNevin (2001)
6.	Neural networks	$R_{TN} = \frac{HRT}{K_{TSRP} + HRT}$	Sidiropoulou et al. (2007)
		$K_{TSRP} = \frac{22.8}{T} 45.5 \left(\frac{n}{1-n}\right)^3$	

Table 24.5 Various mechanistic models used for describing processes in constructed wetlands

No.	Types	References
1.	FITOVERT (VSSF-CWs)	Giraldi et al. (2010)
2.	Constructed wetland two dimensional (CW2D)	Simunek et al. (2006)
3.	STELLA software	Wang and Mitsch (2000)
4.	PHWAT software	Brovelli et al. (2009)
5.	2D mechanistic	Ojeda et al. (2008)
6.	CWM1(constructed wetland model no. 1)	Langergraber et al. (2009)

for the organic matter removal in 80 horizontal flow reed beds for domestic sewage treatment. They found that the combination of Monod kinetics and PF has good agreement with theoretical and actual performance data. Nevertheless, statistical analysis approach requires a huge amount of performance data from different experimental conditions, which is a challenging task. Process-based or mechanistic models that describe both water flow and reactions in treatment wetlands in detail are potentially faster and more economical tools for the qualitative and quantitative interpretation of the complex CW processes and performance.

In Equation 1 above, C_{in} is inlet concentration, C_{out} is outlet concentration, q is hydraulic loading rate HLR (m d-1), and a, b, c are regression coefficients; in Equation 2, k_A is real decomposition constant (m d-1); in Equation 3, k_v is volumetric first-order rate constant, k_o is initial first-order volumetric rate constant (d-1), b

is time-based retardation coefficient (d-1), and τ is retention time (d); in Equation 4, k_{VRC} is first-order volumetric rate constant (d-1), N is number of tanks, and r is rate of biological degradation (mg d-1); in Equation 5, K_{HSC} is half-saturation constant (mg m-3), C is contaminant concentration, and ko,v is zero-order volumetric rate constant (mg m-3d-1); in Equation 6, R_{TN} is TN removal, HRT and K_{TSRP} are time scales of the removal process in days, n is the porosity, and (n/1-n) is an expression, which includes many formulae predicting hydraulic conductivity in porous media.

24.6 Case Study

In this study, toluene was taken as a representative BTEX and *Canna generalis* has been used for plant-enhanced bioremediation. It is a tropical ornamental plant easily available in most of the countries and needs at least 6 h of average sunlight. Researchers have used *C. generalis* for phytoextraction of Pb and Cd from soil (Prasad and Freitas 2003; Wu et al. 2007). *C. indica* has been used in constructed wetlands to absorb Cd, Zn, and Ni from sludge and 30% of total nitrogen (Cui et al. 2010). The efficiency of phytoremediation depends on the plant species, soil and water properties, and physical and chemical properties of the contaminant. A faster biodegradation rate may be achieved by integrating bio-stimulation and bio-augmentation techniques of engineered bioremediation with phytoremediation in treatment wetlands. Therefore, the aim of this study was to investigate the most effective and feasible way of remediating the BTEX-contaminated groundwater.

The primary treated domestic wastewater was collected from the campus of Indian Institute of Technology (IIT), Delhi, in India. The polluted groundwater was collected from shallow hand pumps near a petroleum refinery in India. Both groundwater and domestic wastewater were stored at 4 °C in 20 L containers for further utilization. Batches of 120 mL capacity were assembled by adding appropriate volume of toluene stock solution to get a required initial concentration of 8 ppm. Based on simple mass balance, a headspace of about 110 mL was provided to maintain aerobic condition throughout the experimental period for degrading the total added toluene in all the batches. Viton stoppers (Centurion Scientific, India) sealed with aluminum crimp were used to close the batches for preventing any leakages of toluene to the atmosphere. In each batch, appropriate amount of groundwater or mixture of groundwater, wastewater, and/or rhizospheric water was used to make a final volume of 10 mL. Sterile batches were prepared by adding 60 μL of 10 g/L of $HgCl_2$. After closing the batches airtight, 160 μL of toluene stock was injected through the stopper with a gas-tight syringe. Then, the assembled batches were thoroughly shaken and incubated on an orbital platform at a rotating speed of 150 rpm. All the batches were covered with a black cloth at room temperature to check the light entrance. Liquid sampling interval and the effective concentration of $HgCl_2$ for maintaining sterile conditions were determined by the preliminary batch experiments. These sterile batches were the controls to check the biodegradation.

Thereafter, four sets of batch experiments were performed at room temperature (21.6 ± 0.3 °C) by maintaining the initial substrate concentration as 8 ppm. Only

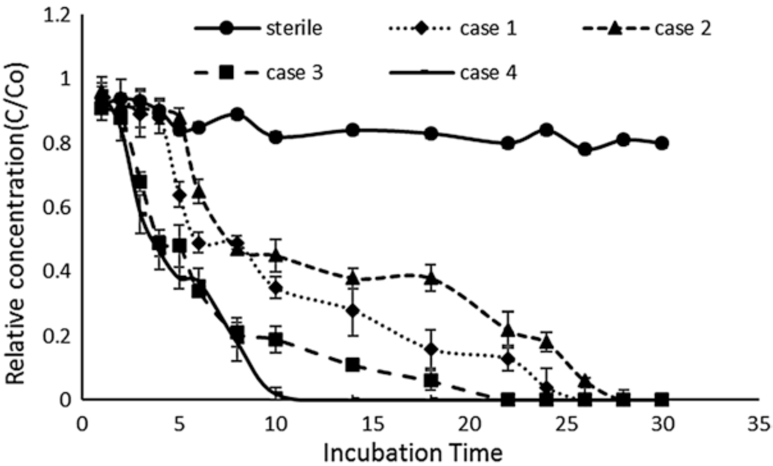


Fig. 24.6 Biodegradation of toluene in live and sterile batches for case 1–4 with time

groundwater was taken for the first set, and a mixture (1:1) of groundwater and domestic wastewater was taken in the second set of the batches. A set of two small wetlands with *C. generalis* were then developed using 40 L of viton-coated containers packed with pea gravels of 0.4 cm size. The collected and domestic wastewater was then used as the growing media in both wetlands. Toluene was not added in one treatment wetland, and approximately 50 ppm of toluene concentration was maintained in another treatment wetland for initial 5 weeks and allowed to attenuate the BTEX during the last week of the experiment. Similarly, a total acclimatization time of 6 weeks was provided to the second wetland before utilizing the rhizospheric water for batch experiments. A small-diameter viton tube was attached to both the treatment wetlands for collecting the rhizospheric water samples used in the batch experiments. A constant volume of water was maintained in the wetlands by adding daily water lost due to evapotranspiration. A mixture (1:1) of groundwater and rhizospheric water of wetlands developed with and without presence of toluene was taken for the third and fourth set of batch experiments, respectively.

Preliminary batch experiments showed that indigenous microbes present in the collected groundwater degraded the BTEX compound under natural conditions. The first case of natural degradation (Fig. 24.6) of toluene shows that toluene concentration decreases slowly with time and 26 h in total is taken by indigenous microbes to degrade the entire toluene mass in groundwater. In the second case, bio-stimulation was studied by adding wastewater to the contaminated groundwater. For the second case of bio-stimulation, there was no significant change in the rate of degradation, but a small increment of 2 h in time of degradation was observed by the addition of nutrients-laden municipal wastewater. This shows that the collected groundwater has sufficient nutrients during the entire phase of degradation for the added mass of toluene. In the remaining cases, two pot-scale wetlands were used to investigate plant-assisted biodegradation strategies involving bio-stimulation and bio-augmentation.

The third set of synergistic effect of bio-stimulation and plant-assisted degradation gave better degradation rate than bio-stimulation alone. The rate of degradation increased to 44.85% when compared to natural bioremediation case. The rhizosphere microbiota that is stimulated by root exudates proves to be more effective than the indigenous microbial population of bio-stimulation case. Narayanan et al. (1998b) emphasized that plant root exudates have a wide range of compounds that varied from amino acids, sugars, and carbohydrates to essential vitamins, which act as growth and energy substrates for the microbes. Another important finding of this case is the duration of lag phase. The lag phase is of shorter duration, only 2 h, for plant-assisted bio-stimulation as compared to the lag time of 5 h for case 2. This disappearance of long lag phase is primarily attributed to root exudates, which are the most favorable carbon source for indigenous microbes and hence are capable to degrade the target pollutants with lesser acclimatization period. In the fourth case of plant-assisted bio-augmentation and bio-stimulation, the lag phase was not observed and the degradation time was shortest (11 h). This treatment had the maximum rate of degradation with increment of 97.93% in comparison to the natural biodegradation. This finding fortifies the positive role of root zone in quick acclimatization and growth of toluene degraders in polluted soil-water systems. Apparently, the bio-augmented microbiota acclimatizes to degrade toluene due to the presence of the BTEX in the surroundings. These findings are indirectly consistent with the previous study by Weishaar et al. (2009) who observed that vegetated BTEX-contaminated site has more BTEX degrading population than the barren contaminated land. Lendvay et al. (2003) and Lin et al. (2010) also concluded that bio-stimulated bio-augmentation was faster and more efficient in controlling perchloroethylene (PCE) plume as compared to bio-stimulation alone. So the rate of degradation of toluene was found as natural degradation $\simeq$ bio-stimulation < plant-assisted bio-stimulation < combination of bio-augmentation and bio-stimulation.

To investigate the role of plants in enhanced bioremediation and to quantify the uptake of BTEX by root and shoot biomass pot-scale wetlands with and without shoot biomass along with unplanted gravel beds were studied under controlled conditions. One wetland, with fully-grown plants, was spiked with 150 mg/L of toluene to acclimatize the rhizospheric microbes with the pollutant. The second wetland was similar except that the plant shoot biomass was chopped off. The remaining plant stems were sealed by silicone jelly for blocking the transpiration loss from the xylem. The growing media (collected groundwater) of the wetlands was recirculated in a closed loop at 500 mL/h by connecting inlets and outlets with a viton tube of diameter 3 mm using a peristaltic pump. The surface of all the three wetlands was covered with aluminum foils and mulches to minimize the volatilization of toluene and water to the surrounding atmosphere. The toluene and water loss from the wetlands were measured regularly after spiking the mesocosms with an initial toluene concentration of 120 mg/L.

The total degradation time for the unplanted wetland was observed to be 96 h followed by wetland without shoot biomass (82 h) and wetland with shoot biomass

Table 24.6 Experimental and simulated uptake by shoot biomass

Time (h)	Cumulative uptake (experimental) in mg/L	Cumulative uptake (simulated) in mg/L
8	13.76	4.00
24	21.42	9.94
32	28.57	16.01
40	35.72	21.70
48	36.66	26.65
56	35.26	30.75
65	35.85	33.99
72	36.16	36.46

Table 24.7 Mass of toluene in root and shoot biomass with time

Time (h)	Mass of toluene (roots) in mg	Mass of toluene (shoots) in mg
8	2.43	2.52
24	4.87	2.24
32	6.10	4.59
40	8.56	5.69
48	9.79	6.78
56	12.19	9.14
72	14.6	9.11

(72 h). The natural attenuation of toluene in gravel beds shows the degrading capability of indigenous microbiota present in the groundwater. Though the selected BTEX compound is degraded by natural attenuation, the time required for biodegradation is reduced up to 25% in the presence of plants. The attenuation of the toluene in gravel bed also confirms that sampled groundwater has sufficient nutrients for the degradation of the pollutant as reported by Yadav et al. (2013) for the same site. A faster rate of degradation during the later phases of the experiment can be attributed to the role of plants in the form of root uptake and rhizo-degradation in root zone of planted wetlands (Powell et al. 2014). The root exudates known for their capability to enhance the breakdown of organic pollutants (Susarla et al. 2002) seem to help in reducing the total time taken for degradation. The uptake of toluene from the rhizospheric water of the wetlands with and without shoot biomass is calculated using mass balance of toluene in root zone and plant biomass. The total toluene uptake is exponential in nature in the initial phase of the experiment, increasing with time and reaching a steady state toward the end. Similar trend was observed by Ting et al. (1989) and Yadav et al. (2011) for metal extraction by plants from aqueous solutions. The initial phase of exponential uptake takes place due to a higher tendency of roots to adsorb the organic compound and a sharp diffusion/concentration gradient with the contamination in the exterior solution. With time, the amount of organic compound accumulated in the shoot biomass decreased indicating a state of saturation in plants with decreasing concentration gradient in the exterior solution.

Table 24.8 List of parameters used for simulation in wetland with and without shoot biomass

Parameters	Values	Unit	References
Initial concentration C_t	121.89[a], 118.35[b]	mg/L	Experimental
Total volume, V_t	4.0	L	Experimental
Rate constant, K_t	0.04	hr^{-1}	Experimental
Root concentration factor, R_{cf}	4.13	Dimensionless	Narayanan et al. (1998a)
Root surface volume, V_{rs}	0.267	L	Yadav et al. (2011)
Diffusion rate constant, D_r	0.05	hr^{-1}	Calibrated
Water lost in transpiration, Q_{trans}	2.77	L/hr	Experimental
Transpiration stream concentration factor, T_{scf}	0.74	Dimensionless	Boonsaner et al. (2011)

[a]Wetland without shoot biomass
[b]Wetland with shoot biomass

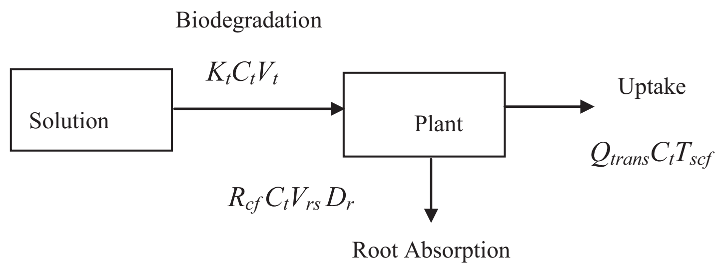


Fig. 24.7 Conceptual model of processes in wetland with and without shoot biomass

Further, the cumulative uptake in the shoot biomass is predicted using linear kinetics using a mean value of first-order rate constant. Initially some discrepancy between the measured and the simulated values are observed which is narrowed down during the last phase of the experiments (Table 24.6). Mass balance of the toluene in the pot-scale wetlands shows that with time the toluene mass in root biomass predominates due to absorbance and immobilization of toluene in root biomass (Table 24.7). The uptake of toluene from the rhizospheric water of the wetland with and without shoot biomass is simulated using a set of mass balance equations (Eqs. 24.13 and 24.14) and parameters given in Table 24.8 that include diffusion of toluene in the aqueous phase toward the root surface and its subsequent translocation from root to shoot biomass (Fig. 24.7). A uniform aqueous phase concentration of toluene (*Ct*) is considered around the root biomass for formulating the equations for wetlands without and with shoot biomass:

$$V_t = \frac{\partial C_t}{\partial t} = -K_t C_t V_t - \mathrm{R}_{cf} C_t V_{rs} Dr \tag{24.13}$$

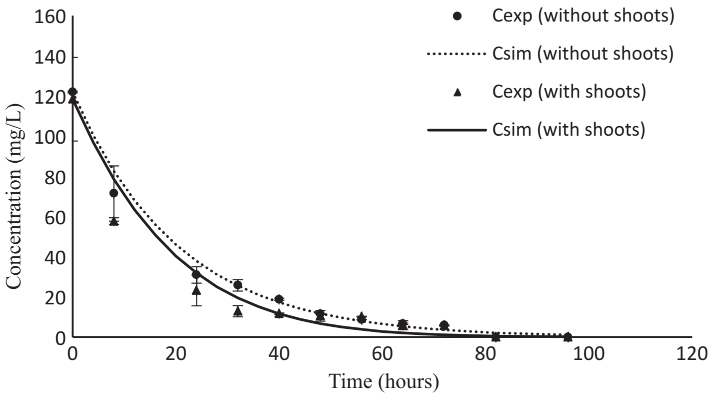


Fig. 24.8 Simulated and experimental toluene concentration comparison for wetland with and without shoot biomass. Error bars represent ± standard error for three replicates

$$V\frac{\partial C_t}{\partial t_t} = -K_t C_t V_t - R_{cf} C_t V_{rs} D_r - Q_{\text{trans}} C_t T_{scf} \tag{24.14}$$

where V_t is the total volume of rhizospheric water (in liters) remaining after time t, K_t is the first-order rate constant in hour^{-1}, V_{rs} is the root surface volume and considered as 8% volume of the total root biomass (Brennan and Shelley 1999) and it is observed that 1 g of live root biomass has a volume of 0.96 mL (±0.0306) (Yadav et al. 2011), R_{cf} is the plant root concentration factor defined as $R_{\text{cf}} = 0.82 + 10\ (0.77 \log(K_{\text{ow}}) - 1.52)$ (Davis et al. 1993), T_{scf} is the plant's transpiration stream concentration factor defined as $T_{\text{scf}} = 0.784 \exp.(\{-(\log k_{\text{ow}} - 1.78)2)/2.44$ (Davis et al. 1993), Q_{trans} is the water uptake by plants, and D_r is the effective diffusion rate between the solution and root surface layer. The residual concentration of toluene, C_t, in the rhizospheric water at any time can be calculated for wetland with and without shoot biomass expressed in mg/L. Equations 2 and 3 utilize the linear first-order rate constant K_t, which is taken as an average value from the experiment. The data points calculated from first-order kinetics match well with that from the experiment on wetland without shoot biomass. A slight discrepancy in some observed and simulated values for the case of wetland with shoot biomass may be due to the adsorption onto gravel bed (Fig. 24.8).

When the simulated values for wetland with and without shoots are plotted on the Y-axis and the experimental values on the X-axis, we get straight lines with R^2 = 0.9903 and R^2 = 0.9634 for wetland without and with shoot biomass, respectively.

24.7 Summary and Conclusions

Many hydrocarbons including BTEX can be removed from polluted soil-water resources using plants and their associated rhizospheric microorganisms in treatment wetlands. In order to understand the treatment behavior in wetlands, various modeling approaches ranging from simple empirical to more complex physically based models have been developed. The simple first-order degradation kinetics is applicable widely in modeling treatment wetlands having low concentration level of dissolved hydrocarbons. The nonlinear Monod kinetics is used frequently to describe the microbial processes in wetlands accurately. Simulating tools like FITOVERT, CW2D, STELLA, PHWAT, and CWM1 are used widely to explain the mechanistic processes in a systematic way. In the case studies, four different techniques of bioremediation treatments were initially studied for the degradation of a BTEX compound under controlled conditions. The rate of degradation of toluene, the selected hydrocarbon, was found as natural degradation $\simeq$ bio-stimulation $<$ plant-assisted bio-stimulation $<$ combination of bio-augmentation and bio-stimulation. In the second part, pot-scale wetlands with and without shoot biomass along with unplanted gravel beds were studied in the laboratory. It was seen that plant-assisted bioremediation was faster than natural attenuation and the removal time of toluene was reduced by 25% in the presence of shoot biomass as compared to unplanted gravel beds. Thus, for successful implementation of emerging bioremediation methods, the described processes and their respective simulation tools can be useful for planning the remediation task along with estimating the involved treatment cost.

Acknowledgments The authors would like to acknowledge the Department of Science and Technology (DST) and Council of Scientific and Industrial Research (CSIR) in India for their financial support to this research as Ramanujan Award and Senior Research Fellowship to the authors. We are also thankful to Prof. Majid Hassanizadeh from Utrecht University for his valuable contribution and suggestions.

References

Alvarez PJJ, Illman WA (2006) Bioremediation and natural attenuation, process fundamentals and mathematical models. Wiley-Interscience, p 1:24

Armstrong J, Armstrong W (1991) A convective through-flow of gases in Phragmites australis (Cav.) Trin. ex Steud. Aquat Bot 39:75–88

Basu S, Yadav B, Mathur S (2015) Enhanced bioremediation of BTEX contaminated groundwater in pot-scale wetlands. Environ Sci Pollut Res 22(24):20041–20049. doi:10.1007/s11356-015-5240-x

Bedessem ME, Ferro AM, Hiegel T (2007) Pilot-scale constructed wetlands for petroleum-contaminated groundwater. Water Environ Res 79:581–586. doi:10.2175/106143006X111943

Boonsaner M, Borrirukwisitsak S, Boonsaner A (2011) Phytoremediation of BTEX contaminated soil by *Canna generalis*. Ecotoxicol Environ Saf 74:1700–1707. doi:10.1016/j.ecoenv.2011.04.011

Brennan MA, Shelley ML (1999) A model of the uptake, translocation, and accumulation of lead (Pb) by maize for the purpose of phytoextraction. Ecol Eng 12:271–297. doi:10.1016/S0925-8574(98)00073-1

Briggs GG, Bromilow RH, Evans AA (1982) Relationships between lipophilicity and root uptake and translocation of non-ionised chemicals by barley. Pestic Sci 13(5):495–504

Bromilow RH, Chamberlain K (1995) Principles governing uptake and chemicals in plant contamination: modelling and simulation of organic chemical processes Trapp S McFarlane JC (Eds), Lewis Publishers, pp 37–68

Brovelli A, Malaguerra F, Barry DA (2009) Bioclogging in porous media: model development and sensitivity to initial conditions. Environ Model Softw 24:611–626

Burken JG, Schnoor JL (1999) Distribution and volatilization of organic compounds following uptake by hybrid poplar trees. Int J Phytoremediat 1:139–151. doi:10.1080/15226519908500012

Carlson RW, Bazzaz FA (1977) Growth reduction in American sycamore (*Plantanus occidentalis* L.) caused by Pb Cd interaction. Environ Pollut 12:243–253

Cheng S, Xiao J, Xiao H et al (2007) Phytoremediation of triazophos by *Canna indica* Linn. in a hydroponic system. Int J Phytoremediat 9:453–463

Cooper P (1999) A review of the design and performance of vertical-flow and hybrid reed bed treatment systems. Water Sci Technol 40(3):1–9

Corseuil HX, Moreno FN (2001) Phytoremediation potential of willow trees for aquifers contaminated with ethanol-blended gasoline. Water Res 35:3013–3017. doi:10.1016/S0043-1354(00)00588-1

Cui L, Ouyang Y, Lou Q et al (2010) Removal of nutrients from wastewater with *Canna indica* L. under different vertical-flow constructed wetland conditions. Ecol Eng 36:1083–1088. doi:10.1016/j.ecoleng.2010.04.026

Cunningham SD, Berti WR (1993) Remediation of contaminated soils with green plants: an overview. Vitr Cell Dev Biol 29:207–212

Davis LC, Erickson LE, Lee E et al (1993) Modeling the effects of plants on the bioremediation of contaminated soil and ground water. Environ Prog 12:67–75. doi:10.1002/ep.670120112

El Fantroussi S, Agathos SN (2005) Is bioaugmentation a feasible strategy for pollutant removal and site remediation? Curr Opin Microbiol 8:268–275. doi:10.1016/j.mib.2005.04.011

Gessner TP, Kadlec RH, Reaves RP (2005) Wetland remediation of cyanide and hydrocarbons. Ecol Eng 25:457–469. doi:10.1016/j.ecoleng.2005.07.015

Giraldi D, de Michieli VM, Iannelli R (2010) FITOVERT: a dynamic numerical model of subsurface vertical flow constructed wetlands. Environ Model Softw 25:633–640. doi:10.1016/j.envsoft.2009.05.007

Grosse W, Büchel HB, Tiebel H (1991) Pressurized ventilation in wetland plants. Aquat Bot 39:89–98

Hijosa-Valsero M, Sidrach-Cardona R, Martín-Villacorta J et al (2011) Statistical modelling of organic matter and emerging pollutants removal in constructed wetlands. Bioresour Technol 102:4981–4988. doi:10.1016/j.biortech.2011.01.063

Ji G, Sun T, Zhou Q et al (2002) Constructed subsurface flow wetland for treating heavy oil-produced water of the Liaohe Oilfield in China. Ecol Eng 18:459–465

Jobson AM, Cook FD, Westlake DWS (1974) Effect of amendments on the microbial utilization of oil applied to soil. Appl Microbiol 27:166–171

Jordahl JL, Foster L, Schnoor JL, Alvarez PJJ (1997) Effect of hybrid poplar trees on microbial populations important to hazardous waste bioremediation. Environ Toxicol Chem 16:1318–1321

Kadlec RH (1992) Hydrological factors in wetland water treatment. In: Hammer D (ed) Constructed wetlands for wastewater treatment: municipal, industrial and agricultural. Lewis Publishers, Chelsea, pp 25–29

Kadlec RH (2000) The inadequacy of first-order treatment wetland models. Ecol Eng 15:105–119

Kadlec RH (2003) Effects of pollutant speciation in treatment wetlands design. Ecol Eng 20:1–16
Kumar JLG, Zhao YQ (2011) A review on numerous modeling approaches for effective, economical and ecological treatment wetlands. J Environ Manag 92:400–406. doi:10.1016/j.jenvman.2010.11.012
Lahvis MA, Baehr AL, Baker RJ (1999) Quantification of aerobic biodegradation and volatilization rates of gasoline hydrocarbons near the water table under natural attenuation conditions. Water Resour Res 35:753–765
Langergraber G (2008) Modeling of processes in subsurface flow constructed wetlands: a review. Vadose Zo J 7:830. doi:10.2136/vzj2007.0054
Langergraber G, Haberl R (2001) Constructed wetlands for water treatment. Minerva Biotechnol 13:123–134
Langergraber G, Rousseau DPL, García J et al (2009) CWM1: a general model to describe biokinetic processes in subsurface flow constructed wetlands. Water Sci Technol 59:1687–1697
Lendvay JM, Löffler FE, Dollhopf M et al (2003) Bioreactive barriers: a comparison of bioaugmentation and biostimulation for chlorinated solvent remediation. Environ Sci Technol 37:1422–1431. doi:10.1021/es025985u
Lin C-W, Chen L-H, Y-P I, Lai C-Y (2010) Microbial communities and biodegradation in lab-scale BTEX-contaminated groundwater remediation using an oxygen-releasing reactive barrier. Bioprocess Biosyst Eng 33:383–391. doi:10.1007/s00449-009-0336-7
Llorens E, Saaltink MW, Garcia J (2011a) CWM1 implementation in Retraso Code Bright: first results using horizontal subsurface flow constructed wetland data. Chem Eng J 166(1):224–232
Llorens E, Saaltink MW, Poch M, García J (2011b) Bacterial transformation and biodegradation processes simulation in horizontal subsurface flow constructed wetlands using CWM1-RETRASO. Bioresour Technol 102(2):928–936
Lyman WJ, Reidy PJ, Levy B (1992) Mobility and degradation of organic contaminants in subsurface environments. C. K. Smoley, Chelsea
Mascolo G, Ciannarella R, Balest L, Lopez A (2008) Effectiveness of UV-based advanced oxidation processes for the remediation of hydrocarbon pollution in the groundwater: a laboratory investigation. J Hazard Mater 152:1138–1145
Mathur S, Yadav BK (2009) Phytoextraction modeling of heavy metal (lead) contaminated site using maize (*Zea mays*). Pract Period Hazard Toxic Radioact Waste Manag 13:229–238
Mitchell C, McNevin D (2001) Alternative analysis of BOD removal in subsurface flow constructed wetlands employing Monod kinetics. Water Res 35:1295–1303
Monod J (1949) The growth of bacterial cultures. Annu Rev Microbiol 3:371–394
Moore BJ, Headley JV, Dupont RR et al (2002) Abatement of gas-condensate hydrocarbons in a natural wetland. J Environ Sci Health A 37:425–438
Narayanan M, Davis LC, Tracy JC et al (1998a) Modeling the fate of toluene in a chamber with alfalfa plants. 2. Numerical results and comparison study. J Hazard Subst Res 1:40–84
Narayanan M, Tracy JC, Davis LC, Erickson LE (1998b) Modeling the fate of toluene in a chamber with alfalfa plants. 1. Theory and modeling concepts. J Hazard Subst Res 1:1–30
Niell WLO, Nzengung VA (2004) In-situ bioremediation and phytoremediation of contaminated soils and water: three case studies. Environ Res Eng Manag 4:49–54
Nikolopoulou M, Kalogerakis N (2009) Biostimulation strategies for fresh and chronically polluted marine environments with petroleum hydrocarbons. J Chem Technol Biotechnol 84:802–807
Ojeda E, Caldentey J, Saaltink MW, García J (2008) Evaluation of relative importance of different microbial reactions on organic matter removal in horizontal subsurface-flow constructed wetlands using a 2D simulation model. Ecol Eng 34:65–75
Omari K, Revitt M, Shutes B, Garelick H (2003) Hydrocarbon removal in an experimental gravel bed constructed wetland. Water Sci Technol 48:275–281

Ottová V, Balcarová J, Vymazal J (1997) Microbial characteristics of constructed wetlands. Water Sci Technol 35:117–123

Powell CL, Goltz MN, Agrawal A (2014) Degradation kinetics of chlorinated aliphatic hydrocarbons by methane oxidizers naturally-associated with wetland plant roots. J Contam Hydrol 170:68–75. doi:10.1016/j.jconhyd.2014.10.001

Prasad MNV, Freitas HMDO (2003) Metal hyperaccumulation in plants—biodiversity prospecting for phytoremediation technology. Electron J Biotechnol 6:110–146

Ranieri E, Gikas P, Tchobanoglous G (2013) BTEX removal in pilot-scale horizontal subsurface flow constructed wetlands. Desalin Water Treat 51:3032–3039. doi:10.1080/19443994.2012.748453

Rousseau DPL, Vanrolleghem PA, De Pauw N (2004) Model-based design of horizontal subsurface flow constructed treatment wetlands: a review. Water Res 38(6):1484–1493

Salmon C, Crabos JL, Sambuco JP et al (1998) Artificial wetland performances in the purification efficiency of hydrocarbon wastewater. Water Air Soil Pollut 104:313–329

Schnoor JL, Licht LA, McCutcheon SC et al (1995) Phytoremediation of organic and nutrient contaminants. Environ Sci Technol 29:318A–323A. doi:10.1021/es00007a747

Seagren EA, Rittmann BE, Valocchi AJ (1994) Quantitative evaluation of the enhancement of NAPL-pool dissolution by flushing and biodegradation. Environ Sci Technol 28:833–839

Seidel K (1967) Biologischer Schutz unserer Seen durch Pflanzen. Osterrreichische Fischerei 1:3–7

Shepherd HL, Tchobanoglous G, Grismer ME (2001) Time-dependent retardation model for chemical oxygen demand removal in a subsurface-flow constructed wetland for winery wastewater treatment. Water Environ Res 73:597–606

Shimp JF, Tracy JC, Davis LC et al (1993) Beneficial effects of plants in the remediation of soil and groundwater contaminated with organic materials. Crit Rev Environ Sci Technol 23:41–77

Sidiropoulou MG, Moutsopoulos KN, Tsihrintzis VA (2007) Determination of Forchheimer equation coefficients a and b. Hydrol Process 21:534–554

Simunek J, van Genuchten M, Th Sejna M (2006). The HYDRUS software package for simulating two- and three-dimensional movement of water, heat, and multiple solutes in variably-saturated media, technical manual, Version 1.0, PC Progress Prague, Czech Republic

Stein OR, Biederman JA, Hook PB, Allen WC (2006) Plant species and temperature effects on the $k–C_*$ first-order model for COD removal in batch-loaded SSF wetlands. Ecol Eng 26(2):100–112

Stone KC, Hunt PG, Szögi AA et al (2002) Constructed wetland design and performance for swine lagoon wastewater treatment. Trans ASAE 45:723–730

Sun G, Saeed T (2009) Kinetic modeling of organic matter removal in 80 horizontal flow reed beds for domestic sewage treatment. Process Biochem 44:717–722

Susarla S, Medina VF, McCutcheon SC (2002) Phytoremediation: an ecological solution to organic chemical contamination. Ecol Eng 18:647–658. doi:10.1016/S0925-8574(02)00026-5

Tang X, Tang X, Eke PE et al (2009) Processes impacting on benzene removal in vertical-flow constructed wetlands. Bioresour Technol 100:227–234. doi:10.1016/j.biortech.2008.05.038

Ting YP, Lawson F, Prince IG (1989) Uptake of cadmium and zinc by the alga *Chlorella vulgaris*: part 1. Individual ion species. Biotechnol Bioeng 34:990–999

Toscano A, G Langergraber and GL Cirelli (2006) Simulation of hydraulics and pollutant removal of a pilot-scale two-stage constructed wetlands functioning as secondary or tertiary treatment. p. 1303–1311. In: Proceedings of IWA Specialized Group Conference on Wetland Systems for Water Pollution Control, Vol. 2, 10th, Lisbon, Portugal. 23–29 Sept. 2006. International Water Association, London

Trapp S (2000) Modelling uptake into roots and subsequent translocation of neutral and ionisable organic compounds. Pest Manag Sci 56:767–778

Uddameri V (2010) An analytical solution to model aquaculture wetlands subject to intermittent loading and variable initial concentrations. Environ Model Assess 15:27–35

USEPA, (1993) Subsurface flow constructed wetlands for wastewater treatment: a technology assessment. United States Environmental Protection Agency Report 542- R-01-004. Washington, DC.

USEPA (2000) A handbook of constructed wetlands: a guide to creating wetlands for: agricultural wastewater, domestic wastewater, coal mine drainage stormwater in the mid – atlantic region: volume 1: general considerations. United States Environmental Protection Agency, EPA Report Number 843B00005, ISBN 0–16- 052999-9. Washington, DC.

USEPA (2006). Edition of the drinking water standards and health Advisories. EPA 822-R-06-013, Washington, DC

Venosa AD, Lee K, Suidan MT et al (2002) Bioremediation and biorestoration of a crude oil-contaminated freshwater wetland on the St. Lawrence River. Bioremdiation J 6:261–281

Vymazal J (2005) Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment. Ecol Eng 25:478–490

Wallace SD and Knight RL (2006) Small-scale constructed treatment systems: feasibility, design criteria, and O and M requirements. Final report, Project 01-CTS-5. Water Environment Research Foundation, Alexandria, Virginia

Wang N, Mitsch WJ (2000) A detailed ecosystem model of phosphorus dynamics in created riparian wetlands. Ecol Model 126:101–130

Weishaar JA, Tsao D, Burken JG (2009) Phytoremediation of BTEX hydrocarbons: potential impacts of diurnal groundwater fluctuation on microbial degradation. Int J Phytoremediation 11:509–523. doi:10.1080/15226510802656326

Wemple, C. and Hendricks, L. (2000) Documenting the recovery of hydrocarbon impacted wetlands: a multi-disciplinary approach. In: Wetlands and remediation: An International Conference, Battelle Press, Columbus, Ohio, p 73–78

Williams JB (2002) Phytoremediation in wetland ecosystems: progress, problems, and potential. CRC Crit Rev Plant Sci 21:607–635. doi:10.1080/0735-260291044386

Wu L-Qi., Cheng S.-P., Yang L.-H., and Wu Z.-B., (2007) Stress responses and resistance mechanism of *Canna indica* Linn. to cadmium and copper. J Agro-Environ Sci: 2007-04

Yadav BK, Hassanizadeh SM (2011) An overview of biodegradation of LNAPLs in coastal (semi)-arid environment. Water Air Soil Pollut 220:225–239. doi:10.1007/s11270-011-0749-1

Yadav BK, Siebel MA, Van Bruggen JJA et al (2011) Rhizofiltration of a heavy metal (lead) containing wastewater using the wetland plant *Carex pendula*. CLEAN – Soil Air Water 39:467–474. doi:10.1002/clen.201000385

Yadav BK, Ansari FA, Basu S (2013) Remediation of LNAPL contaminated groundwater using plant-assisted biostimulation and bioaugmentation methods. Water Air Soil Pollut. doi:10.1007/s11270-013-1793-9

Yerokun OA, Christenson DR (1990) Relating high soil test phosphorus concentrations to plant phosphorus uptake. Soil Sci Soc Am J 54:796–799

Zhu X, Suidan MT, Venosa AD (2004) Literature review on the use of commercial bioremediation agents for cleanup of oil-contaminated estuarine environments. USEPA

Part VII

Wetland Restoration

Wetland Creation: A Strategy for Mitigating Wetland Loss by Restoring Wetlands to Landscapes

25

Ketan S. Tatu and James T. Anderson

Abstract

Owing to an ever-growing human population and the subsequent need for land development in India and other parts of South Asia, wetlands are bound to get adversely impacted. The outcome of adverse impacts may vary from wetland degradation to wetland loss, and mitigation is an effective strategy in minimizing such damages. One of the proven effective strategies of wetland mitigation is wetland creation that restores wetlands to a landscape that suffered wetland loss. Wetland creation efforts typically lead to construction of "replacement wetlands" (also called "mitigation wetlands") whose total area in an affected landscape has to be similar to or larger than the original wetland area impacted in that landscape. The replacement wetlands should be constructed mainly for ecological well-being of the landscape. Wetland creation to replace lost wetlands in a landscape may require reestablishing original vegetation, hydrology, or other parameters to restore original or closer to original functions of wetlands. For constructing a replacement wetland, an area having diameter of at least 25 m can be selected as wetland construction site in a flat barren land. In India, such land can be a "forest land" under the jurisdiction of a state forest department. Creation of a replacement wetland may be carried out using manual tools or heavy equipment depending on type of site selected, size of the replacement wetland required, and complexity level of the structure of the replacement wetland. Some

K.S. Tatu (✉)
Gujarat Ecological Education and Research (GEER) Foundation, Indroda Nature Park, PO Sector 7, Gandhinagar 382007, India
e-mail: ketantatu@gmail.com

J.T. Anderson
Division of Forestry and Natural Resources, West Virginia University, PO Box 6125, Morgantown, WV 26506-6125, USA
e-mail: jim.anderson@mail.wvu.edu

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_25

experience and knowledge regarding engineering surveys and use of survey instruments might be desirable.

Keywords
Mitigation • Replacement wetland • Wetland creation • Wetland loss

25.1 Mitigating Wetland Loss

Collin's dictionary defines mitigation as "making or becoming less severe or harsh." If we apply this term to an environmental or ecological context, it would mean making environmental or ecological problems less severe or harsh. As per Constrained Long-Range Transportation Plan (CLRP 2007), mitigation activities from an environmental viewpoint may include:

(a) Avoidance of all impacts
(b) Reducing the size or intensity of a proposed project
(c) Implementation of abatement measures to reduce the impacts of the construction phase
(d) Implementation of special features to reduce impacts
(e) Compensating for environmental impacts by substituting environmental resources that have similar or higher value

Ideally, all impacts to wetlands could be avoided and certainly minimized. However, that is not likely to be the case always as land development for an ever-growing human population continues, thus making environmental mitigation activity most relevant in the context of wetland conservation. This chapter focuses on such mitigation activities. The mitigation efforts, particularly in the context of wetland conservation, can be described as compensating for developmental impacts causing wetland loss by providing suitable replacement wetlands of equivalent or greater value, on- or off-site (CLRP 2007).

We are aware that wetlands in India, South Asia, and several other parts of the world face multiple threats. Natural or human-made wetlands are degraded or lost as they are often ignored in the development plans. Wetlands are treated as cesspools for discharge of wastewaters as well as disposal of solid wastes (Gopal 2015). As a result, many wetlands in India and elsewhere in Asia have already been degraded or destroyed, and many others face degradation or destruction. Degradation and loss of wetlands are global phenomena. The world has undergone long-term losses of natural wetlands, between 54% and 57%, since 1700. There is 3.7 times increase in the rate of wetland loss during twentieth and twenty-first centuries, resulting in 64–71% loss of wetlands since 1900s (Davidson 2014). After European settlement, the United States lost 53% of its wetlands (Mitsch and Gosselink 2000), and according to the National Wetlands Working Group (1988) of Canada, various wetland areas of Canada (e.g., Atlantic tidal and coastal marshes, Lower Great Lakes, Prairie Potholes, and Pacific coastal estuarine wetlands) have experienced 65–80% loss. Australia has lost 50% of its wetlands; New Zealand and Europe have lost more than 90% each, and China has lost 60% of its wetlands (Mitsch and Gosselink 2000). The rate of wetland loss in Asia has proceeded rapidly due to conversion of coastal and inland natural wetlands, which continues to this day (Davidson 2014). Bassi et al. (2014) report that 5,000 km^2 of wetland area in Asia alone is lost annually due to agriculture, dam construction, and other uses or activities. Only 4.5% of India's land area is covered by wetlands, though the world average is more than 6% (Gopal 2015). If the rivers (which make up to 80% of total natural wetlands) are excluded, the overall wetland area in India is less than 3%. About 38% of inland freshwater wetlands had disappeared in recent decades (Gopal 2015).

To cope with this wetland loss, there is a need to develop and implement wetland mitigation strategies. Creation of replacement wetlands has gained momentum in developed countries such as the United States. Section 404 of the United States' Clean Water Act requires that anyone dredging or filling in the nation's waters (e.g., wetlands) must request a permit from the US Army Corps of Engineers (Mitsch and Gosselink 2000). The US Army Corps of Engineers has stated that an environmentally indispensable area (e.g., a wetland) constitutes a valuable productive and public resource, the unnecessary change or devastation of which should be discouraged as contrary to the public interest (Mitsch and Gosselink 2000).

In the United States and certain other countries, wetland creation, restoration, or enhancement is required to compensate for degraded wetlands or to replace wetlands lost to land development. Replacement wetlands, also called mitigation wetlands, are constructed to compensate for the loss or destruction of wetlands and are intended to be at least the same size as the lost wetlands (Mitsch and Gosselink 2000). In many cases, the replacement wetlands are larger than the wetlands originally impacted due to mitigation ratios based on wetland type. In most cases, the mitigation ratio is greatest for destruction of forested or scrub-shrub wetlands, intermediate for emergent wetlands, and lowest for open water wetlands. Thousands of square kilometers of wetlands and their associated terrestrial environs have been gained due to the enforcement of Section 404 (Mitsch and Gosselink 2000).

Curiously, as wetland creation leads to restoration of a landscape that might have experienced wetland loss, wetland creation is often referred to as wetland restoration. However, in a true technical sense, creation refers to creating a wetland from upland or true aquatic areas that were not previously wetlands, and restoration refers to creating a wetland from an area that historically had been a wetland, but then perturbations, most likely anthropogenic, converted the wetland into upland habitat. Restoration is often aimed at reestablishing the historical hydrology and thus restoring the wetland. In this chapter, we will use the terms "wetland creation" and "wetland restoration" interchangeably, and it will mean creation or construction to replace lost wetlands in a landscape and thus restoring the landscape from a wetland point of view.

25.2 Wetland Creation

Wetland creation is an effort to create wetlands in areas previously classified as upland and/or non-vegetated. In other words, it is the conversion of a persistent upland area into a wetland via human activity. In its National Engineering Handbook (NEH), the USDA Soil Conservation Service defined wetland creation as the creation of a wetland on a site that was historically non-wetland (SCS 1997). Wetland creation to replace lost wetlands in a landscape may involve reestablishing original vegetation, hydrology, or other parameters to restore original or closer to original functions of wetlands (Osmond et al. 1995). The creation of new wetlands where wetlands once existed provides substantial opportunity for reversing the trend of decreasing wetland resources and for providing aesthetic and lost ecosystem functions to the landscape (Mitsch and Gosselink 2000). However, the task can often be challenging, both ecologically and economically.

The first step in wetland creation is to consider the design of the wetland to be created. A few points that must be considered in wetland design are listed in Fig. 25.1.

Many village and countryside ponds or wetlands in rural landscapes as well as many suburban ponds of India, especially those in semi-arid and arid regions, are seasonal or temporary and periodically dry up. In general, such wetlands dry up in late summer and are filled up again every year by precipitation (Biebighauser 2002). Though these wetlands might be seasonally rich in waterfowl and other biodiversity aspects, they are ecologically unreliable on a long-term basis because the majority of them are constructed for satisfying irrigation or some other socioeconomic needs instead of increasing ecological area. Furthermore, they are often at the mercy of man's multifarious developmental activities. Many natural seasonal ponds are now covered by expensive infrastructure such as roads, buildings, and parking lots (Biebighauser 2002). In India, several village ponds remain underwater year-round due to waters received from major canal networks, which hampers the natural wetland characteristic of seasonality. To compensate for wetland loss in a rural or suburban landscape, it might be useful to restore the landscape by creating ponds with the primary purpose of ecological restoration. Seasonality is an important characteristic of a large number of natural and human-made village ponds, countryside ponds, and suburban ponds in northern India that have been in existence for decades or centuries supporting man's socioeconomic needs. Therefore, efforts for restoring a landscape with ponds for ecological functions should also be directed toward creating seasonal wetlands. Fortunately, reestablishment of seasonal ponds for ecological restoration purpose is possible (Biebighauser 2008). Such wetlands may automatically contribute to the socioeconomic well-being of the villages in the landscape by helping in recharging/restoring groundwater levels. Ecological restoration of ponds can also be used for well-regulated secondary socioeconomic purposes, which may include fetching water for everyday domestic needs (though prohibiting washing or bathing activities at the pond itself) and providing drinking water to livestock (without bringing the livestock to the shore). By applying basic site selection skills (Strager et al. 2011), new wetlands can be set up in the same

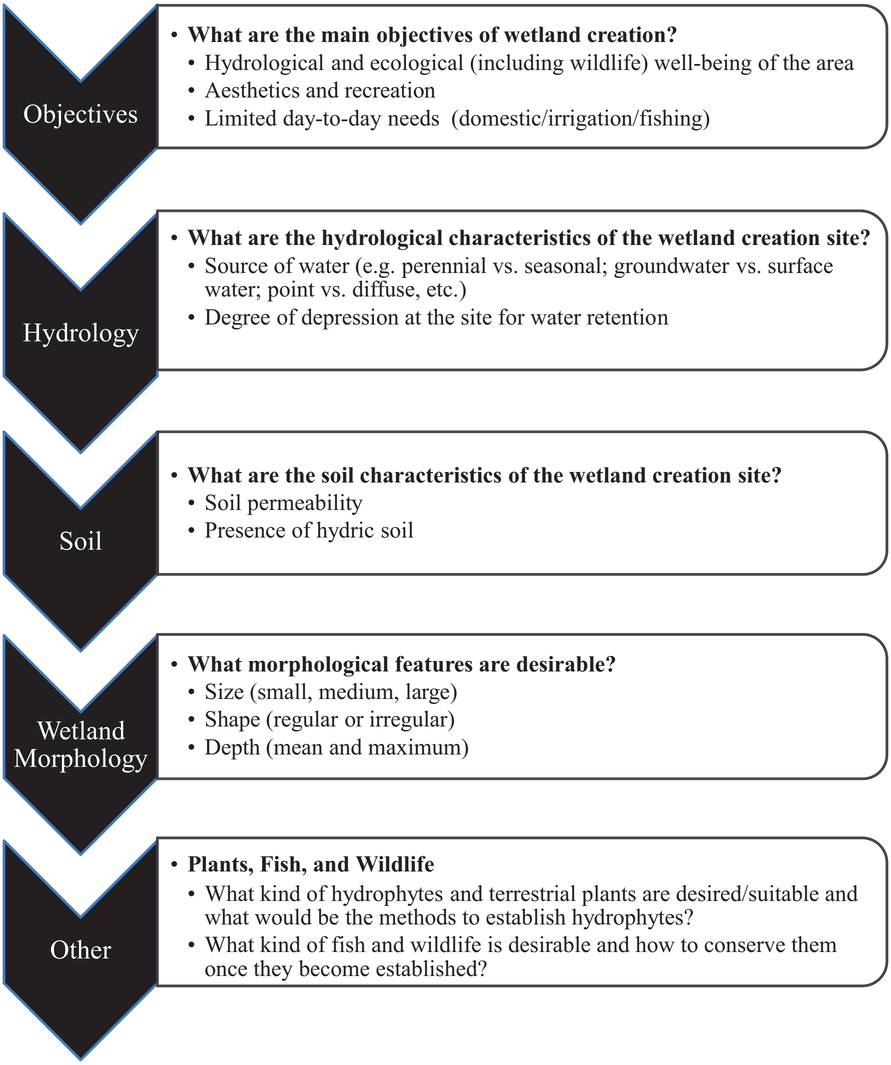


Fig. 25.1 A few points to consider in wetland design (Based on: Anonymous 2007 and Ontario Naturalists 2000)

general area where they once occurred, restoring an important component of the landscape (Biebighauser 2002).

25.3 Steps for Wetland Creation with Particular Reference to India

During the early 1990s, wetland restoration and creation were relatively new sciences in the United States, with little scientific documentation (Barber 1992). Perhaps this observation is applicable to India and other developing countries in South Asia in the modern time frame. Though numerous water bodies are made in suburban or rural area from a socioeconomic angle, wetland creation with an ecological perspective is largely an unfamiliar activity. Salient steps to create wetlands from the viewpoint of ecological restoration of a rural landscape are mainly adopted from Biebighauser (2002, 2008) as outlined in the following paragraphs.

The foremost step in creating a replacement wetland is to identify a piece of land for wetland creation from an ecological viewpoint. One should be aware that one of the most important factors influencing identification of land for creation of a replacement wetland in developing and populated countries of South Asia is the accessibility to the land. It is widely known that land procurement even for compensatory afforestation is difficult in India as land is a limited resource that, on one hand, is required for multiple purposes and on other hand faces multiple issues like unclear land titles and difficulties in complying with procedures for land use (Chaturvedi 2015). What is true for the compensatory afforestation would also be true for replacement wetland creation. The situation might be similar in other populated countries of South Asia too. To cope up with such land resource limitation, a piece of land can be selected in a wasteland. Alternately, it can also be identified in forest land. In the rural landscape of India, often there are areas of land known as forest lands that are under the jurisdiction of the state-level forest departments, which are overseen by the Ministry of Environment, Forest and Climate Change (MoEF & CC). Many such forest lands are often barren despite conventionally being called “forests”. These lands can be considered for the ecological purpose of restoring landscapes with replacement wetlands to compensate for overall wetland destruction due to development processes. Moreover, the work of creating replacement wetlands can be undertaken by the forest departments of the respective states of India as these departments have already been engaged in protection of ecosystems like forests, desert, grasslands, and wetlands, as well as corresponding wildlife species. Irrigation departments in various states create and maintain irrigation reservoirs and dams, but their primary and often only purpose is irrigation. Though these wetlands do support aquatic biodiversity, there is no certainty that aquatic biodiversity will get protection as the ultimate purpose of these wetlands is the irrigational well-being of the area. However, if forest departments in various states are assigned the task of creating “ecological ponds” on appropriate forest lands in respective states, then they will have an added mission of creating and maintaining

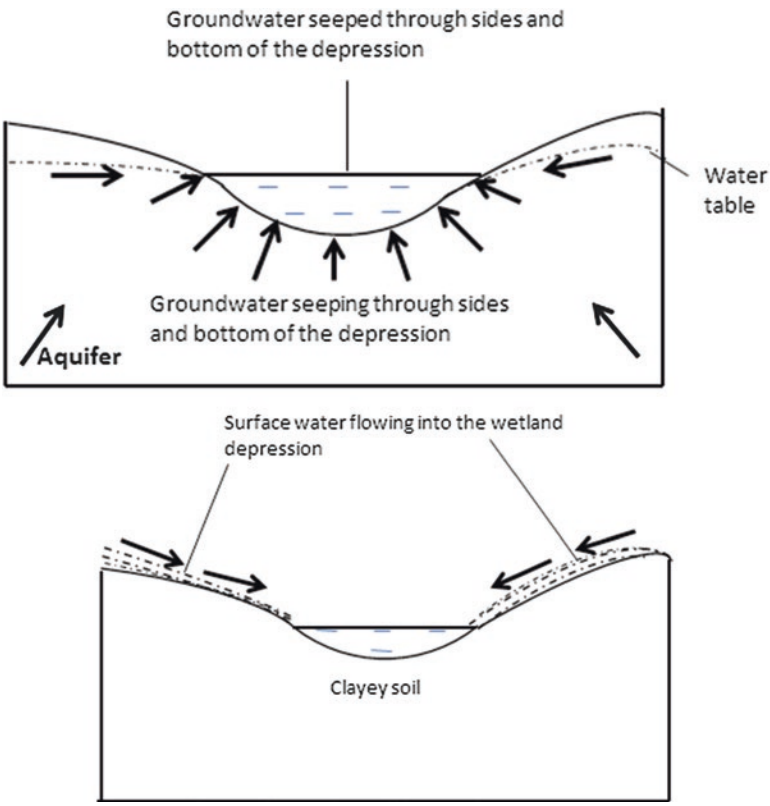


Fig. 25.2 Created wetlands having groundwater (top) and surface water (bottom) as water source

replacement or "ecological" wetlands in which the ultimate aim will be the ecological well-being of the landscapes. Forest departments have already been engaged in developing and nurturing human-made forests through afforestation. Parallel to that, they may be assigned the role of creating and maintaining human-made replacement wetlands (that may be called "ecological wetlands") on the forest lands. The identified land for creating replacement wetland should be as flat as possible, although sloped surfaces surrounding the wetland are desirable for surface water wetlands. Biebighauser (2002) has mentioned that a wetland of any size and shape (preferably irregular, oval, or round blending into surrounding landscape) can be created. Biebighauser (2008) opined that an area of approximately 25 m in diameter will be spatially sufficient for giving a natural appearance to the human-made wetland to be constructed. This will constitute the wetland construction site and mark the boundary. The actual water spread area of the wetland can be up to half of the total area within the marking. The area between the proposed water area and marking will be used to pile up wooden debris, vegetation, and topsoil, and to build a dam, if required. Further, it is to be determined whether the wetland to be created will be supplied by surface water or groundwater. A surface water wetland would hold rainwater just like a clay bowl holds liquid. In contrast, a groundwater wetland would hold groundwater that seeps through its sides and bottom similar to a dug well. A schematic presentation of this concept is given in Fig. 25.2.

Whether the wetland to be created should be a "surface water wetland" or "groundwater wetland" can be determined by excavating a few holes in the ground of the wetland creation site. Such holes should be at least 1 m deep and should be in the center of the wetland creation site. After digging such holes, if the groundwater seeps into it from the bottom and sides and fills up the hole at least partly, it would indicate a high water table. In that case, the created wetland should be a groundwater-based wetland. In other words, groundwater would function as source of water for such a wetland. If groundwater does not seep into the dug hole, it might indicate the possibility that the created wetland will have to depend on surface water as a source. It may be noted that while excavating the depression for a wetland, one may come across "mineral soil," which typically lies below the topsoil. For a created wetland that must be fed with surface water, the mineral soil should contain considerable amounts of clay and silt, or else it cannot effectively hold the water.

Start to modify the landscape to create a replacement or restoration wetland. For that purpose, make a sketch depicting the shape, size, and exact location of the planned pond and its immediate environs. Keep it available for discussions among those involved in its creation. The planned shape, location, and size of the wetland to be created should be marked on the ground using flags or stakes.

(a) Shape should be irregular, circular, or oval since other shapes such as square and rectangular do not merge naturally into surroundings.
(b) Size should be at least 2 ha, and maximum water depth should be in the range of 50–60 cm; with this depth, the ecological goal for wetland creation would include provisioning of habitat to surface-feeding waterfowl.
(c) Slope of the shoreline should be gradual (e.g., 5:1, Pataki and Cahill 1997).

Creating a wetland in a contemporary, modified landscape often requires construction of at least some infrastructure to manipulate water levels, soil, and vegetative species composition (Heitmeyer et al. 2013). The extent and intricacy of such structuring and landscape modification will depend on the type of site selected and size of the pond. Moreover, the level of complexity will also decide whether one should use manual tools or heavy equipment for excavation and pond construction.

Manual pond digging is a common practice in villages of India. In the drought-affected, semi-arid, and arid portions of rural areas of northwestern and western India, it has been a common practice of state governments to engage poor and needy villagers as manual labor for digging ponds as a means of relief work during drought years since the 1970s. Through this relief work, the governments create artificial ponds that store rainwater, mainly for domestic use, and pay poor villagers daily wages for their labor. In fact, wetland creation, either through forest departments or as a community effort, may not require major use of heavy machines. This is especially true if a planned pond is small and simple.

However, if construction of a new wetland requires moving a considerable amount of soil, then the use of heavy machines like a dozer and a track hoe becomes necessary (Biebighauser 2002). Moreover, some experience and knowledge regarding engineering surveys and use of survey instruments (e.g., construction level, staff, and chain link) might be necessary. Very technical matters like how to use the engineering instruments (e.g., construction level, stack, staff, chain links, etc.) and for what purposes they should be used are matters beyond the scope of this article. Those interested in such matters can refer to Biebighauser (2002, 2008).

25.4 Limitations of Wetland Creation

The USDA Soil Conservation Service (SCS 1997) has mentioned that creation of large and complex wetlands can have high costs and management requirements. In creating wetlands at places where they never existed, one has to face the challenges of establishing a balanced wetland hydrology and developing hydric soils in short-time periods, as hydric soils are mandatory for the establishment of a hydrophyte community. Though we can create replacement wetlands to compensate for lost natural wetlands, the created wetlands may appear as an artificial patchwork in the landscape. Moreover, not all created wetlands match the functions of natural wetlands.

25.5 Conclusion

Avoiding wetland degradation and loss is the most effective strategy for maintaining wetland function. However, wetland mitigation can be an effective strategy for combating wetland degradation and wetland loss when avoidance is impractical. Wetland creation is an effective way of mitigating wetland loss in a landscape if it replaces the lost wetlands' function by creating a replacement wetland with equal or great ecological function. Although we can create replacement wetlands to compensate for lost natural wetlands, there are limitations to wetland creation activity, as not all created wetlands can perform the same functions as natural wetlands. We must strive to maintain a balance of avoiding wetland impacts when practical and creating new wetlands.

References

Anonymous (2007) Wetland Restoration Guide (Preserving and Re-creating Our Wildlife Water Wonderlands in the Bay of Plenty). Environment Bay of Plenty, New Zealand. https://www.boprc.govt.nz/media/29543/Guide-090618-WetlandRestorationGuide.pdf. Accessed 1 Nov 2015

Barber R (1992) Restoring and creating wetlands: a planning guide for the central states region: Iowa, Kansas, Missouri, and Nebraska. United States Environmental Protection Agency, Kansas City

Bassi N, Dinesh Kumar M, Sharma A, Pardha-Saradhi P (2014) Status of wetlands in India: a review of extent, ecosystem benefits, threats and management strategies. J Hydrol Reg Stud 2:1–19

Biebighauser TR (2002) A guide to creating vernal pond. USDA forest service in cooperation with Ducks Unlimited Inc. and the Izaak Walton League of America. KY, USA.

Biebighauser TR (2008) Build your own wetland. Ky Woodlands Mag 3(2):12–15

Chaturvedi A (2015) The compensatory afforestation fund bill, 2015. PRS Legislative Research, New Delhi

CLRP (2007) Draft Discussion of Potential Environmental Mitigation Activities for Agency Review. Metropolitan Washington Council of Governments, Washington, DC. http://www.mwcog.org/regionaltransportationplan/activities/PDFs/env_mitigation_discussion_Oct07.pdf. Accessed 5 June 2015

Davidson NC (2014) How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar Freshw Res 65(10):934–941

Gopal B (2015) Wetland conservation for biodiversity and ecosystem services needs a shift in land and water resources policies (Policy Brief). National Institute of Ecology, New Delhi

Heitmeyer M, Fredrickson L, Lubhan M, Nelson F, Pogue G, Helmers D, King W (2013) Wetland design and development. In: Anderson JT, Davis CA (eds) Wetland techniques-applications and management-Vol.3, Springer, New York, p 270

Mitsch WJ, Gosselink JG (2000) Wetlands. Wiley, New York

National Wetlands Working Group (1988) Wetlands of Canada. Ecological land classification series, no. 24. Environment Canada and Polyscience Publications, Ottawa, pp 452

Ontario Naturalists (2000) Wetland restoration and rehabilitation. Federation of Ontario Naturalists, Ontario http://www.ontarionature.org/discover/resources/PDFs/misc/wetland_restoration.pdf. Accessed 1 May 2015

Osmond DL, Line DE, Gale JA, Gannon RW, Knott CB, Bartenhagen KA, Turner MH, Coffey SW, Spooner J, Wells J, Walker JC, Hargrove LL, Foster MA, Robillard PD, Lehning DW (1995) Watersheds: water, soil and hydro environmental decision support. System. http://h2osparc.wq.ncsu.edu. Accessed 5 June 2015

Pataki GE, Cahill JP (1997) Technical guidance for creating wetlands (as part of unconsolidated surface mining reclamation). division of fish, wildlife and marine resources & division of mineral resources. New York State Department of Environmental Conservation, New York

SCS (1997) Wetland Restoration, Enhancement or Creation (Chapter 13). In: Engineering Field Handbook (Part 650), Soil Conservation Service (SCS) Natural Resources Conservation Services, U.S. Department of Agriculture, Washington DC. http://www.engr.colostate.edu/~bbledsoe/CIVE413/Wetland%20RestorationEnhancement_or_Creation.pdf. Accessed 1 June 2015

Strager MP, Anderson JT, Osbourne JD, Fortney R (2011) A three-tiered framework to select, prioritize, and evaluate potential wetland and stream mitigation banking sites. Wetl Ecol Manag 19:1–18

Mangrove Restoration: An Overview of Coastal Afforestation in India

26

G.A. Thivakaran

Abstract

Mangroves, a major wetland type in the intertidal belt, are one of the most productive ecosystems in the world. With their annual disappearance at the rate ~1%, mangrove conservation through plantation has gained an unprecedented significance in the recent decades. Many South and Southeast Asian countries are regularly engaged in mangrove restoration initiatives through massive plantation initiatives. Akin to this trend, mangrove wetland restoration in terms of plantation is underway in the Indian state of Gujarat where plantation to the tune of 30,000 ha has been completed so far. The Gulf of Kachchh (GoK) coast of Gujarat in India has witnessed sustained mangrove plantation efforts in the last two decades. *Avicennia marina* is the preferred candidate species in this region due to its environmental plasticity.

In the Gulf of Kachchh, three different plantation techniques, namely, (a) transplantation of nursery-raised saplings, (b) raised bed method, and (c) direct propagule dibbling, are generally followed either singly or in combination to raise mangrove plantation. These different techniques have their own pros and cons though transplantation of nursery-raised saplings is considered as most successful. Many unresolved issues such as high incidence of mortality, poor site selection, poor technical skills, and legal bottlenecks in obtaining appropriate sites cripple mangrove plantation in the GoK. Proactively involving coastal industries in mangrove restoration activities together with participation of other stakeholder coastal communities could be more meaningful and productive. Thus, an integrated sustainable mangrove management plan encompassing different stakeholders is suggested. It is also recommended that instead of plantation

G.A. Thivakaran (✉)
Gujarat Institute of Desert Ecology (GUIDE), P.B. No. 83, Mundra Road,
Bhuj, Kachchh 370 001, Gujarat, India
e-mail: athivakaran028@gmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_26

as the sole measure of restoration, other restoration techniques such as biophysical amendments could be undertaken.

Keywords
Avicennia marina • Gujarat • Mangrove plantation • Stakeholders

26.1 Introduction

Wetland ecosystem covers an area of about 8.3–10.1 million km^2 in the world and constitutes about 6.4% of the global landmass (Lehner and Döll 2004). Wetlands include diverse habitats ranging from extensive peats, bogs, tropical mangrove forests, seasonal ponds and marshes, floodplains, riparian swamps, freshwater lakes, margin of reservoirs, salt lakes, brackish lagoon, estuaries, and coastal salt marshes (Gopal 1995; Gopal and Sah 1995). Wetlands are among the most productive ecosystems on earth, producing food and raw materials for many people and freely providing valuable services. Maltby (1986) aptly describes wetland as waterlogged wealth. During the last few decades, tropical wetlands have been destroyed, degraded, and considerably altered, driving many associated species to near extinction. The recent "Millennium Assessment" of ecosystem puts wetland biodiversity as the most threatened of all types of biodiversity.

As a prominent wetland in the ecotone between land and sea, ecological, economical, and social services of mangroves are numerous. They are a distinct ecosystem composed of peculiar plants, animals, and microbes. A vast coastal populace depends on this ecosystem for their traditional livelihoods. Nevertheless, indiscriminate degradation and reclamation (in fact, filling up) of this valuable ecosystem continues unabated. India reportedly lost nearly 38% of wetlands during 1990s (Khaleel 2009). In case of mangroves, which make up less than 0.4% of world forests, a worldwide loss of 1% per annum and 0.66% in India has been earlier reported (Kathiresan and Bingham 2001; FAO 2007). In some areas, the rate of reclamation and degradation is as high as 2–8% per year (Miththapala 2008). It is estimated that within 100 years from now, mangrove wetlands may become so degraded that they would be considered as "functionally disappeared" (Duke et al. 2007). It is apparent that the present rate of mangrove disappearance could be controlled only through effective and refined mangrove plantation, restoration, and rehabilitation measures. The three different terms, namely, rehabilitation, restoration, and plantation, are interchangeably used to denote mangrove plantation. Field (1999) defines rehabilitation as return of degraded mangrove land to a fully functional mangrove ecosystem and restoration as returning the degraded mangrove land to something like its presumed original state. The term, plantation in this chapter in particular, relates to raising mangroves in a technically suitable coastal belt where mangroves were absent earlier.

Globally, mangrove conservation through restoration, rehabilitation, and plantation has a long history and it is discussed in detail by several authors (Watson 1928; Chapman 1976; Lewis 1982; Hamilton and Snedaker 1984; Lewis 1990; Crewz and Lewis 1991; Saenger and Siddiqi 1993; Field 1996; Lewis 1999; Lewis and Streever 2000; Macintosh et al. 2012). Since early 1990s, many South Asian and Southeast Asian countries, which harbor nearly 80% of mangrove cover of the world, are engaged in mangrove restoration and plantation initiatives. Efforts to conserve, protect, and restore them can be seen in many South and Southeast Asian countries such as Bangladesh, India, Indonesia, Myanmar, Seychelles, Sri Lanka, Pakistan, Thailand, and Vietnam (Macintosh et al. 2012). Since 1985, in Pakistan 800 km^2 of mangroves is planted in the Sindh and Balochistan coast (Memon 2012). Among South Asian countries, Bangladesh is pioneering in mangrove plantation as massive mangrove afforestation program is in operation since 1960s, resulting in restoring/planting about 1773 km^2 of mangroves in four coastal provinces (Ahmad 2012). This probably is the highest extent of mangrove plantation undertaken by any country. Mangrove restoration through plantation gained further impetus post-Indian Ocean tsunami in 2004, which unambiguously proved mangroves' shoreline protective role. In Indian Sunderban alone, 17,288 ha of mangrove plantation has been carried out by 2011. Among Indian states, Gujarat so far has carried out plantation to an extent of 25,000 ha since last two decades that, probably, is the highest extent of mangrove plantation among Indian maritime states.

In South and Southeast Asian countries, restoration is mostly through plantation. In countries like Pakistan, Sri Lanka, Bangladesh, Indonesia, and Myanmar, plantation is mostly carried out through transplanting nursery-raised seedlings (Memon 2012) with some minor variations. For example, in Pakistan, along with transplantation of nursery-raised saplings, plantation of seedlings collected from wild and broadcasting seeds are followed as a supplementary to seedling transplantation. In India, though nursery method is common, planting techniques vary regionally, e.g., planting seedlings in coconut shells is practiced in Karnataka, using cut bamboos to raise seedlings is practiced in Kerala, and raising seedlings in earthen pots and planting seedlings along artificially constructed canals is practiced in Tamil Nadu. One method specific to Gujarat is "raised beds" wherein seeds are dibbled on raised circular or square earthen beds in order to counter tidal currents.

26.2 Mangrove Plantation in Gujarat, India

Implementation of mangrove plantation with stakeholder communities like fishermen, livestock tenders, and other resource users is increasingly becoming a norm for mangrove plantation in the Gulf of Kachchh (GoK), Gujarat, India. It stems from the belief that community-raised mangroves will be taken care by the stakeholders since their livelihood is directly related to mangrove well-being. Conservation efforts without envisioning the local needs and values have failed in many instances (Ostrom 1990). However, mangrove plantation in participatory mode is generally opted by government and non-government agencies. While according sanction to new coastal industries, Ministry of Environment, Forest and Climate Change (MoEF & CC), New Delhi, mandates mangrove plantation as a condition specifying the extent of plantation to be raised by the industry. This legal directive has prompted many industries to take up mangrove plantation in the coastal stretches of Gujarat. From 1996 to 2015, government agencies and coastal industrial houses have completed around 25,000 ha of mangrove plantation in several stretches of Kachchh coast alone which forms northern coastal belt of GoK.

26.3 Techniques Followed in Mangrove Plantation

Identifying suitable intertidal stretch for mangrove plantation is the first step in the mangrove plantation activity. A list of biophysical parameters such as gradient of the intertidal belt, soil nature, number of days of tidal flushing, presence/absence of natural mangroves in the vicinity, and availability of adequate intertidal extent are considered while choosing an intertidal belt for plantation. One major parameter that is paid special attention is the number of days of tidal flushing which in turn is influenced by the gradient of the intertidal area; intertidal stretches with gentle gradient receiving good tidal flushing for >15 days in a month are chosen for plantation.

26.3.1 Method of Plantation

A sound knowledge of the site is prerequisite to choose which method/s are to be followed. In GoK, three different methods as given below are generally adopted either singly or in combination to raise mangrove plantation based on the site conditions and potential for obtaining higher survival percentage.

1. Transplantation of nursery-raised saplings (polybag method)
2. Raised bed method (locally called *Otla* method)
3. Direct propagule dibbling (locally called *Sing* plantation)

26.3.1.1 Transplantation of Nursery-Raised Saplings (Polybag Method)

Nursery method is considered as the most reliable and best method yielding high success rate in mangrove plantation. Another major advantage of establishing a mangrove nursery is that it extends the period of plantation activity and a ready-made stock of saplings are available which could be utilized for plantation at appropriate timing of the year. Transplanting nursery-raised saplings shows higher survival rate than other methods since saplings have a well-established root system and they are maintained under simulated conditions for longer duration. Further, incidence of crabs eating the seeds and seedlings are minimal in nurseries. However, this method is cost and labor intensive and takes more time than other plantation methods. In spite of its higher cost and longer time, nursery method is the most preferred method in GoK coast.

Nurseries are developed in beds of 1000 or less polythene bags placed parallel to the tidal water sources such as creek systems and minor channels, which daily flush the nursery beds. In GoK, though three species, namely, *Avicennia marina*, *Ceriops tagal*, and *Rhizophora mucronata*, are used in the plantation, *A. marina* is the preferred species for nursery raising. Generally, polythene bags of 5×8 inches are filled with clayey sediment collected from nearby mudflats during low tide to raise the seedlings. The filled polybags are kept in shade for few days before they are arranged on the nursery bed. In many coastal stretches of India, mangrove nurseries are developed indoor with care and regular watering, yielding 100% survival of saplings (Selvam et al. 2005). However, this indoor nursery practices are seldom attempted in GoK, and it is always a practice that nurseries are developed in an extensive manner in outdoor conditions along minor creek banks where they are fed by tidal flows. In this extensive nursery preparation method, many factors like natural tidal watering and water logging are beyond the control resulting in lesser survival rates. Transplantation of nursery-raised saplings is undertaken when saplings attain a particular height. Different densities and gaps are followed to produce a final sapling density of 5,000–10,000/ha after an anticipated 10% mortality of planted saplings.

26.3.1.2 Raised Bed Method (*Otla* Method)

This method of plantation is unique to Gujarat and is not practiced in any other coastal stretches of India. In GoK, this method is preferably followed in majority of the plantation ventures since it is perceived to give better results while countering strong tidal currents. In this method, earthen mounts of 10–15 cm height are raised, and propagules numbering 15–20 are sown on the surface of the raised bed. Generally, the number of raised beds per hectare is more than 400 and may go up to 1500 beds by adopting different spacing. Mounts in each row are raised in alternate fashion in order to reduce tidal velocity in ebb and flow tidal currents. In the coastal stretches with moderate tidal currents, raised earthen mounts counter the ebb and flow of tidal currents and prevent uprooting of the planted saplings/propagules.

26.3.1.3 Direct Propagule Dibbling

Direct propagule dibbling is less cost and labor-intensive. This method is frequently used to restore potential mudflats and is often used to supplement other methods of plantation in order to raise survival percentage. This method is simple and even untrained laborers can follow it. In this method, mangrove propagules are dibbled in mudflats at specific intervals. Propagules are dibbled in such a way that nearly two-thirds of it is above the sediment surface while one-third is buried into the sediment. Different spacing is maintained between each dibbled propagule based on the type of mangrove forest to be developed. Generally, a spacing of 1×1 m^2 is preferred, and propagules are soaked in freshwater for nearly 24 h in order to fasten the germination and achieve higher survival rate.

26.4 Issues in Mangrove Plantation

By virtue of possessing the largest extent of mudflats suitable for mangrove plantation, GoK of late is witnessing extensive mangrove plantation both by government agencies and by industrial houses. Nevertheless, many unresolved issues cripple mangrove plantation efforts in the area. The foremost problem faced in many plantation activities is poor survival. Often, plantation activities are undertaken in technically unsuitable sites resulting in high mortality of planted mangroves. Site selection, the most important criterion that determines the extent of plantation success and requires scientific input, is often ignored resulting in poor survival in the plantation. In addition, poor technical skill and failure to understand the governing scientific principles of plantation lead to costly failures. Engaging trained and skilled workforce with good knowledge of site-specific conditions will ward off failure in many plantation efforts.

Increasing the technical capacity of different organizations engaged in mangrove plantation is essential. This could be done through (a) awareness programs; (b) conducting scientific studies and developing technical packages for plantation in a participatory manner by expert consultants, implementing agencies, and community organization involved; and (c) through training programs on ecological and economic value of the mangroves and other aspects of restoration and regeneration. Similarly, awareness programs and exposure visits to other project sites with the participation of local community and various other agencies will enable exchange of ideas and learning new techniques.

Coastal industries and corporate houses that are mandated to carry out mangrove plantation are often constrained by legal bottlenecks like non-availability of suitable plantation sites in revenue land. Though Kachchh coast has several potential mudflats for plantation activities, they fall under the legal jurisdiction of forest department, which, as per law, cannot be leased out to corporate houses. This legal constraint prevents many coastal industries from taking up plantation, which needs to be addressed before involving industries in mangrove plantation.

Coastal industries in Gujarat are in a position to contribute better for mangrove conservation through plantation. A series of activities by forest department could be initiated to involve industries in mangrove plantation, which will go a long way to conserve mangroves. Some of the measures that could be initiated are:

- Forming a forum of industries in coastal regions with the mandate to regenerate and restore mangroves
- Working out mechanisms to enable availability of forest land in the coastal belt to aspiring industries for plantation
- Organizing workshops and meetings with industrial association/industries to motivate them to take mangrove regeneration
- Exposure visits for key personnel from the industries
- Linkages and networking with NGOs and community organizations for lobbying against industries that are not complying with environmental protection laws

It is often claimed that impact of industries on mangroves by way of direct reclamation and chronic degradation is the primary cause for areal shrinkage of mangroves in GoK. However, there is dearth of studies that tangibly point out this impact. In fact, involving industries in mangrove restoration works by the earlier India-Canada Environment Facility (ICEF) funded project, which was implemented in different parts of Gujarat, has yielded very limited results. One of the serious constraints identified in involving the industries in mangrove plantation is related to availability of lands. A mechanism has to be developed by industries and government agencies by which industries can undertake mangrove restoration and conservation activities without bureaucratic delays.

Invariably, most of the mangrove plantations in Kachchh are single species in nature with *A. marina* as the only candidate species. Few multispecies plantation attempts with *Rhizophora mucronata* and *Ceriops tagal* by some coastal industries and forest department achieved very limited success. Inherent hypersaline coastal waters and aridity of the zone are major hindrances to multispecies plantation efforts. Ease of plantation due to proven and standardized technique, high adaptation to prevailing coastal *milieu*, increased survival due to its hardy nature, and high seed resources are reasons rendering *A. marina* as the only candidate species in all plantation activities in Kachchh.

In many coastal stretches of Gujarat and particularly in Kachchh, macrolevel environmental factors such as climate, rainfall, freshwater runoff, and supply of sediments are not favorable to support high species diversity and luxurious growth of mangroves as in Sundarbans or Bhitarkanika of Odisha. However, it is possible to grow mangroves in the mid-tidal areas of the vast mudflats by manipulating microlevel environmental factors such as soil conditions and tidal flow. In many plantations of Kachchh, survival and growth of mangrove seedlings are poor, and there is constant exposure or uprooting of seedlings due to high tidal currents. Coastal geomorphology of Kachchh, except in some locations, has hard rocky formation just below the surface that prevents establishment of the saplings. This is one of the main causes for exposure of the roots of the seedlings. This problem can be addressed and growth may be enhanced by suitable technical means like deep pits. This highlights the underlying need for experimentation and innovations, which will improve the plantation success. In the readjustment of project design, considerable scope is to be given to conduct experiments, assess the results, and document the process.

Most of the mangrove plantation efforts by coastal industries are not in participatory mode. Coastal communities are involved only as laborers without any other stakes. The post-plantation care, which is essential to raise the planted mangrove into a full-fledged ecosystem, is taken care by the community in participatory mode. By negating community participation, many of the plantation activities tend to fail. Mangrove plantation in Gujarat in general faces the menace of grazing by livestock, mostly owned by nearby coastal villages. Grazing and browsing by cattle largely could be controlled in participatory mode as villagers take an active interest to prevent their livestock from grazing in the raised plantation and that does not happen in single institutional plantation activities.

In order to ensure greater sustainability and reduce the communities' degree of dependence on mangrove resources, formation of village *samithis* and creation of grass plots near villages was attempted in some instances. The best example is the ICEF funded project on community-based mangrove plantation. In this attempt, along with mangrove plantation, promotion of grassland was undertaken to reduce dependency on mangrove resources through raising alternate fodder sources. A robust benefit sharing mechanism was worked out to ensure equated distribution of gross production in tune with the cattle holding of each household. Though the annual grass yield from these plots met only a small portion of the fodder requirement, it amply demonstrated how an alternative fodder resource could be raised to wean the villagers from relying on a single resource. However, this attempt yielded only limited success since villagers often complain about lack of funds to maintain the raised grassland and mangrove plantation.

Post-plantation maintenance has emerged as a major issue in plantations raised in Gujarat. It is realized that participatory mode of plantation with local community involvement is the best means to enable raised plantation to become a functional ecological entity. An essential requirement in post-plantation maintenance is the creation of adequate funds for villagers for post-plantation activities.

An integrated sustainable mangrove management plan encompassing different sectors and players is to be aimed in all plantation activities to ensure that goods and services derived from mangrove forests meet the present-day fodder and ecological needs while securing their continued availability and contribution to long-term development. Sustainable mangrove management encompasses administrative, legal, technical, economic, social, and environmental aspects of conservation and use of mangroves. It also strives to integrate conservation and restoration of mangroves with the development in that coastal belt. Once in place, it is to be ensured that the plantation activities result in such a sustainable situation by continuous midcourse correction in all the activities. Instead of treating mangrove plantation as a mere physical activity, more attention and actions are to be taken to make the impact felt at social, ecological, and economic realm of the coastal mass. Mangrove villages as an ecosystem with its components of agriculture, animal husbandry, fisheries, rural development, and a host of other factors interacting with forestry in the form of fodder, fuel, manure, medicines, and aesthetics need to be kept as the basis while designing the strategies in a mangrove restoration program.

26.5 Discussion

It is apparent that the present rate of mangrove disappearance of 0.66% in India could be controlled only through effective and improved mangrove plantation, restoration, and rehabilitation. The current scenario in GoK clearly underlines the need for further refinement of the whole process by way of imparting technical skills to planters, more participatory mode of plantation, enhanced involvement of stakeholders like coastal communities, awareness creation, and involvement of industries. Inter-sectoral interest, which often hinders plantation activities, needs to be addressed by appropriate integrating mechanisms. The limitations inherent in the sectoral approach are in fact now recognized as major constraint for conserving mangrove resources (Olsen and Arriaga 1989; Nuruzzaman 1993). Though a sound ecological understanding is stressed while undertaking mangrove plantation (Ellison 2000), documented knowledge on mangrove ecology in Southeast Asia including India is poor (Biswas et al. 2009). Often researches leading to detailed understanding of ecological processes that govern success or failure in plantation activities are lacking (Biswas et al. 2009). Similarly, traditional knowledge on mangrove conservation and promotion is often neglected. Rist and Dahdouh-Guebas (2006) emphasize the use of science and traditional knowledge in management of natural resources. This kind of approach in participatory mode will yield better results in terms of successful plantations than programs purely based on scientific expertise.

In GoK, mangrove plantation sites are mostly chosen based on availability of suitable coastal stretches. In the absence of suitable sites, gaps among mangrove stands and even dense mangrove stands are chosen for plantation. Foremost criterion considered in defining a suitable site for mangrove plantation is tidal flushing. Though the field staffs are aware that site selection is the foremost criterion for successful mangrove plantation, they are often constrained by unavailability of good sites forcing them to choose sites of lesser suitability among scrubby or even dense vegetation. Analysis of factors that lead to low survival revealed that high natural erosion and the resultant tidal currents are the major reasons rendering the survival poor. Nevertheless, the practical experience possessed by the field staff coordinating plantation activities contributed positively. Implementers of plantation are generally aware that different sites have their own biophysical uniqueness and understanding the site properly and choosing the appropriate plantation technique is the key to success. In spite of this inherent knowledge, it would be further beneficial to impart them with basic practical methods of mangrove restoration/plantation in order to hone their practical skills.

Of all the plantation techniques adopted in GoK, raised bed (*Otla*) method is predominant one. Usually raised beds are made to counter the impact of tidal currents to prevent uprooting of the saplings. Arrangement of *Otla* beds in relation to the direction of incoming current is another factor to be considered. In majority of sites where raised bed method is followed, an alternate arrangement of *Otla* rows with adjacent rows could be observed that lessens the velocity of receding tidal currents and prevents sapling uproot. In order to reduce tidal impact and to enhance survival, this method could be followed uniformly in all future plantations.

As of now, plantation is the sole measure resorted for mangrove conservation. It is recommended that other restoration techniques by biophysical amendments to increase tidal flow to the stunted mangroves, rather than going for outright plantation could be attempted in future plantation activities; especially in scrubby/stunted stands facing inadequate tidal flushing, this restoration effort will yield better results. For example, desilting of natural canals will enhance tidal flushing rates and number of tidal days in natural stunted stands, rendering it healthier, viable, and a better functional ecosystem. These physical amendments in natural mangrove formations could be undertaken in sites where there is severe blockage to tidal flushing due to natural and human-induced causes. This could be done in a cost-effective manner yielding better results than direct plantation. A thorough and detailed surveillance and categorization of sites requiring different restoration approaches such as desilting, canal widening, removing blockage at canal mouth, and even constructing new canals could be more productive, rendering stunted formations into denser one.

Though GoK mangroves are known to have around eight true mangrove species, *A. marina* is the most predominant species, indicating nature's preference to this species. In view of its natural predominance, this species is most preferred in all plantation activities. Environmental plasticity of *A. marina* to tolerate extremes of salinity, temperature, and light intensity and its adaptation to different soil conditions is well proven (Downton 1982; Clough 1984; Macnae 1986; Shalom-Gordon and Dubinsky 1993; Ye et al. 2005; Jayatissa et al. 2008; Patel et al. 2010). Since GoK waters exhibit some of these environmental conditions, *A. marina*, as a candidate species, yields higher success rate in plantation ventures compared to other species whose tolerance limit is often limited. Easy seed availability, faster germination in high saline water, tolerance to prolonged drought situation, and higher growth rates enable good success rates for *A. marina*. Since species such as *R. mucronata* and *C. tagal* are less tolerant to water/soil salinity, they are planted close to waterfront in order to enhance tidal flushing. In such multiple species plantations, *R. mucronata* are planted near the waterfront followed by *C. tagal* and *A. marina* mimicking their natural zonation. Both *R. mucronata* and *C. tagal* are highly sensitive to salinity fluctuations. Their germination and sustained growth requires considerably less sediment and water salinity that is often unavailable in GoK coastline. Species-specific niche requirement like fringe areas of creeks and higher tidal flushing rates for both *R. mucronata* and *C. tagal* do not permit these species to be used in mass plantation efforts. Using other species like *Aegiceras corniculatum*, *Ceriops decandra*, and *Excoecaria agallocha* as candidate species for plantation is not feasible in GoK similar to other coastal *milieu* in proximity such as Pakistan and other Gulf countries, again due to the prevailing hypersaline environment.

26.6 Conclusion and Recommendations

It is generally believed that curbing mangrove deforestation is economically and ecologically more viable than restoration through plantation. In the context of Gujarat, deforestation has been largely arrested, and mangrove cover has registered an overall improvement due to increased conservation and restoration measures such as plantation. Long-term sustainability of mangrove restoration involves multifaceted approach such as robust management planning, capacity building at grassroot level, and awareness among all stakeholders and managers. Scope for streamlining the present restoration efforts in Gujarat is plenty that will manifold enhance the restoration outcome. Scientific input and intervention in terms of proper site selection, choosing carefully appropriate restoration method in tune with the biophysical condition of the site, and rigorous training to field staff engaged in plantation efforts are some crucial factors deserving immediate attention. Poor site selection as a single factor contributes to majority of plantation failures in Gujarat. Though many legal and technical bottlenecks cripple proper site selection, it could be overcome with an integrated approach. Another major lacuna observed is inadequate involvement of mangrove stakeholders such as coastal fishing communities, coastal industries, and cattle tenders. Promoting such public participation in mangrove plantation will ensure long-term sustainability of the raised resource ensuring that they become a fully functional ecological entity. Equally glaring is lack of restoration specific technical development and research that will render the plantation efforts more robust and technically sound. Despite these shortcomings, an overall positive approach toward mangroves is unfolding in recent years among stakeholders and policy makers, which needs to be transformed into actionable programs. Since Gujarat is pioneering among Indian states in mangrove restoration through plantation, concrete integrated management planning supported by a strong political will is most essential.

Acknowledgment The author is grateful to Gujarat Institute of Desert Ecology (GUIDE), Gujarat, India, for providing facilities and encouragement.

References

Ahmad IU (2012) Status of mangrove plantations in the living delta: an overview of the coastal afforestation experience of Bangladesh. In: Macintosh DJ, Mahindapala R, Markopoulos M (eds) Sharing lessons on Mangrove restoration. Mangroves for the Future and Gland, IUCN, Bangkok

Biswas SR, Mallik AU, Junaid K, Choudhury J, Nishat A (2009) A unified framework for the restoration of Southeast Asian mangroves-bridging ecology, society and economics. Wetl Ecol Manag 17:365–383

Chapman VJ (1976) Mangrove vegetation. J. Cramer, Vaduz, Liechtenstein p 477

Clough BF (1984) Growth and salt balance of the mangrove *Avicennia marina* (FORSK.) VIERH. and *Rhizophora stylosa* GRIFF. in relation to salinity. Aust J Plant Physiol 11:419–430

Crewz DW, Lewis III RR (1991) An evaluation of historical attempts to establish emergent vegetation in marine wetlands in Florida., Florida Sea Grant Technical Publication No. 60. Gainesville, Florida Sea Grant.

Downton WJS (1982) Growth and osmotic relations of the mangrove, *Avicennia marina* as influenced by salinity. Aust J Plant Physiol 9:519–552

Duke N, Meynecke J, Dittmann S et al (2007) A world without mangroves. Science 317(5834):41–42

Ellison AM (2000) Mangrove restoration: do we know enough? Restor Ecol 8(3):219–229

FAO, 2007. The world's mangroves 1980–2005, forest resources division, the food and agriculture organization of the United Nations. FAO Forestry Paper 153. Rome

Field CD (ed) (1996) Restoration of mangrove ecosystems, Okinawa: international society for mangrove ecosystems. Okinawa, Japan, p 89

Field CD (1999) Mangrove rehabilitation: choice and necessity. Hydrobiologia 413:47–52

Gopal B (1995) Handbook of wetland management. WWF, New Delhi

Gopal B, Sah M (1995) Inventory and classification of wetlands in India. Vegetatio 118:39–48

Hamilton LS, Snedaker SC (eds) (1984) Handbook of mangrove area management. East West Centre, Honolulu

Jayatissa LP, Wickramasinghe WAADL, Dahdough-Guebas F, Huxham M (2008) Interspecific variations in responses of mangrove seedlings to two contrasting salinities. Int Rev Hydrobiol 93:700–710
Kathiresan K, Bingham BL (2001) Biology of mangroves and mangrove ecosystems. Adv Mar Biol 40:81–251
Khaleel KM (2009) Study of the ecosystem services and socio economic impact of mangrove wetlands of North Malabar. Kerala State Council for Science Technology and Environment (KSCSTE), 124.
Lehner B, Döll P (2004) Development of validation of a global database of lakes, reservoirs, and wetlands. J Hydrol 296:1–22
Lewis RR III (1982) Mangrove forests. In: Lewis RR (ed) Creation and restoration of coastal plant communities. CRC Press, Boca Raton, pp 153–172
Lewis RR (1990) Creation and restoration of coastal plain wetlands in Florida. In: Kusler JA, Kentula ME (eds) Wetland creation and restoration: the status of the science. Island Press, Washington, DC, pp 73–101
Lewis III RR (1999) Key concepts in successful ecological restoration of mangrove forests. In: TCE-Workshop No. II, Coastal Environmental Improvement in Mangrove/Wetland Ecosystems, Bangkok. Network of Aquaculture Coordination in Asia, p19
Lewis III RR, Streever W (2000) Restoration of mangrove habitat. Technical Note, ERDC TN-WRP-VN-RS-3.2. Vicksburg: U.S. Army, Corps of Engineers Waterways Experiment Station, p 23
Macintosh DJ, Mahindapala R, Markopoulos M (eds) (2012) Sharing lessons on mangrove restoration. Bangkok, Thailand: mangroves for the future and gland. IUCN, Switzerland
Macnae W (1986) A general account of the fauna and flora of mangrove swamps and forest in the Indo-west-Pacific region. Adv Mar Biol 6:73–270
Maltby E (1986) Waterlogged wealth. Earthscan, London
Memon SH (2012) An overview of mangrove restoration efforts in Pakistan. In: Macintosh DJ, Mahindapala R, Markopoulos M (eds) Sharing lessons on Mangrove restoration. Mangroves for the Future and Gland, IUCN, Bangkok
Miththapala S (2008) Mangroves. Coastal ecosystems series volume 2. Colombo: Ecosystems and Livelihoods Group, Asia. IUCN 28
Nuruzzaman AKM (1993) Cluster of ideas and actions for fisheries development in Bangladesh. Fish Publishers, Technology and Engineering, p 416
Olsen S, Arriaga L (1989) A sustainable shrimp mariculture industry for Ecuador. Technical Report Series TR-E-6. International Coastal Resources Management Project. The University of Rhode Island Coastal Resources Center. Narragansett, RI p 276
Ostrom E (1990) Governing the commons: the evolution of institutions for collective action. Cambridge University Press, New York
Patel NT, Gupta A, Pandey AN (2010) Salinity tolerance of *Avicennia marina* (Forssk.) Vierh. from Gujarat coast of India. Aquat Bot 93:9–16
Rist S, Dahdouh-Guebas F (2006) Ethnosciences – a step towards the integration of scientific and traditional forms of knowledge in the management of natural resources for the future. Environ Dev Sustain 8:467–493
Saenger P, Siddiqi NA (1993) Land from the sea: the mangrove afforestation programme of Bangladesh. Ocean Coast Manag 20:23–29
Selvam V, Ravishankar T, Karunakaran VM, Ramasubramanian R, Eganatan P, Parida AK (2005) Toolkit for establishing coastal bio-shield. MS Swaminathan Research Foundation, Chennai, p 117
Shalom-Gordon N, Dubinsky N (1993) Diurnal pattern of salt secretion in leaves of the black mangrove *Avicennia marina* on the Sinai coast of the Red Sea. Pac Sci 47:51–58
Watson JG (1928) Mangrove forests of the Malay Peninsula. Malayan Forester, Record No. 6. Federated Malay States
Ye Y, Tam NFY, Lu CY, Wong SH (2005) Effects of salinity on germination, seedling growth and physiology of three salt secreting mangrove species. Aquat Bot 83:193–205

Part VIII

South Asian Wetlands: Legislations and Policies

Conservation of Coastal Wetlands: An Appraisal of the Policy and Legal Framework in South Asian Nations

27

R. Ramesh, R. Purvaja, P. Krishnan, Ahana Lakshmi, K.R. Abhilash, and Paul W. Kingsley

Abstract

Coastal wetlands are highly productive ecosystems that provide wide range of ecosystem services. South Asia, with its long coastline, has diverse coastal wetland ecosystems that are subject to serious threats caused by pollution and overexploitation of resources. The legal environmental instruments of different nations illustrate their intent towards the sustainable environmental governance. South Asian nations have formulated policies and legal framework for efficient management of coastal wetland resources and to meet the standards set by international regulatory instruments. This chapter discusses the national legal instruments and institutional frameworks structured to address the issues faced by coastal wetlands of the five maritime South Asian nations, namely, India, Sri Lanka, Maldives, Bangladesh and Pakistan. It also discusses the international instruments, the guiding principles for development of national instruments, to be enforced to conserve and manage the coastal resources in a sustainable and effective way.

Keywords

Act • Coastal wetlands • Conservation • Environmental governance • Policy

R. Ramesh (✉) • R. Purvaja • P. Krishnan • A. Lakshmi • K.R. Abhilash • P.W. Kingsley
National Centre for Sustainable Coastal Management (NCSCM), Ministry of Environment Forest & Climate Change, Anna University Campus, Chennai 600 025, Tamil Nadu, India
e-mail: rramesh_au@yahoo.com; purvaja.ramachandran@gmail.com; krishnanars@yahoo.com; ahanalakshmi@gmail.com; abhilaashkr@gmail.com; paulwkingsley@aol.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_27

27.1 Introduction

27.1.1 Coastal Wetlands: An Overview

The wetlands are areas covered by water either at or near the surface of the soil, either all through the year or temporarily (seasonally). As per the Ramsar Convention, the wetlands are defined as 'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters' (Ramsar Convention Secretariat 2010).

The coastal wetlands play an important role in supporting a wide spectrum of biodiversity characterized by the presence of water-dependent species of plants and animals along the coast, as well as maintaining many natural cycles. These diverse and complex ecosystems provide goods and services that contribute towards the nation's economy. The ecosystem services provided by these wetlands to the communities are broadly classified as provisioning services, regulating services, supporting services and cultural services.

27.1.2 Status of Coastal Wetlands of South Asia

The South Asia (SA) comprises the sub-Himalayan and adjoining countries to the west and east and includes Afghanistan, India, Pakistan, Bangladesh, Sri Lanka, Nepal, Bhutan and Maldives. Of these, Afghanistan, Nepal and Bhutan are landlocked countries and hence are not considered in this chapter. While Bangladesh, India and Pakistan are situated on the Asian mainland, Maldives and Sri Lanka are island nations. A summary of the major features of the five maritime countries of South Asia is given in Table 27.1.

The coasts of South Asia harbour a wide range of coastal ecosystems and habitats, *viz*. mangroves, coral reefs, sand dunes, mudflats, salt marshes and seagrass

Table 27.1 Geographic and demographic information

Country	Population	Area (km^2)	Coastline (km)	Area within EEZ (km^2)	Shelf area (km^2)
Bangladesh	14,97,72,364 (Census, 2011)	1,47,570	580	86,392	66,438
India	1,21,01,93,422 (Census, 2011)	3,28,80,00,000	7,517	2,305,143	4,02,996
Maldives	4,07,660 (Census, 2014)	300	644	9,23,322	34,538
Pakistan	1,32,352 (Census, 1998)	7,96,095	1,046	2,35,999	51,383
Sri Lanka	2,03,59,439 (Census, 2012)	65,610	1,340	5,32,619	32,453
Total	**1,38,08,65,237**	**3,28,90,09,575**	**11,127**	**40,83,475**	**5,87,808**

Table 27.2 Coastal wetlands of South Asian countries

Country	Wetland areas (km^2)					
	Inland	Coastal	Manmade	Total wetland area	Mangroves	Coral reefs[a]
Bangladesh	46,000[b]	51,968[c]	73,587[c]	171,555	4,365.70[d]	<50
India	66,230.67[e]	37,039.71[e]	43,779.77[e]	147,050.15	4,628[f]	5,790
Maldives	1.75[g]					8,920
Pakistan	74,079.2[h]		1,956.7[f]		1,683[i]	<50
Sri Lanka	60,935.9[j]	2,170.64[j]	8,400.7[k]	71,507.24	6,080[k]	680

[a]Spalding et al. (2001)
[b]CBD (2012)
[c]Byomkesh et al. (2009)
[d]Dahdouh-Guebas and Satyanarayana (2012)
[e]SAC (2011)
[f]FSI (2013)
[g]UNEP (2006)
[h]Rais et al. (2013)
[i]Abbas et al. (2011)
[j]CBD (2009)
[k]IUCN Sri Lanka and CEA (2006)

meadows. The significant ones are the reefs of Gulf of Mannar, Lakshadweep Islands in India, atolls of Maldives and mangroves of the Sundarbans spread across India and Bangladesh. The large coastal lagoons of Chilika and Puttalam are located in India and Sri Lanka, respectively. The entire coastline from Pakistan to Bangladesh runs to about 10,000 km, with wetlands occupying 134,161 km^2 (UNEP and DA 2008). The distribution of coastal wetlands in the South Asian countries is provided in Table 27.2.

The coastal wetlands face various challenges due to the complex interactions among physical, biological and anthropogenic factors. The human populations are concentrated along the coasts, which has affected and altered the coastal ecosystems worldwide (Adger et al. 2005). The anthropogenic pressures include those from industrial, agricultural, aquaculture and urban developmental activities, which result in the discharge of wastes into waterways, over-exploitation of the coastal and marine resources and the physical alteration and destruction of habitats. The waste disposed into the rivers and estuaries ultimately reach the coastal waters and contribute to eutrophication and deterioration of the water quality. Reclamation of wetlands, as well as encroachment for various activities, has also shrunk the areal extent of the wetlands in many places (MEA 2005). Further, the coastal wetlands are also threatened by climate change including the increasing temperature, sea level rise (SLR) and other extreme events (Day et al. 2008).

Each South Asian country possesses significantly diverse coastal wetland biodiversity, which is discussed in the ensuing sections. An estimated 135 million people, accounting to about to 22.5% of the global coastal population, inhabit the coastal zone of South Asia. The coastal zones account for about 40% of the economic activities in the region. Because of the high levels of interlinkages between the natural ecosystems, especially wetlands, the conservation actions need to be implemented at scales that commensurate with the ecological processes, features and services, in order to achieve meaningful habitat and biodiversity-oriented goals. Hence, only the efforts at ecosystem and landscape scale would yield reliable results. Recognizing this, the conservation efforts of coastal wetlands are carried out through various soft and hard regulatory instruments at the international level and through appropriate policy and legislations at national level, often derived from international frameworks.

This chapter reviews the status of various instruments at the global level focusing on the conservation of coastal wetland ecosystems, as well as the relevant policy and legal frameworks adopted by different coastal South Asian countries. This chapter also offers a review of the current regulatory provision for conservation of coastal wetlands in South Asia and the way forward.

27.2 Global Perspective on Wetland Conservation

A number of 'soft' instruments such as consultative conference, declarations and guidelines, and 'hard' instruments such as bilateral and multilateral treaties and conventions have been promulgated over the years that have components for the conservation of wetlands.

27.2.1 Conference Declarations

The United Nations Conferences: beginning in 1972, four conferences have been held.

The *United Nations Conference on the Human Environment* held in 1972 at Stockholm, Sweden, was the first of the series. The principle 2 of the Stockholm Declaration stated that 'The natural resources of the earth, including the air, water, land, flora and fauna and especially representative samples of natural ecosystems, must be safeguarded for the benefit of present and future generations through careful planning or management, as appropriate' (UN 1972). Many countries, including India, followed up this conference declaration by enacting framework legislations to protect the environment.

In 1992, the *United Nations Conference on Environment and Development* (UNCED) was held in Rio de Janeiro, Brazil. Also known as the Earth Summit, the Agenda 21 brought out during the conference has been considered a blueprint for sustainable development (UN 1992). The conference called for integrated coastal zone management (ICZM) and ecosystem-based approach, which replaced the sectoral approach. The agenda classifies the coastal wetlands as fragile environment that needs priority for prevention from desertification and degradation. It encouraged the states to identify the coastal ecosystems that exhibit high levels of biodiversity and productivity for effective management. It also called for demarcation of coastal areas that require intense conservation and protection by establishing protected areas. The objective of these proposed recommendations at the conferences in *Agenda 21* aimed at wise and sustainable use and management of natural resources for longer sustenance of resource-dependent community livelihoods. Three important multilateral agreements, Convention on Biological Diversity (CBD), United Nations Convention to Combat Desertification (UNCCD), and United Nations Framework Convention on Climate Change (UNFCCC), collectively called the Rio Conventions were opened for signature by the participating parties during the Earth Summit, of which the CBD is of high relevance with respect to conservation of biodiversity including that of wetlands (UNCED 1993).

In 2002, the *World Summit on Sustainable Development* (WSSD) was held at Johannesburg, South Africa. The Johannesburg Declaration on Sustainable Development and Johannesburg Plan of Implementation (JPoI) called on states to, inter alia, 'develop national, regional and international programmes for halting the loss of marine biodiversity, including coral reefs and wetlands; implement the Ramsar Convention, including its joint work programme with the Convention on Biological Diversity, and the programme of action called for by the International Coral Reef Initiative to strengthen joint management plans and international networking for wetland ecosystems in coastal zones, including coral reefs, mangroves, seaweed beds and tidal mud flats; and reduce the risks of flooding and drought in vulnerable countries by, inter alia, promoting wetland and watershed protection and restoration, improved land use planning, improving and applying more widely techniques and methodologies for assessing the potential adverse effects of climate change on wetlands and, as appropriate, assisting countries that are particularly vulnerable to those effects' (UN 2002).

Recently, in 2012, the *United Nations Conference on Sustainable Development* (Rio+20) was held in Rio de Janeiro, Brazil. The conference had two main themes of green economy in the context of sustainable development and poverty eradication and the institutional framework for sustainable development for international coordination and highlighted seven priority areas including water and oceans (UN 2012).

Thus, the various United Nations Conferences have emphasized the need for conservation and protection of wetlands, especially those in coastal areas, and, in some cases, given explicit instructions on the way forward, usually achieved through international conventions and national legislation.

27.2.2 Multilateral Agreements

The Ramsar Convention on Wetlands, the United Nations Convention on the Law of the Sea (UNCLOS), the CBD, the Convention on the Conservation of Migratory Species of Wild Animals (CMS) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) are the most relevant multilateral agreements in force today and are briefly discussed in the following sections.

27.2.2.1 Ramsar Convention

The Convention on Wetlands of International Importance, especially as Waterfowl Habitat, better known as Ramsar Convention, provides the framework for the conservation and wise use of wetlands and their resources. The convention was adopted in the Iranian city of Ramsar in 1971 and came into force in 1975. Although the convention originally emphasized the conservation of the wetlands as habitat for waterfowl, over time, its scope broadened to encompass all aspects of wetland conservation and sustainable use (UN 1971). The central philosophy of Ramsar Convention is the 'wise use' of wetlands, 'the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development' (Ramsar Convention Secretariat 2010). The contracting parties commit to work towards the wise use of all the wetlands and water resources in their territory, through national plans, policies and legislation, management actions and public education.

To facilitate the conservation of wetlands, the convention has broadly classified the wetlands into five major types: (1) *marine* (coastal wetlands including coastal lagoons, rocky shores and coral reefs), (2) *estuarine* (deltas, tidal marshes and mangrove swamps), (3) *lacustrine* (wetlands associated with lakes), (4) *riverine* (wetlands along rivers and streams), and (5) *palustrine* (marshes, swamps and bogs) (Ramsar Convention Secretariat 2004).

All the coastal states of South Asia, except Maldives, are contracting parties to the Ramsar Convention (Table 27.3). Being a signatory to the convention, the member countries are entitled to access (1) expert advice on national and location-specific problems of wetland conservation and management and (2) international support for conservation. It also brings increased publicity and prestige for the designated wetlands and provides an opportunity to the member states to make their voice heard in the principal intergovernmental forum (Ramsar Convention Secretariat 2013). The major success of the convention is in enhancing the

Table 27.3 South Asian countries and membership in international conventions

Country	Ramsar[a]	CMS[b]	UNCLOS[c]	CBD[d]	CITES[e]
Bangladesh	21.09.1992	Party (2005)	27.07.2001	01.08.1994	20.11.1981
India	01.02.1982	Party (1983)	29.06. 1995	19.05.1994	20.07.1976
Maldives	Not a member	Range state	07.09.2000	29.12.1993	12.12.2012
Pakistan	23.11.1976	Party (1987)	26.02.1997	24.10.1994	20.04.1976
Sri Lanka	15.10.1990	Party (1990)	28.07.1995	21.06.1994	04.05.1979

[a]Ramsar (2015)
[b]CMS (2015)
[c]UNCLOS (2015)
[d]CBD (2015)
[e]CITES (2015)

awareness of the importance of wetlands for a wide range of ecosystem services they provide and the conservation of designated Ramsar sites. Further, the convention has also helped in poverty alleviation through implementation of 'working for water' and 'working for wetlands' programmes.

27.2.2.2 Convention on Migratory Species of Wild Animals

The CMS, also known as the Bonn Convention, which was signed in 1979, came into force in 1983. This multilateral treaty aims to conserve terrestrial, aquatic and avian migratory species throughout their range. It provides a global platform for the conservation and sustainable use of migratory animals and their habitats, bringing together the states through which migratory animals pass (range states), and lays the legal foundation for internationally coordinated conservation measures throughout a migratory range (CMS 2005). The migratory species threatened with extinction are listed on Appendix I of the convention. The CMS parties strive for protecting these animals, conserving or restoring the places where they live, mitigating obstacles to migration and controlling other factors that might endanger them (Matz 2005). The migratory species that need or would significantly benefit from the international cooperation are listed in Appendix II of the convention. The agreements between the states in various forms help in concerted action to protect the migratory species and their habitats. Among the five South Asian maritime states, Maldives is listed as a range state, while the others are parties to the convention (Table 27.3).

27.2.2.3 United Nations Convention on the Law of the Sea, 1982

Recognized as the 'Constitution of the Oceans', UNCLOS came into force on 16 November 1994. The Articles 61 and 62 deal with the conservation and utilization of living marine resources within the exclusive economic zone (EEZ), and the Articles 117–119 deal with the conservation of living resources in the high seas. The UNCLOS serves as a framework convention for other international treaties such as CBD. All the five South Asian maritime nations are signatories to UNCLOS (Table 27.3).

27.2.2.4 Convention on Biological Diversity

One of the three Rio Conventions, the CBD came into force on 29 December 1993. Its main goals are conservation of biological diversity, sustainable use of its components and fair and equitable sharing of benefits arising from genetic resources. Among the seven thematic programmes established by the convention, the programme on marine and coastal biodiversity evolved from the Jakarta Mandate, a global consensus on the importance of marine and coastal biological diversity and a part of the ministerial statement at the Conference of the Contracting Parties (COP) meeting in Jakarta in 1995. It identifies the key operational objectives and priority activities within the key programme elements, namely, implementation of integrated marine and coastal area management, marine and coastal living resources, marine and coastal protected areas, mariculture and alien species and genotypes. It uses the ecosystem approach as one of the basic principles for the implementation of the programme of work. The CBD works in cooperation with Ramsar and other conventions to conserve biodiversity through various coordinated activities, and all the five maritime nations of South Asia are parties (Table 27.3).

27.2.2.5 Convention on International Trade in Endangered Species of Wild Fauna and Flora

The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) came into force on 1 July 1975. The aim of this convention is to ensure that international trade in specimens of wild animals and plants does not threaten their survival. As the trade in wild animals and plants crosses borders between countries, the effort to regulate it requires international cooperation to safeguard certain species from over-exploitation. The convention accords varying degrees of protection to more than 35,000 species of animals and plants, regardless of the form in which they are traded. The CITES provides a framework to enable parties to adopt their domestic legislation to implement CITES at the national level. Though it does not specifically target wetlands, its scope encompasses the biodiversity of the wetlands by focusing on their trade to ensure that the wetland bioresources are not over-exploited. All five South Asian maritime nations are parties to CITES (Table 27.3). A bill to amend India's Wildlife (Protection) Act was introduced in the Upper House of Parliament in 2013. This amendment includes provisions relating CITES to control illegal trade of wildlife and the insertion of new Schedule VII to the act listing flora and fauna for purpose of regulation of international trade under CITES in which a number of coastal and marine species have been included (MoEF 2013).

27.2.3 Regional Instruments

There are a number of regional level instruments in the form of cooperative agreements and action plans focusing on various parts of the environment especially with respect to the conservation initiatives related to coastal ecosystems.

27.2.3.1 South Asia Co-operative Environment Programme

The South Asia Co-operative Environment Programme (SACEP) is an intergovernmental organization, established in 1982 by the governments of South Asia region to promote and support protection, management and enhancement of the environment in the region (SACEP 2015). Since its creation, SACEP has implemented a number of projects and programmes in the areas of environment education, environment legislation, biodiversity, air pollution and the protection and management of the coastal environment. Presently, the programme focuses on the development of strategies to cope with the natural disasters. Further, the ICZM, development and implementation of National and Regional Oil and Chemical Spill Contingency Planning, implementation of Marine Litter Programme and institutional strengthening and capacity development for the long-term management and conservation of Marine and Coastal Protected Areas (MCPAs) encompassing coral reefs in South Asia are some of the priority areas of SACEP.

The SACEP is also the secretariat for the South Asian Seas Programme (SASP), one of United Nations Environment Programme's (UNEP's) Regional Seas Programme. The South Asian Seas Action Plan (SASAP), adopted in March 1995, focuses on ICZM, oil spill contingency planning, human resource development and the environmental effects of land-based activities. Although there is no regional convention yet, SASAP follows existing global environmental and maritime conventions and considers Law of the Sea as its umbrella convention.

27.2.3.2 Mangroves for the Future

The Mangroves for the Future (MFF) is a unique partner-led initiative to promote investment in the coastal ecosystem conservation for sustainable development and is co-chaired by IUCN and United Nations Development Programme (UNDP) (MFF 2015). This initiative applies an ecosystem-based approach to build community resilience in diverse coastal habitats. It initially focused on the countries that were worst affected by the tsunami in 2004 but now includes other countries as well. While the mangroves are the central focus of this initiative, MFF is inclusive of all types of coastal ecosystems and habitats. The MFF grants facility offers small, medium and large grants to support initiatives that provide practical and hands-on demonstrations of effective coastal management in action. Each country manages its own MFF programme through a national coordinating body with representation from government, non-governmental organizations (NGOs) and private sector.

27.2.3.3 Instruments of the Convention on Migratory Species

The Central Asian Flyway (CAF) covers a large continental area of Eurasia between the Arctic and Indian Oceans and the associated island chains. The CAF includes various habitats that provide abode to migratory waterbirds, and an action plan was drafted to conserve those migratory waterbirds and their habitats. The plan covers over 182 migratory waterbird species, which includes 29 globally threatened and near-threatened species (CMS 2005). It represents several important migration routes relevant to waterbirds covering 30 countries of North, Central and South Asia and the Transcaucasus region. The Central Asian Flyway states have undertaken to promote the conservation of migratory waterbirds and their habitats. The nesting habitat of these species in the countries of their flyway are identified and protected. Their habitats range from inland deserts to coastal wetlands. The Plan calls for a collaborative approach of national/international and state/non-state agencies.

Indian Ocean-South-East Asian Marine Turtle Memorandum of Understanding is an intergovernmental agreement concluded under the auspices of the Convention on Migratory Species (CMS). It aims to protect, conserve, replenish and recover marine turtles and their habitats of the Indian Ocean and South-East Asian region, working in partnership with other relevant actors and organizations. The species of marine turtles covered by the MoU are the loggerhead (*Caretta caretta*), olive ridley (*Lepidochelys olivacea*), green sea turtle (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), leatherback (*Dermochelys coriacea*) and flatback (*Natator depressus*). The conservation and management plan under the MoU containing 24 programmes and 105 specific activities focus on reducing threats, conserving critical habitats, exchanging scientific data, increasing public awareness and participation, promoting regional cooperation and seeking resources for implementation.

27.3 Policy Frameworks for Wetland Conservation

Conservation policies are broad statements of intent to deal with the environmental issues that aid in framing appropriate legislation. These policies are framed in consonance with the environmental and social principles, set by the international regulatory instruments. The guiding environmental principles include the ecological sustainability, the polluter pays principle and the precautionary principle. The social principles that guide policymaking include equity, human rights and public participation. However, the economics dictate the implementation and execution of the environmental policy. Providing incentives for the implementation of the policies and the market-oriented approach has been widely adopted at national and international levels. A brief account of the environmental policies of the five coastal South Asian nations for addressing the protection, governance and conservation of their national wealth of coastal wetlands is presented hereafter.

27.3.1 Bangladesh

27.3.1.1 National Water Policy, 1999

The National Water Policy (NWP) of Bangladesh was framed to address the issues surrounding river basin planning, water rights and allocation, participation of public and private institutions, water supply and sanitation, fisheries, navigation, agriculture, industry and environment (MoWR 1999). Fisheries and wildlife play a critical role in the economic development of Bangladesh, and, in order to safeguard these resources, the policy takes measures to minimize the disruption to the natural aquatic environment in streams and waterways. The policy also indicates that any sort of developmental activities requiring direct access to waterways should not interfere with fish migration and breeding that could pose threat to their population. Aquaculture developments in brackish areas are given special zones to limit their influence on the coastal wetland ecosystems. This policy addresses the concern over the availability of water for the protection, restoration and preservation of the ecosystems such as wetlands and other national forests. In addition, the quality of water available for environmental sustainability was emphasized as it plays a crucial role in sustaining a balanced ecosystem. The policy highlights the environmental issues faced by the coastal ecosystems, especially by the wetlands, such as groundwater depletion, watershed degradation and deforestation, salinization of agricultural lands, excessive sedimentation, reduction of biodiversity, wetland loss, saltwater intrusion and coastal zone habitat loss. Further, the National Environmental Management Action Plan (NEMAP) and the National Water Management Plan (NWMP) were framed. Additionally, the policy enunciated the importance of upland water flow to preserve the coastal estuarine ecosystems by minimizing the seawater intrusion. It encourages extensive afforestation, stop clearance of vegetation on newly accreted agricultural lands and reduction of discharge of pollutants into the environment.

27.3.1.2 Coastal Zone Policy, 2005

The Coastal Zone Policy (CZP) was framed as a step to protect Bangladesh's vulnerable coastal zone, which is prone to natural disaster such as cyclone, floods, storm surges, coastal erosion, increase of soil salinity and coastal pollution. The objectives of this policy are to (1) conserve the coastal resources for their contribution to the national economy, (2) improve the socioeconomic status of the coastal livelihoods and (3) protect the coastal zone from natural disasters and prevent further deterioration of the coastal environment. The policy provides the general guidance for managing and developing the coastal zone of Bangladesh. It inculcated the concept of ICZM for better understanding and management of the coastal zone (MoWR 2005). The policy framework is based on eight principles that include economic growth, opportunities for livelihoods, reduction of vulnerabilities, sustainable management of natural resources, equitable distribution, empowerment of communities, women empowerment and conservation and improvement of critical ecosystems.

The protection of coastal zone has been incorporated into the Comprehensive Disaster Management Plan, with the introduction of sea dykes as the primary line of defence against storm surge (MoWR 2005). The sustainable use of coastal resources and environmentally adapted and socially responsive aquaculture activities are encouraged along the coastal areas, which would have minimal impact on the coastal wetland ecosystems. The afforestation of the coastal areas and the conservation of coastal forests with a socially responsible use of coastal forestry resources are intended. The policy acknowledges the importance of international instruments and agreements during the formulation of the coastal conservation and management plan. Bangladesh also has developed the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) in 2009.

27.3.2 India

27.3.2.1 National Forest Policy, 1988

The National Forest Policy, 1988, aims at maintaining the environmental stability of the forest, restoring the ecological balance of the forests and conserving the country's natural heritage (forests). It has a check over the extension of sand dunes along the coastal tracts, and it promotes the increase in forest cover along the ocean shores through afforestation and thereby increasing their productivity (MoEF 1988).

27.3.2.2 National Conservation Strategy and Policy Statement on Environment and Development, 1992

This policy statement provides guidelines to develop the nation's environment and aids in the implementation of policies that are framed for protecting the environment (MoEF 1992). The policy statement gives an outline of the legal instruments, institutions and the measures taken to prevent various aspects of environmental concerns such as pollution control, forest and wildlife conservation, land and soil conservation, environmental impact assessment and environmental awareness programmes. Under Section 2, Environmental Problem: Nature and Dimensions, it is clearly mentioned that problems of pollution and over-exploitation are being faced by the country's unique wetlands that provide not only food and shelter but also serve as the breeding and spawning grounds for the marine and freshwater fishes and that the coastline as well as coastal ecosystems such as mangroves and coral reefs are under stress due to over-exploitation. It suggested various steps to be taken for the sustainable use of land and water including conservation of wetlands for ensuring sustainable ecological and economic benefits and for conservation of biodiversity through a network of protected areas including biosphere reserves, marine reserves, national parks, sanctuaries, gene conservation centres, wetlands and such other natural habitats of biodiversity.

27.3.2.3 National Environmental Policy, 2006

The National Environmental Policy (NEP) aims at plugging the gaps in the policy instruments framed for conserving and protecting the environment. With respect to wetlands, the policy recognized the non-existence of a formal system of wetland regulation outside the international commitments made in respect of Ramsar sites. It also called for a holistic view of wetlands, which looks at each identified wetland in terms of its causal linkages with other natural entities, human needs and its own attributes. Further, it suggested that a legally enforceable regulatory mechanism for identified valuable wetlands should be developed along with a national inventory of such wetlands to prevent their degradation and enhance their conservation; conservation and prudent use strategies for each significant catalogued wetland, with participation of local communities and other relevant stakeholders, should be formulated (MoEF 2006). With respect to the coastal resources, the NEP mentions that these resources comprise a diverse set of natural and manmade assets, including mangroves, coral reefs, estuaries, coastal forests, genetic diversity, sand dunes, geomorphological features, sand beaches, land for agriculture and human settlements, coastal infrastructure and heritage sites. It suggested a series of action plans including mainstreaming of sustainable management of mangroves into the forestry sector, supporting regeneration of coral reefs, explicitly considering issues of sea level rise and climate change and adopting a comprehensive approach to integrated coastal zone management.

27.3.3 Maldives

Article 22 of the Constitution of Maldives states that it is a fundamental duty to protect and preserve the natural environment of the country for the benefit of present and future generations. Vision 2020 of the Maldives government expresses the country's aspiration for environmental protection and preservation. One of the six long-term goals envisioned is 'protective measures will be taken to combat global environmental threats and environmentally friendly lifestyles will be adopted'. The first National Environmental Action Plan (NEAP I) had been formulated in 1990, and the second National Environmental Action Plan (NEAP II) was formulated in 1999. The successive national development plans have stressed the importance of sound practices for environmental and natural resources management (GoM 2014).

27.3.4 Pakistan

27.3.4.1 National Environmental Policy, 2005

The NEP of Pakistan provides an overall framework for addressing various environmental issues in Pakistan such as pollution of fresh and coastal waters, air pollution, deforestation, desertification, natural disasters, climate change and loss of biodiversity. The policy clearly gives directives for sectoral and cross-sectoral actions for improving the coastal health, its resources and the dependent communities. The policy was drafted around a set of objectives, *viz*. conservation, restoration and management of environmental resources, adaptation of integrated environmental planning, enhancing the capacity of government agencies and compliance with international obligations (MoE 2005). The policy ensures protection and rehabilitation of mangroves, and in cases of critically threatened ecosystems, it encourages conservation and restoration. The policy lays provision to create national parks and marine protected areas for conservation of biodiversity with the involvement of the community. It encourages the implementation of integrated coastal zone management plans for protection of marine life and/or bioresources.

27.3.4.2 National Wetlands Policy, 2009

The National Wetland Policy (NWP) aims at addressing the threats to Pakistan's wetlands, creating and implementing regulative measures for sustainable use and conservation of wetlands, executing a coordinated approach nationally and internationally to conserve the wetlands, promoting wetland research and database management, capacity building and securing financial resources for sustainable management of wetlands (MoE 2009). The NWP works around the principles of ecosystem and knowledge-based conservation and management of wetlands, equitable sharing of wetland resources, implementation of good governance and stewardship, transboundary coordination, stakeholder participation in managing the wetlands and no net loss of biodiversity in the wetlands in the long run upon implementation of the necessary policy and regulative measures for wetland management.

This policy also provides the strategies for action to meet the objectives of the wetland policy. The policy gives directives for enforcement of the National Environmental Quality Standards that aid in the monitoring of pollutants converging into the coastal wetlands from upstream activities (MoE 2009). It also addresses the issues caused due to climate change that directly affect the wetlands, especially the coastal wetlands.

27.3.4.3 National Forest Policy, 2010

The National Forest Policy (NFP) of Pakistan provides a framework for sustainable management and conservation of forests and its resources. The objectives of the NFP are:

1. Restore and maintain natural forests.
2. Increase their productivity and function to improve the forest-depended livelihoods.
3. Encourage the use of non-wood products and maximize wood substitutes.
4. Enhance carbon sequestration.
5. Develop sectoral forest management plans, tailored to conserve and protect the forest biodiversity and strengthen the forest education and research.
6. Encourage a collaborative and community-involved multi-stakeholder partnership for better management of the forest areas (MoE 2010).

The policy also focuses on improving the mangrove and riverine forests to protect the coastal and estuarine ecosystems, which serve as habitats for fish nurseries, shrimp and other coastal aquatic animals. The policy works towards reduction of pollution in the coastal forest areas, increased freshwater flow into estuaries to minimize seawater influence on coastal ecosystems and estuarine ecosystems and also reduction of the exploitation of the forest resources by the local communities for fuel and fodder (MoE 2010). For these measures, the policy encourages incentive-based management of coastal forest systems. The policy also recognizes the nation's commitment to international treaties that deal with wildlife conservation and emphasizes on the conservation and management of various aquatic habitats and their bioresources.

27.3.4.4 National Climate Change Policy, 2012

The National Climate Change Policy (NCCP) was developed to provide the framework for addressing the issues that would be faced by Pakistan due to climate change. It covers the issues surrounding a wide range of sectors such as water, agriculture, forestry, coastal areas, biological diversity and other vulnerable ecosystems. The policy enunciates the threats the coastal areas would face due to the SLR and the increased cyclonic activity. The policy lists the preventive measures to safeguard the nation's coastal ecosystems by developing the natural barriers as well as raising artificial barriers, maintaining the water flow and reducing the pollution that affects the bay areas and promoting the sustainable use of the coastal wetland resources (MoCC 2012). These steps were not only focused on conserving the coastal wetland resources but also to secure the livelihood of the coastal communities that depend on the wetland resources. The policy was framed with the sound knowledge and assessment of climate change impacts.

27.3.5 Sri Lanka

Sri Lanka has an array of policies for the protection of its valuable environmental resources, which aim at good resource management and socioeconomic development (UN 2015). The environmental policies, concerning coastal wetlands of Sri Lanka, are described hereunder.

27.3.5.1 The National Forest Policy, 1995

The NFP 1995 formulated by the Ministry of Agriculture, Lands and Forestry aims at managing the forests of Sri Lanka in a sustainable way and conserving them with regard to the biodiversity, soil and water of the forest as such and recognizes the historical, cultural, religious and aesthetic values associated with forestry resources (SFD 2011).

27.3.5.2 National Wildlife Policy, 2000

The National Wildlife Policy (NWP 2000) of Sri Lanka provides for conserving the wildlife resources through promoting conservation, maintaining ecological processes and life-sustaining systems, managing genetic diversity, ensuring sustainable utilization and equitable benefit sharing of biodiversity. It emphasizes the need for effective management of protected areas with the participation of local communities. In addition, it promotes the cooperation among all stakeholders through joint decision-making at all levels.

27.3.5.3 National Environmental Policy, 2003

This policy (NEP 2003) aims at promoting the sound management of Sri Lanka's environment, balancing the needs for social and economic development and maintaining the environmental integrity. It also aims to manage the environment by linking together the activities, interests and perspectives of the stakeholders and to ensure the environmental accountability (MoENRS 2003). Specifically, the application of the NEP is to focus on achieving certain outcomes, one of which is 'the wetlands, those that are of importance for their ecological functions are protected'.

27.3.5.4 National Policy on Wetlands, 2006

The formulation of the National Policy on Wetlands (NPW), 2006, is a major step taken by the Ministry of Environment and Natural Resources towards wetland conservation and protection by recognizing their cultural and economic importance to the people of Sri Lanka. The NPW signifies Sri Lanka's commitment to preserve the ecological values and functions of the country's wetlands. The main objectives of the NPW, 2006, are to protect and conserve the wetland ecosystems, prevent illegal utilization of wetlands, enhance the ecosystem services from wetlands, restore the biodiversity and productivity of wetlands, assure the sustainable use by local communities and meet the national commitments to Ramsar Convention (CEA 2006). As a management strategy, the policy states that all the wetlands would be zoned and classified with respect to their levels of ecological, utilitarian, international, national and local significance. It also emphasizes the need for bringing the privately owned wetlands under the government fold through legal reforms. Importantly, the policy supports an integrated approach towards wetland management that involves participatory and collaborative processes. The policy also encourages research programmes that benefit the wetland conservation. The policy had led to the establishment of local level Wetland Management Committees (WMC) under the National Environment Act (NEA) to manage the wetlands with community and other stakeholder participation. It also laid the foundation for the formation of Wetland Facilitating Committees (WFCs) at division and district level (CEA 2006), the functioning of which will be monitored by the National Wetland Steering Committee (NWSC). The policy is supported by a strategy and action plan that explains the functions and responsibilities of each of the governmental and non-governmental institutions, involved in wetland conservation and sustainable management.

27.3.6 Appraisal of Wetland Conservation Policies in South Asia

The South Asian countries have considered the challenges faced by their coastal environment from multiple dimensions, and each country has taken into account the issues of concern into their national policy framework. Based on the complexity of the issues surrounding their respective nation's coastal ecosystems, each state has attempted to address strategic measures to mitigate the effects on both natural and anthropogenic effects separately. All the five coastal South Asian nations have a policy framework, which tries to be in compliance with the international environmental policy guidelines to conserve and protect their respective coastal resources.

While Maldives does not possess a sectoral policy to address issues of their coastal wetlands, it has taken steps to address the threats affecting their environment and the ecosystems through their Climate Change Policy Framework. The CBD has declared the entire country of Maldives as United Nations Educational, Scientific and Cultural Organization (UNESCO) Biosphere Reserve, to be effective from 2017, in order to conserve and protect the natural resources, especially of the coastal environment, which is the major driving force for the island's economy.

Sri Lanka has addressed its commitment towards coastal wetland conservation through NFP, 1995, and NPW, 2006, thereby encouraging an integrated conservation of resources through research and education. The policies highlight the necessity of establishing national, district and local level administrative agencies.

Bangladesh's NWP, 1999, and the CZP, 2005, recognized the major threats to coastal wetlands and give directives for their management. The impacts of aquaculture activities on coastal ecosystems have been recognized, and zoning for aquaculture development to prevent their adverse impacts on the estuarine ecosystems has been suggested. In addition, these two policies focus on the environmental, social and economic development of the coastal resources and the livelihoods of those depending on the coastal ecosystems.

Pakistan has an array of policies, such as the NEP, 2005; the NWP, 2009; the NFP, 2010; and the NCCP, 2012, for addressing the aforementioned issues. All these policies recognize and adhere to their commitment to international environmental agreements and emphasize the importance and effectiveness of integrated and collaborative environmental management. Pakistan has included the issue of climate change into their policy framework via the NCCP, 2012. It also prescribes the need for sustainable and balanced harvesting of wetland resources and advocates (IWRM) for improved management of the watersheds to ensure that the coastal wetlands are supplied with enough water to sustain their ecosystems, especially in the estuarine areas.

India has, in place, the NFP, 1988; National Conservation Strategy and Policy Statement on Environment and Development, 1992; and NEP, 2006, to conserve and protect the ecosystems of the coastal wetlands of India. All these policies aim at maintaining the environmental stability recognizing the ecological, economic and social values of the coastal wetlands. These policies support the concept of sustainable management of coastal wetland ecosystems by directing the agencies with respect to IWRM, identifying ecologically vulnerable ecosystems, which can be declared as protected areas for better conservation of ecosystem resources and promotion of stakeholder participation in environmental management.

The CBD requires all the countries to prepare their respective National Biodiversity Strategy and Action Plan (NBSAP) (or equivalent instrument) and to ensure that this strategy is mainstreamed into the plan addressing all activities of various sectors that could have an impact (positive and negative) on biodiversity. All the five South Asian countries have finalized their National Biodiversity Strategy and Action Plan or equivalent instruments. The states have updated their environmental conservation and developmental strategies in consonance with the Millennium Development Goals and the Aichi Biodiversity Targets.

27.4 Legal and Regulatory Instruments for Wetland Conservation

Each coastal South Asian nation has various legal instruments for conservation of wetlands and associated natural resources.

27.4.1 Bangladesh

27.4.1.1 Bangladesh Environment Conservation Act, 1995

The Bangladesh Environment Conservation Act (BECA), 1995, provides for protection of the environment, improvement of the environmental standards and control and abatement of the pollution of the environment. This act provides for the establishment of Department of Environment by the government and also for declaring an area to be an ecologically critical area. According to the act, where the discharge of an environmental pollutant in excess of the limits prescribed by rules occurs, the person responsible shall be bound to prevent or abate the environmental pollution occurred (BMoEF 1995). It restricts establishment of industrial enterprise by requiring them to obtain an environmental clearance from the director general of Department of Environment.

27.4.2 Maldives

27.4.2.1 Environment Protection and Preservation Act of Maldives, 1993 (Law No. 4/93)

The Environment Protection and Preservation Act of Maldives, 1993, lays down the basic principles and rules of environment protection in the Maldives. It is enacted to protect and preserve the country's land and water resources, flora and fauna as well as the beaches, reefs, lagoons and all natural habitats important for the sustainable development of the country. The act addresses the nation's concern on the harmful and hazardous impacts of disposal of wastes, oil and poisonous substances and toxic or nuclear wastes. It necessitates the assessment of environmental impacts for any developmental projects for the protection and preservation of its environmental resources.

27.4.3 India

27.4.3.1 The Wildlife (Protection) Act, 1972

The Indian Wildlife (Protection) Act (IWPA), 1972, was formed in the backdrop of the rapid decline of India's wild animals and birds, which in some cases have become endangered or extinct. This act has listed all the species, which need protection under six schedules, and each schedule has varying degrees of protection. The species in Schedule I and part II of Schedule II have the maximum protection, and exploitation of those species would result in highest penalty. The plants identified in Schedule VI are prohibited from cultivation and planting (MoEF 1972). Some of the coastal wetland wildlife that are rare and of high ecological importance such as corals, dugongs, sea cucumbers and crabs are listed under Schedule I. Further, the sponges (calcareous) and certain molluscs found in the marine environment are listed under Schedule III and IV, respectively. The act prohibits trade and commerce of scheduled species and provides powers to the empowered officers to function as per the directions given in the act. This act provides the state government the freedom to declare an area as a wildlife sanctuary within its territory if the area shows adequate ecological, faunal, floral, geomorphological, natural or zoological significance for the purpose of protecting, propagating or developing wildlife or its environment. Significant coastal wetlands that are demarcated as protected areas under the act are Gulf of Mannar Marine National Park in Tamil Nadu, Mahatma Gandhi Marine National Park, Wandoor in Andaman and Nicobar Islands, Sundarbans Tiger Reserve (STR) in West Bengal and Gulf of Kachchh (GoK) in Gujarat.

27.4.3.2 Environment (Protection) Act, 1986

The Environment (Protection) Act (EPA), 1986, is considered as an umbrella legislation, which provides the framework to implement the decisions made at the 1972 Stockholm Conference and aids in overseeing the activities of various regulatory agencies under the existing laws and legislations and creation of authorities to govern the environment. This act encourages sustainable development and prohibits those activities that affect human environment and health. Moreover, this act sets standards for the quality of environment with respect to various aspects and lays standards for emission or discharge of environmental pollutants (MoEF 1986). The regulatory instruments of direct relevance to wetlands under the EPA, 1986, are Wetlands (Conservation and Management) Rules, 2010; Coastal (Regulation) Zone (CRZ) Notification, 2011; and Island (Protection) Zone Notification, 2011.

Wetlands (Conservation and Management) Rules, 2010, were drafted keeping in mind the need for conserving and protecting the wetland resources of the country. This is a measure taken in recognition of India's commitment to the Ramsar Convention (MoEF 2010). The wetlands that were identified and require regulation are (1) wetlands of international importance under Ramsar Convention; (2) ecologically sensitive wetlands of importance such as mangroves, coral reefs and areas of outstanding natural beauty and historical or heritage significance, wetlands recognized under UNESCO World Heritage Sites; and (3) inland wetlands that are at high elevation (high-altitude wetlands) and also those spread over 500 ha. The rules list out the activities that are prohibited, regulated and permitted, but with caution that they do not cause any detrimental damage to the wetland ecosystems such as aquaculture, agricultural and horticultural activities, construction of jetties and other authorized activities (MoEF 2010).

Coastal Regulation Zone (CRZ) Notification, 2011, replaces the thither to CRZ, 1991, and was notified with specific objectives of ensuring the livelihood security of coastal communities, conserving and protecting coastal areas and encouraging sustainable development based on scientific ecological principles. For the purpose of regulation, the CRZ notification has classified the coast into four zones, CRZ I–IV (MoEF 2011a). CRZ I brings under its fold the ecologically sensitive areas and includes various coastal wetlands, while CRZ IV refers to the water and seabed up to the territorial limit on the seaward side and includes the tidally influenced waterbodies. The notification focuses on regulating developments and implementing measures to abate pollution from land-based activities, coastal erosion and other forms of coastal environment degradation (MoEF 2011a).

Island Protection Zone (IPZ) Notification, 2011: The IPZ, 2011, was drafted specifically to protect and regulate the natural resources of the two island groups of India: Andaman and Nicobar Islands and Lakshadweep Islands. This notification was framed to give special importance to the complexly unique island ecosystems, as they were treated equally with the mainland coastal ecosystems. The management plans for the island groups are of two categories: (i) Integrated Island Management Plan (IIMP) and (ii) Island Coastal Regulation Zone (ICRZ). The ICRZ is the categorization of the coastal area into four regulative zones: ICRZ I–IV. This ICRZ applies only to the islands of Middle Andaman, North Andaman, South Andaman and Greater Nicobar. The other islands of Andaman and Nicobar, along with the islands of Lakshadweep, are managed by IIMP (MoEF 2011b). The notification provides guidelines for developing the IIMP and lists the permitted, regulated and prohibited activities in both the island groups with the objective of conserving and protecting their pristine coastal ecosystems.

27.4.3.3 Biological Diversity Act, 2002

The Biological Diversity Act was enacted in the year 2002 with the objective of conserving biodiversity, sustainable use of its components and fair and equitable sharing of the benefits of the bioresources. The act recognizes the richness of India's biological diversity and the duty entailed upon the government to protect them, as well as to show their commitment to the CBD (MoEF 2002). The act focuses on sharing the benefits of the bioresources and sustainable utilization of their genetic resources, at the same time protecting the resources from unauthorized exploration and exploitation, especially by foreigners or an organization that is not incorporated or registered in India.

27.4.4 Pakistan

27.4.4.1 Pakistan Environmental Protection Act, 1997

The Pakistan Environmental Protection Act (PEPA) was enacted on the 06th of December 1997, based on series of consultations with stakeholders as a measure to adopt a sustainable method of development through participatory approach (PEPA 2012). The objectives of this act are to protect, conserve, rehabilitate and improve the environment, prevent and control pollution and promote sustainable development.

27.4.5 Sri Lanka

27.4.5.1 National Environmental Act, 1980 (No. 47 of 1980)

The National Environmental Act (NEA), 1980, of Sri Lanka led to the establishment of the Central Environmental Authority (CEA), whose key functional duties are to recommend to the minister the national environmental policy and the criteria to be taken into account for protection of the environment; to undertake surveys and investigations; to conduct, promote and coordinate research; to specify standards and methods to be adopted in taking samples and making tests; to provide information and education to the public; and to promote, encourage and coordinate long-range planning in environmental protection and management (GoS 1980). It requires every project, referred as prescribed project, to submit an Environmental Impact Assessment (EIA) report, which would be subjected to public inspection followed by public hearing for approval of the project (Azmy 2013).

27.4.5.2 Coast Conservation Act, 1981 (No. 57 of 1981)

The Coast Conservation Act (CCA), 1981, was enacted with an aim of surveying the coastal zone of Sri Lanka and preparing a Coastal Zone Management Plan (CZMP) to regulate the developmental activities along the coast. The act defines the coastal zone of the country as the area lying within 300 m landward of the mean high water line, and in the case of rivers, streams, lagoons or any other body of water connected to the sea, either permanently or periodically, the landward boundary shall extend to a limit of 2 km perpendicular to the strait baseline drawn between the natural entrance points thereof and shall include waters of such waterbodies (GoS 1981).

The CZMP addresses the issues concerning the coastal regions of Sri Lanka such as coastal erosion, loss and degradation of coastal habitat, as well as loss and degradation of archaeological, historical and cultural sites and recreational scenic areas. The CZMP was designed to adapt sustainable use of coastal environment and their resources in the long term while supporting the national development goals.

27.4.5.3 National Heritage Wilderness Areas Act (No. 3 of 1988)

The National Heritage Wilderness Areas Act (NHWAA) was enacted for preserving the ecosystem, the genetic resources in their natural state and also the physical and biological formations by precisely delineated areas. It also covers the habitats of threatened species of animals and plants (GoS 1988). The act requires identification and mapping of the wildernesses for better management and protection and details the activities prohibited within such area. It also provides directions for the treatment of protected areas. It has the provision to acquire lands for the purpose of this act through the Land Acquisition (Amendment) Act, 1964.

27.4.5.4 Fauna and Flora Protection (Amendment) Act 2009 (No. 22 of 2009)

The Fauna and Flora Protection Ordinance, dating back to 1937, was the first law enacted to provide protection to habitats in order to conserve the wildlife, including indigenous wild plants and animals, and protect them from commercial exploitation (GoS 1993). It provided for establishment of national reserves and sanctuaries and related matters and classifying the national reserves as strict natural reserves, national parks, nature reserves, marine national parks, jungle corridors or intermediate zones. Apart from this, the ordinance has the provision to protect certain species of fauna outside reserves. The ordinance was subjected to four amendments until 1945 and was made as an act in 1949 – the Fauna and Flora Protection (Amendment) Act 1949 (No. 38 of 1949). Since then the act has been amended five times, the latest being in the year 2009, which deals with the control and management of national reserves, offences relating to amphibians and fishes and prohibitions on import or export of protected animals without permits. The act includes the list of species that are protected under this act and are categorized under eight schedules (I–VIII) with respect to their degree of protection (GoS 2009).

27.4.6 Appraisal of Legal Instruments for Wetland Conservation in South Asia

The governments of the respective states of South Asia have enacted various acts to aid in proper governance of the environment, as per the enabling policy frameworks and commitment to international environmental laws. Maldives, through their Environment Protection and Preservation Act, 1993, has set standards for monitoring, conserving and protecting its environment. It also provides guidelines and the measures to be taken for protecting the coastal ecosystems.

The Government of Sri Lanka has legal and regulatory framework to protect its natural resources. They aim at conserving and maintaining the beauty of the natural resources and wilderness and encourage scientific research for effective science-based protection and management of natural resources. They also contain strict rules on exploitation of aquatic resources within their jurisdiction to conserve the flora and fauna of the ecosystems. In addition, to upgrade the level of protection, the ministries governing their respective ecosystems have the power to declare an area as a protected area. The concept of ICZM was also adopted by the Sri Lankan government.

Bangladesh and Pakistan have enacted the BECA, 1995, and the PEPA, 1997, respectively. These acts address the issues and concerns faced by the environment of their respective countries and have incorporated the concepts of environmental protection that were adopted in various international forums. The BECA focuses on mitigatory measures for containing the pollution affecting the country's environment. The purpose of the act is to abate the biodiversity loss through protecting and conserving their ecosystems, and more specifically the coastal ecosystems, which contribute significantly towards the country's economy. Pakistan, also, through their relevant acts provides directives for conserving its natural resources, particularly to maintain and enhance the country's biodiversity. Both the countries promote the concept of sustainable development through their acts, coherent with the objectives of their national policies.

India has a robust legal framework to conserve, protect and manage the environmental (coastal) resources, the significant ones being the Wildlife (Protection) Act, 1972; the Forest (Conservation) Act, 1980; the EPA, 1986; and the Biological Diversity Act, 2002. Further, under the EPA, 1986, the Wetland (Conservation and Management) Rules, 2010, and the CRZ Notification, 2011, have also been notified with specific mandates. The regulatory provisions recognize the interdependency of different ecosystems and species and how a slight imbalance would cause the degradation of the ecosystems, especially the coastal ecosystems due to their complex relationship between different coastal wetland ecosystems.

27.5 Institutional Mechanism for Wetland Conservation in South Asia

27.5.1 Bangladesh

The BECA, 1995, provides for the establishment of the Department of Environment, headed by the Director General, who in turn, for the purpose of enforcing the provisions of the act, coordinates with other concerned authorities or agencies. The act empowers the government to declare an area as ecologically critical area based on science-based evidences.

27.5.2 India

The Wildlife (Protection) Act, 1972, provided for establishment of the Wildlife Advisory Board for every state and union territory. It enables the government to appoint the director of Wildlife Preservation and the assistant director of Wildlife Preservation for enforcing the provisions of the act. The act also empowers the Chief Wildlife Warden to exercise the regulations and provisions under this act.

The EPA, 1986, empowers the central government to establish authorities [under Section 3(3)] with the mandate of preventing the environmental pollution in all its forms and to tackle specific environmental problems of different parts of the country. The CRZ Notification, 2011, issued under the EPA, 1986, resulted in the formation of the National Coastal Zone Management Authority, as well as the State Coastal Zone Management Authorities and district level committees. The Coastal Zone Management Authority (CZMA) has the duty to examine and issue permissions for the development of permissible activities as per the CRZ notification in various zones. The CZMA is also responsible for the enforcement of the Island (Protection) Zone Notification, 2011.

The Wetland Conservation and Management Rules, 2010, provide for constituting the Central Wetland Regulatory Authority under the Ministry of Environment, Forest and Climate Change. The authority can appraise proposals for identification of new wetlands and projects upon consultation with the local authorities. It assists the state governments in conservation, preservation and wise use of wetlands. It also reviews the list and the status of wetlands periodically and details the prohibited and regulated activities.

The *Biological Diversity Act, 2002*, established the National Biodiversity Authority (NBA) to aid in the implementation of the act and regulations under it. The NBA is an autonomous body that governs the status of the biodiversity and prevents any unauthorized exploration or exploitation of natural resources. It is also responsible for the intellectual property rights for any research-based innovation related to biodiversity from India.

27.5.3 Maldives

The Ministry of Planning, Human Resources and Environment of Maldives is the authority enforcing the Environment Protection and Preservation Act of Maldives, 1993. The ministry oversees the legislative recommendations of the act and enforces the rules and penalties for efficient coastal resource management and governance. The Ministry has the liberty to identify, protect and enforce regulatory measures to marine protected areas within its jurisdictional waters.

27.5.4 Pakistan

The PEPA, 1997, established the Pakistan Environmental Protection Council that is chaired by the prime minister of the country. The council is responsible for framing and enforcing the regulations for the protection of the environmental resources. The council also drafts the National Environment Report. A Federal Environmental Protection Agency was established to exercise the powers and functions under the provisions of the PEPA. The act mandates every provincial government of Pakistan to establish an Environmental Protection Agency, headed by the Director General. The act provides for the establishment of environmental tribunals to hear the cases relating to violation of the act. In addition, the act provides for creation of a Provincial Sustainable Development Fund for funding various measures taken under different provisions of the act.

27.5.5 Sri Lanka

The CEA was established under the NEA, 1980. The Ministry of Environment administers the act. The act also led to the establishment of the Environmental Council, whose members are appointed by the Minister of Environment. The act provides for the formation of the District Environmental Agency. The functions of the CEA are to recommend to the Ministry of Environment on relevant issues and oversee the implementation of the regulatory provisions under the act. The CEA also provides directives to the District Environmental Authority and overlooks the functioning of the authority as defined by the act.

The Coast Conservation Act, 1981, is administered by the Coast Conservation Department under the Ministry of Fisheries and Aquatic Resources. The act established the Coast Conservation Advisory Council (CCAC), whose function is to provide suggestions and advices to the minister in charge on the coastal activities and developments. The council also reviews the CZMP that promotes sustainable development of the coast of Sri Lanka. The Fauna and Flora Protection Ordinance, 1993, is administered by the Department of Wildlife Conservation, and the minister in charge has the privilege to declare an area as national reserve upon reviewing scientific research and biosurvey evidences. This act is administered at the local level by the municipal council and the urban council.

The Forest Department is the administering authority of the National Heritage Wilderness Areas Act, 1988. The Minister of Environment declares an area as a National Heritage Wilderness Area upon consultation with the Ministers of Wildlife Conservation, Fisheries, Agriculture, Cultural Affairs and of the Indigenous Medicine. This act has given the authority to the minister to frame regulations for the National Heritage Wilderness Area.

A summary of the institutional structures for implementation of the relevant acts in different South Asian countries is given in Table 27.4.

Table 27.4 Institutional structure for implementation/enforcement of the provisions of different acts in the coastal states of South Asia

Country	Acts	Institutions
Pakistan	Pakistan Environmental Protection Act, 1997	Pakistan Environmental Protection Council
		Environmental tribunal
Bangladesh	Environment Conservation Act, 1995	Department of Environment
Sri Lanka	National Heritage Wilderness Areas Act, 1988	Forest Department
	National Environmental Act, 1980	Central Environmental Authority
		Environmental Council
		District Environmental Agency
	Coast Conservation Act, 1981	Coast Conservation Department
	Fauna and Flora Protection Ordinance, 1993	Department of Wildlife Conservation
		Municipal Council
		Urban Council or *Pradeshiya Sabha*
Maldives	Environment Protection and Preservation Act of Maldives, 1993	Ministry of Planning, Human Resources and Environment
India	Wildlife (Protection) Act, 1972	Wildlife Advisory Board
	Forest Conservation Act, 1980	Committee Constituted by the Government
	Environmental (Protection) Act, 1986	Ministry of Environment, Forest and Climate Change and Environment Departments in the coastal states
	Wetland (Conservation and Management) Rules, 2010	Central Wetland Regulatory Authority
	Coastal Regulation Zone Notification, 2011	National Coastal Zone Management Authority
	Island Protection Zone Notification, 2011	National Coastal Zone Management Authority
	Biological Diversity Act, 2002	National Biodiversity Authority

27.6 Conclusion

The South Asian region is rich in biological diversity, especially in the marine environmental realm. The countries recognize the importance of their coastal resources as they form the livelihood basis for a large proportion of their population. The countries undertake different modes of action to prevent deterioration of the quality of coastal wetlands. Every country possesses specific legislative and policy frameworks, which address and regulate the concerned resources/activities to minimize the threats to the environment and natural resources. Additionally, they all have given importance to the natural disasters that frequently hit the coastal regions of South Asia, due to climate change.

However, a comparative regional assessment makes it clear that there are voids to be filled by each country in addressing their issues relating to their coastal wetland management. Though all the South Asian countries have defined their coastal boundaries, India is the only country among the five coastal states of South Asia, which has demarcated and mapped the coastal zones for better regulatory purposes. India has incorporated the concept of ICZM into its policy framework and is currently pursuing ICZM in certain areas in a phased manner. India is also a pioneer in drafting notifications under the relevant acts to intensify the degree of regulations governing the coastal zone. While environmental standards, as for air quality and water quality, are defined, no such standards are defined for each of the coastal ecosystems that are needed to be maintained for the purpose of long-lasting sustenance of the ecosystem. In addition, the growing demand for development needs have, in many cases, set aside environmental priorities though it is also seen that many local initiatives (supported at the national and international levels) are steadily working towards recovery of anthropogenically stressed wetlands. Measures such as environmental impact assessments, public consultations and education and awareness have helped a great deal in this.

Although the countries have legislations to govern the coastal wetlands, there are overlaps of executive functions due to the involvement of multiple governing authorities/agencies, which has hampered implementation of the provisions of the regulations by the enforcing authorities that govern the coastal regions. There are many reasons that compound the resource depletion in the South Asian region which need to be addressed and resolved.

Some areas of concern with respect to the implementation of the conservation measures of the acts and policies by the respective implementation authority are:

1. Involvement of multiple agencies at various levels of the government which creates ambiguity in roles and responsibilities of different functionaries
2. Transboundary nature of some resources
3. Differential perspectives on the need for environmental conservation and sustainable development among different stakeholders
4. Lack of reliable data on the value of coastal wetlands
5. Financial limitations
6. Inadequate representation of local community in environmental decisions

7. Insufficient national level educational programmes on environmental conservation and protection

To address these issues, countries require sufficient financial support for improvization of technologies, undertaking research on natural resources and institutionalization of programmes and approaches for coastal management. The South Asian countries have the advantage of strengthening their cooperation in various fields, due to common interest, to address these issues related to coastal governance, by sharing experiences and expertise, and thus secure the coasts for the future.

References

Abbas S, Qamar FM, Hussain N, Saleem R, Nitin KT (2011) National level assessment of mangrove forest cover in Pakistan. International archives of the photogrammetry, remote sensing and spatial information sciences, volume XXXVIII-8/W20, 2011 ISPRS Bhopal 2011 Workshop, 8 Nov 2011, Bhopal

Adger W, Hughes T, Carl F, Carpenter S, Rockstrom J (2005) Social-ecological resilience to coastal disasters. Science 309(5737):1036–1039

Azmy SAM (2013) Sri Lanka report on coastal pollution loading and water quality criteria. http://www.boblme.org/documentRepository/BOBLME-2011-Ecology-14.pdf. Accessed on 18 June 2015

BMoEF (1995) The Bangladesh Environment Conservation Act, 1995 (Act No.1 of 1995). Bangladesh Ministry of Environment and Forests. http://faolex.fao.org/docs/pdf/bgd42272.pdf. Accessed on 21 June 2015

Byomkesh T, Nakagoshi N, Md. Shahedur R (2009) State and management of wetlands in Bangladesh. Landsc Ecol Eng 5(1):81–90

CBD (2009) Fourth country report from Sri Lanka to the United Nations Convention on Biological Diversity. https://www.cbd.int/doc/world/lk/lk-nr-04-en.pdf. Accessed on 4 June 2016

CBD (2012) Action plan for implementing the convention on biological diversity's programme of work on protected areas. https://www.cbd.int/doc/meetings/mar/cbwsoi-seasi-01/other/cbwsoi-seasi-01-bangladesh-en.pdf. Accessed on 4 Aug 2015

CBD (2015) Convention on biological diversity country profile. https://www.cbd.int/countries/. Accessed on 14 June 2015

CEA (2006) National wetland policy and strategies. Central Environmental Authority, Sri Lanka. http://www.ramsar.org/sites/default/files/documents/library/national_wetland_policies_-_sri_lanka.pdf. Accessed on 18 June 2015

CITES (2015) Cites list of contracting parties. https://www.cites.org/eng/disc/parties/chronolo.php. Accessed on 14 June 2015

CMS (2005) Central Asian flyway action for the conservation of migratory waterbirds and their habitat. Convention on the Conservation of Migratory Species of Wild Animals. http://www.cms.int/sites/default/files/document/Annex4_CAF_Action_Plan_0.pdf. Accessed on 17 June 2015

CMS (2015) CMS parties and range states. http://www.cms.int/en/parties-range-states. Accessed on 14 June 2015

Dahdouh-Guebas F, Satyanarayana B (eds) 2012 Proceedings of the International Conference 'Meeting on Mangrove ecology, functioning and Management – MMM3', Galle, Sri Lanka, 2–6 Jul 2012. VLIZ Special Publication, p 57

Day JW, Christian RR, Boesch DM, Yanez-Arancibia A, Morris J, Twilley RR, Naylor L, Schaffner L, Court S (2008) Consequences of climate change on ecogeomorphology of coastal wetlands. Estuar Coasts 31:477–491

FSI (2013) India state of forest report. http://fsi.nic.in/cover_2013/mangroves_in_india.pdf. Accessed on 4 Aug 2015
GoM (2014) Maldives climate change policy framework. http://www.environment.gov.mv/v1/wpcontent/blogs.dir/1/files/downloads/Maldives_Climate_Change_Policy_Framework_draft_3.pdf. Accessed on 24 June 20015
GoS (1980) National Environmental Act, 1980 (No.47 of 1980). http://faolex.fao.org/docs/pdf/srl13492.pdf. Accessed on 21 June 2015
GoS (1981) Coast Conservation Act, 198. http://faolex.fao.org/docs/pdf/srl11456.pdf. Accessed on 22 June 2015
GoS (1988). National Heritage Wilderness Areas Act (No.3 of 1988). http://theredddesk.org/sites/default/files/national_heritage_wilderness_act.pdf. Accessed on 21 June 2015
GoS (1993) The Fauna & Flora Protection (Amendment) Act, 1993. http://faolex.fao.org/docs/pdf/srl12503.pdf. Accessed on 21 June 2015
GoS (2009) The Fauna & Flora Protection (Amendment) Act, 2009. http://www.dwc.gov.lk/documents/ordinanceeng.pdf. Accessed on 31 June 2016
IUCN Sri Lanka & CEA (2006) National wetland directory of Sri Lanka, Colombo
Matz N (2005) Chaos or coherence? – Implementing and enforcing the conservation of migratory species through various legal instruments. http://www.zaoerv.de/65_2005/65_2005_1_a_197_216.pdf. Accessed on 15 June 2015
MEA (2005) Ecosystem and human well being: wetlands and water synthesis. World Resources Institute, Washington, DC. http://www.millenniumassessment.org/documents/document.358.aspx.pdf. Accessed on on 9 June 2015
MFF (2015) Mangrove for the future https://www.mangrovesforthefuture.org/. Accessed on 16 June 2015
MoCC (2012) National Climate Change Policy, Government of Pakistan. Available at http://www.mocc.gov.pk/. Accessed on 20 June 2015
MoE (2005) National Environmental Policy. Government of Pakistan. http://environment.gov.pk/NEP/Policy.pdf. Accessed on 19 June 2015
MoE (2009) Pakistan National Wetlands Policy, Pakistan Wetlands Programme. http://waterinfo.net.pk/sites/default/files/knowledge/National%20Wetlands%20Policy%202009.pdf. Accessed on 19 June 2015
MoE (2010) National Forest Policy, Government of Pakistan. http://sindhforests.gov.pk/admin/MediaLibrary/National%20Forest%20Policy%202010.pdf. Accessed on 20 June 2015
MoEF (1972) The Wildlife Protection Act, 1972. Government of India. http://envfor.nic.in/legis/wildlife/wildlife1c1.pdf. Accessed on 22 June 2015
MoEF (1986) The Environment Protection Act, 1986. http://www.moef.nic.in/sites/default/files/eprotect_act_1986.pdf. Accessed on 22 June 2015
MoEF (1988) National Forest Policy 1988, Government of India. http://www.moef.gov.in/sites/default/files/introduction-nfp.pdf. Accessed on 20 June 2015
MoEF (1992) National Conservation Strategy and Policy Statement on Environment and Development, Government of India. http://www.moef.gov.in/sites/default/files/introduction-csps.pdf. Accessed on 20 June 2015
MoEF (2002) The Biological Diversity Act, 2002. http://bamu.ac.in/dept/zoology/3.%20The%20biological%20Diversity%20act,%202002.pdf. Accessed on 24 June 2015
MoEF (2006) National Environmental Policy, 2006. Government of India.http://www.moef.gov.in/sites/default/files/introduction-nep2006e.pdf. Accessed on 20 June 2015
MoEF (2010) Wetland Conservation and Management Rules, 2010. http://www.moef.nic.in/downloads/public-information/Wetlands-Rules-2010.pdf. Accessed on 23 June 2015
MoEF (2011a) Coastal Regulation Zone Notification, 2011. http://www.moef.nic.in/downloads/public-information/CRZ-Notification-2011.pdf. Accessed on 23 June 2015
MoEF (2011b) Island protection zone notification. http://www.iomenvis.in/pdf_documents/ICRZ.pdf. Accessed on 23 June 2015

MoEF (2013) The Wild Life (Protection) Amendment Bill, 2013. http://www.moef.nic.in/sites/default/files/WildlifeProtectionAmendmentBill2013.pdf. Accessed on 31 Mar 2016

MoENRS (2003) National Environmental Policy and Strategies. http://www.preventionweb.net/files/15417_nationalenvironmentpolicyandstrateg.pdf. Accessed on 15 June 2015

MoWR (1999) National Water Policy, Government of the People's Republic of Bangladesh. http://wptest.partnersvoorwater.nl/wp-content/uploads/2011/07/WARPO2004_National-Water-Policy.pdf. Accessed on 19 June 2015

MoWR (2005) Coastal Zone Policy, Government of the People's Republic of Bangladesh. http://www.warpo.gov.bd/pdf/czpo_eng.pdf. Accessed on 19 June 2015

NEP (2003) National Environmental Policy of Sri Lanka, 2003. http://www.preventionweb.net/files/15417_nationalenvironmentpolicyandstrateg.pdf. Accessed on 21 June 2015

NWP (2000) National Wetland Policy of Sri Lanka, 2000. http://www.dwc.gov.lk/index.php/en/2015-01-26-04-14-43/wildlife-policy. Accessed on 21 June 2015

PEPA (2012) Pakistan Environmental Protection Act, 1997. http://www.environment.gov.pk/act-rules/envprotact1997.pdf. Accessed on 21 June 2015

Rais M, Khan MZ, Ghalib SA, Nawaz R, Akbar G, Islam SL, Begum A (2013) Global conservation significance of Chitiari wetlands complex, Sangahr, Sindh, Pakistan. J Anim Plant Sci 23(6):1609–1617

Ramsar (2015) Ramsar country profile http://www.ramsar.org/country-profiles. Accessed on 14 June 2015

Ramsar Convention Secretariat (2004) The Ramsar convention manual: a guide to the convention on wetlands (Ramsar, Iran, 1971. 3rd edn. http://www.dlist.org/sites/default/files/doclib/The%20Ramsar%20Convention%20Manual.pdf. Accessed on 10 June 2015

Ramsar Convention Secretariat (2010) Handbook 21: the Ramsar strategic plan 2009–2015. Ramsar handbooks 4th edn. http://www.ramsar.org/sites/default/files/documents/pdf/lib/hbk4-21.pdf. Accessed on 11 June 2015

Ramsar Convention Secretariat (2013) Ramsar convention manual: a guide to the convention on wetlands, (Ramsar, Iran, 1971), 6th edn. http://www.ramsar.org/sites/default/files/documents/library/manual6-2013-e.pdf. Accessed on 9 June 2015

SAC (2011) Information brochure – national wetland inventory & assessment, sponsored by ministry of environment and forests. Govt. of India. Space Application Centre –ISRO, Ahmedabad, p 24

SACEP (2015) South Asia Co-operative Environment Programme http://www.sacep.org/. Accessed on 16 June 2015

SFD (2011) National Forest Policy of Sri Lanka, 1995.http://www.forestdept.gov.lk/web/index.php?option=com_content&view=article&id=110&Itemid=105&lang=en. Accessed on 18 June 2015

Spalding MD, Ravilious C, Green EP (2001) World Atlas of coral reefs. Prepared at the UNEP World Conservation Monitoring Centre. University of California Press, Berkeley

UN (1971) Convention on Wetlands of International Importance especially as Waterfowl Habitat. Concluded at Ramsar, Iran, on 2 February 1971: No. 14583. https://treaties.un.org/doc/Publication/UNTS/Volume%20996/volume-996-I-14583-English.pdf. Accessed on 10 June 2015

UN (1972) Report of the United Nations Conference on the Human Environment, Stockholm, 5–16 June 1972. http://www.un-documents.net/aconf48-14r1.pdf. Accessed on 12 June 2015

UN (1992) Rio Declaration on Environment and Development. http://www.jus.uio.no/lm/environmental.development.rio.declaration.1992/portrait.a4.pdf. Accessed on 16 June 2015

UN (2002) Report of the World Summit on Sustainable Development. Johannesburg, South Africa, 26 Aug–4 Sept 2002. http://www.unmillenniumproject.org/documents/131302_wssd_report_reissued.pdf. Accessed on 14 Jul 2015

UN (2012) Report of the United Nations Conference on Sustainable Development. Rio de Janeiro, Brazil, 20–22 June 2012. http://www.uncsd2012.org/content/documents/814UNCSD%20REPORT%20final%20revs.pdf. Accessed on 16 June 2015

UN (2015) A list of major environment policies of Sri Lanka. http://unpan1.un.org/intradoc/groups/public/documents/apcity/unpan042380.pdf. Accessed on 15 June 2015

UNCED (1993) Agenda 21: programme of action for sustainable development; Rio Declaration on Environment and Development; Statement of Forest Principles: the final text of agreements negotiated by governments at the United Nations Conference on Environment and Development (UNCED), 3–14 June 1992, Rio de Janeiro, Brazil. New York: United Nations Dept. of Public Information

UNCLOS (2015) UNCLOS status of states. http://www.un.org/depts/los/reference_files/status2010.pdf. Accessed on 14 June 2015

UNEP (2006) Maldives post-tsunami environmental assessment. http://www.unep.org/tsunami/reports/maldives.pdf. Accessed on 4 Aug 2015

UNEP & DA (2008) South Asia Environment Outlook 2009: UNEP, SAARC and DA. http://www.unep.org/pdf/SAEO-2009.pdf. Accessed on 11 June 2015

Involvement of Community in Managing Coastal Wetlands in South Asia: Status, Issues and Challenges

28

R. Ramesh, K.R. Abhilash, Margi Purohit, P. Krishnan, Ahana Lakshmi, R. Purvaja, and Paul W. Kingsley

Abstract

The development and population pressures on the coastal states of South Asia have significant impact on their coastal resources. As a large number of coastal communities are highly dependent on the coastal resources, the decline in resources affects their livelihoods. To manage the coastal resources effectively from further damage, a community-oriented mode of resource management is highly recommended, as it imparts the sense of stewardship and accountability in extraction and use of the resources. The community participation in ecosystem conservation and management has been implemented in South Asia through various enabling policies, regulatory frameworks and community practices. Conservation through involvement of people has not only yielded benefits to coastal environment and resources but also helped people to gain food security and income through tourism. This chapter discusses about various international and national policies and legal frameworks, which provide support for community-based resource management and empower the people of the local community in designing and implementing coastal resource conservation and management plans.

Keywords

Coastal resources • Collaborative management • Community-based management • Legislation • South Asia

R. Ramesh (✉) • K.R. Abhilash • M. Purohit • P. Krishnan • A. Lakshmi • R. Purvaja
P.W. Kingsley
National Centre for Sustainable Coastal Management (NCSCM), Ministry of Environment Forest & Climate Change, Anna University Campus, Chennai 600 025, Tamil Nadu, India
e-mail: rramesh_au@yahoo.com; abhilaashkr@gmail.com; margicmr@gmail.com; krishnanars@yahoo.com; ahanalakshmi@gmail.com; purvaja.ramachandran@gmail.com; paulwkingsley@aol.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_28

28.1 Introduction

The coastal wetlands include a wide array of habitats along the coast, both natural and human-made. Being highly productive, they provide a critical interface between terrestrial and marine environment, serving as shock absorbers, reducing the impacts of upstream riverine and land-based activities that may otherwise affect the coastal waters directly. The coastal wetlands are under serious pressure and stress because of societal dependence on various ecosystem goods and services they provide. Various studies have shown that the loss of coastal wetland ecosystems is contributing towards global warming. All these call for better management of these invaluable resources to sustain life and natural wealth.

All coastal nations have frameworks for conservation and management of coastal wetland resources. A few countries have promoted community-based coastal resource management for conserving their coastal wetlands upon viewing its success in some of the Southeast Asian countries, especially the Philippines. We see in this chapter, how community-based resource management has taken shape in South Asian countries and analyze their effectiveness in conserving the biodiversity of their coastal ecosystems.

28.2 Community-Based Wetland Management: An Overview

28.2.1 Concept of "Community" and "Participation"

The humans live alongside rivers, lakes, forests, wetlands and many other natural resources to which they are deeply connected. These resources are threatened due to overexploitation, pollution and other problems that need to be addressed and resolved to ensure the survival and well-being of the present and future generations. Of late, there has been an increased recognition of the involvement of communities in managing and protecting the environment as an act of securing resources on which their livelihoods depend. This practice has been in place for thousands of years, especially among the indigenous peoples who were the original inhabitants of the land and who were wholly dependent on natural resources. Although those practices have not always been backed by scientific evidence, they define in fact the concept of sustainable resource/environmental management. The resource-dependent communities have the highest degree of connectivity and association with the ecosystems that support their livelihoods and their conservation practices have been built over generations.

The development of an environment management plan, either by a government agency or by an NGO, requires the support and input from the people associated with the environment as they have better knowledge about the system. In addition, the participation of local communities would facilitate easier and better implementation of the management plan. Participatory approaches encourage shared decision-making, cooperation, collaboration, mutual respect, confidence building and empowerment. Incorporating such elements into various levels of developmental activities helps in the active engagement of communities and other stakeholders in conservation of the ecosystem resources, which builds capacity, increases learning and strengthens participant ownership of the constructs and strategies underlying the project activities (NOAA 2015).

The methods for the participation of the communities can be classified into three categories, namely, top-down, bottom-up and collaborative management (co-management). The top-down method is set on directive terms where the State dictates through laws and regulative measures to ensure protection of the natural resources and their biodiversity. The bottom-up approach inclines more towards the community-based management of the natural resources, where the decision-making and governance lie solely with the people who are associated with or dependent on the ecosystem, without much interference and influence from the government. The co-management is a new concept in resource management where the local communities and the government work together in partnership to avoid any conflict of interest that may arise from the other two methods of management, mentioned above. The co-management works towards the sustainable management as well as the wise use of resources. Therefore, the concept of community participation in decision-making for natural resource management is essential for better conservation and protection of the sensitive ecosystems.

28.2.2 History and Evolution of Community Involvement

The colonial governments in Asian subcontinent generally created three categories of land, *viz*. private land, state land and community land. The management of land and the natural resources was considered the responsibility of the state. For the local residents, especially indigenous communities, this situation meant that they did not have any role to play in major decisions regarding the use and allocation of the natural resources and land. They were often restricted to the use of natural resources only for subsistence and prevented by law from any form of commercial use of the natural resources. The community-based natural resource management has emerged again over the last 20 years with the realization that for sustainable use of the natural resources, people living with and benefitting from the resources should be responsible for their management.

The concept of community involvement/participation in resource management seems to have been adopted as a new concept in environmental conservation and management around the globe, especially after the recommendation made in the Agenda 21 of the United Nations Conference on Environment and Development (UNCED), held at Rio de Janeiro, Brazil, in 1992. However, this approach has been in existence from the time when people started relying on their surrounding environmental resources for their lives and livelihoods. With increased dependence on the environmental resources, the nature-society relationship slowly developed into a sociocultural relationship, which further developed into traditional belief systems and became causative of implementing conservation practices to safeguard their resources not only from a survival standpoint but also from a cultural standpoint.

This attitude developed a sense of respect towards the resources, which feed their community, resulting in orienting the community to view the ecosystems they depend on with ethical/religious sentiments. The religious attachment towards their environment can still be seen among the indigenous and tribal people who claim ownership and authority over their resources and conserve them with their traditional practices, which today may be identified as sustainable practices.

28.2.3 Importance of Involving Community in Wetland Management

The ever-increasing stress over wetland resources, poor land-use practices, uncoordinated sectoral policies, fast-track development activities and overexploitation of resources vitiate the functionality of wetland ecosystems, especially in coastal areas. Therefore, the involvement of local communities in managing coastal wetland ecosystems is to be appreciated as they play vital roles in protecting and sustaining them. The combination of all the strength attributes and resources available within a community, society or organization can be used to achieve the agreed goals. A prime reason for adopting community-based environmental management is the fact that the State's policies and regulations conventionally had poor outcomes. This is largely due to insufficient knowledge and understanding of the ecosystems, as they seldom take the views and knowledge of the local community, further derailed due to corruption and inefficient implementation (Agarwal and Gibson 1999).

A community-based participatory wetland management is a way of establishing the community's rights over the ecosystems with which they are closely associated. It also shows the commitments and the responsibilities the community shoulders to protect their environment. The community participation builds upon educating the community about the wetland ecosystems and about the processes and interactions happening in those ecosystems, which would lead to the development of better policies and conservation plans. It also increases the accountability of the community members and makes the plan of action framed by their planning body more acceptable and implementable. The community-oriented management of coastal wetlands aids in tackling the problems that cannot be defined or dealt with by any other means (rights and claims, lifestyle) and creates a space for every community member to voice opinions and concerns relating to the resource management. The management of common property resources is a collective action, an alternative to privatization or state regulation.

28.2.4 Common Property Resource (CPR)

The common property resource (CPR) is broadly defined as a natural resource on which a group of people have common user rights (not necessarily ownership rights). The lakes, rivers, estuaries and marine areas are generally considered as CPRs. Traditionally the CPRs are not having open access but are often subject to unwritten rules and norms of the local community, such as the Ostrom's principles of governance of commons. The Ostrom's principles are:

(i) Clearly defined boundaries
(ii) Congruence between appropriation and provision rules and local conditions
(iii) Collective-choice arrangements
(iv) Monitoring appropriators
(v) Graduated sanctions for violators
(vi) Resolution of conflicts
(vii) Minimal recognition of rights complying within the governmental rules
(viii) Building a nested enterprise in multiple layers (Ostrom 1990)

During and after the colonial period, such CPRs have come under state control, indigenous institutions have been marginalized and people's participation in management of CPRs has significantly decreased. The CPRs are community lifelines and almost all people have a stake in their well-being. The public awareness has to be raised and local people have to be involved in CPR management.

28.2.5 Integrated Approach to Community-Based Ecosystem Management

The integrated natural resource management is a means to resolve complex problems associated with natural resources on which people are highly dependent for livelihoods, especially to minimize conflicts among the resource users. This method attempts to balance the environmental, economic and social requirements of the society (CNRA 2010). The approach would involve interaction between the local community and the scientific community, which would facilitate the exchange of knowledge and help to pool scientific and traditional knowledge about the ecosystem(s) (Marshal 2011). The stakeholder interactions and knowledge sharing would lead to more sustainable decision-making. However, the participatory processes, thus institutionalized, form a platform upon which negotiations and the decision-making for resource management are amicably resolved (Reed 2008). The effectiveness of the integrated community-based ecosystem management depends on the degree to which suggestions from the community, including indigenous people, are considered for decision-making.

28.2.6 Community-Based Management of Coastal Wetlands

There is an increase in the participation of communities in decision-making for environmental conservation and management in recent years in the areas of water resource management, agricultural practices, ecosystem development and environmental governance (Luyet et al. 2012). The community-based coastal resource management encourages the participation of all sectors of a community for sharing their traditional knowledge, experiential knowledge as well as the local knowledge. The indigenous knowledge on the coastal ecosystem is the knowledge in practice to sustain both the livelihoods and the coastal resources those supported and sustained the community livelihoods (Ruiz-Mallén and Corbera 2013). Berkes (2010) reported that the inherited knowledge in South and Southeast Asia helped in quicker response to the tsunami recovery process, substantiating the fact that the indigenous and traditional knowledge keepers are well informed of their local ecosystems. The traditional knowledge assists not only in environmental conservation and development but also in understanding and responding to the socioecological status of their livelihood. Therefore, the community-based coastal wetland management that involves all the stakeholders complements as well as supports the science-based ecosystem analysis during the formulation of conservation measures. Such management plans show high effectiveness in the resource management.

28.3 Enabling Provisions for Involving Community for Wetland Management

28.3.1 International Policies and Agreements

The United Nations Conference on the Human Environment, 1972, stressed the importance of the community-based environmental planning to support the low-income groups and, thereby, rural development (UN 1972). It also promoted the facilitation of social and cultural indicators of the environment for assessing the environmental developments.

The Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention), 1971, identified and recognized the importance of community participation in wetland development and management and recommended the creation of public awareness on the wetlands for the benefit of the people (UN 1971). The community involvement and participation in management decision-making for the sites included in the List of Wetlands of International Importance (Ramsar sites) and other wetlands were recognized as essential in the Ramsar Convention, with the premise that the local and indigenous people's involvement in wetland management can substantially contribute to the effective management practices that further Ramsar Convention's wise-use objectives.

The seventh meeting of the Conference of the Contracting Parties (COP) to the Convention, held in Costa Rica in 1999, recognized the importance of the local community and indigenous people's participation in the management of wetlands in the Resolution VII.8 (Ramsar 1999). The terms, such as the collaborative management, co-management or joint management, are largely synonymous. The COP urged the parties to create the guidelines, legal and policy framework to encourage the participation of indigenous and local community people in the national and local decision-making for sustainable use and management of the wetlands. It encouraged the collaboration among the technical experts, community and specifically the indigenous people for the best use of science and traditional knowledge in management of wetlands. The COP encouraged setting up of indigenous community wetland education centres and NGOs to facilitate better participation of all segments of people in wetland management.

The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), 1973, recognizes the importance of the people and community in protecting the biodiversity of an ecosystem (fauna and flora). The 6th Resolution of COP-16 emphasized the importance of communities in the conservation of species listed in CITES. It recognized that engagement of rural communities would benefit in meeting the goals of CITES through proper implementation of the action plans as well as in the contribution of traditional knowledge of CITES listed species in their natural habitat (CITES 2013). It also promoted the empowerment of the rural communities by enabling them to participate in the development and implementation of the policies and uphold transparency in the process of participation and decision-making.

United Nations Conference on Environment and Development (UNCED), 1992, brought out the *Agenda 21*, in which Chap. 17 deals with “protection of the oceans, all kinds of seas, including enclosed and semi-enclosed seas and coastal areas and the protection, rational use and development of their living resources”. It suggested an integrated approach to the management of coastal resources in collaboration with the academic and private sectors, NGOs, local community and indigenous people (UNCED 1993). In addition, the development of management plans on the lines of sustainable resource development and wise land use was emphasized for improvement of the livelihoods of coastal human settlements, conservation and restoration of altered critical coastal habitats and creation of awareness among the communities along the coast.

The World Summit on Sustainable Development (WSSD), 2002, recognized that multidisciplinary and multisectoral coastal management programmes, involving community participation at national and regional levels, are essential for good governance and management of coastal resources (UN 2002). It was proposed to promote people’s empowerment and their organizations for encouraging sustainable development programmes, that work towards poverty reduction. These programmes reflect their priorities and enable them to increase access to productive resources, public services and institutions, in particular land, water, employment opportunities, credit, education and health. It recognized that the traditional and direct dependence on the renewable resources and ecosystems, including sustainable harvesting, continues to be essential to the cultural, economic and physical well-being of indigenous people and their communities. It also promotes full participation and involvement of indigenous communities in decision-making that affect them and integrates indigenous knowledge, heritage and values in all the development initiatives.

The United Nations Conference on Sustainable Development (UNCSD), 2012, stressed the importance of conservation of coastal areas and reliance on ecosystem-based management of natural resources in collaboration with the community (UN 2012). The Sustainable Development Goals (SDGs), one of the main outcomes of UNCSD through its Goal 14, aims to conserve and sustainably use the oceans, seas and marine resources; and it promotes multi-stakeholder partnership to facilitate sharing of knowledge, expertise, technologies and financial resources with effective public, private and civil society partnership through its Goal 17.16 and 17.17 (ICSU 2015).

28.3.2 Policy and Regulatory Framework for Community Involvement in South Asia

28.3.2.1 Sri Lanka

Coast Conservation Act, 1981, defines the administrative boundaries of the coastal areas of Sri Lanka and provides for drafting the Coastal Zone Management Plan (CZMP) (GoS 1981). The CZMP addresses the critical coastal issues of Sri Lanka and provides the management framework to resolve those issues. It sets the base for public and community participation in drafting the conservation measures for critical coastal systems. The Act mandates the involvement of local and provincial officials and the coastal communities in formulating plans and strategies. It includes acquiring information on coastal resources (corals, lagoons, sand dunes, mangroves, estuaries, etc.) from local communities those would aid in the process of drafting the management plan by the Coast Conservation Department.

National Wetland Policy and Strategy, 2006, was framed to protect, conserve and restore the biological diversity and productivity of the wetlands, thereby enhancing their ecosystem services, and it stresses the guarantee of allowing the traditional sustainable practices of the local communities on their respective local wetland ecosystems. The policy was framed on the principle of sustainable use and managing and conserving them through multiple stakeholder participation, especially the local communities (CEA 2006). The policy supports and encourages active participation of the community members in the conservation of wetlands. It provides for establishment of local level Wetland Management Committees at various administrative levels, with registered Community-Based Organizations (CBOs) and NGOs at the respective level.

28.3.2.2 Bangladesh

National Water Policy, 1999, was framed to address issues relating to the nation's water and the loss of biodiversity. The policy recognizes the vital roles of the people, the community, villages and each individual that are important in managing the water resources of Bangladesh (MoWR 1999). As per the policy, the participation of the local communities is drawn into design and implementation of management plans to conserve and protect the (coastal) waters of the country. As long as there is no greater national interest in any water related projects, the local communities are given free hand to manage the (coastal) water resources, thereby protecting the community rights and interest on the wetlands. These community-oriented plans were framed on the premise that restoring the coastal resources would reduce the pressures on coastal wetlands and habitat losses.

Coastal Zone Policy, 2005, works on the lines of Integrated Coastal Zone Management (ICZM). It primarily aims at conserving Bangladesh's coastal zones with the participation of community and CBOs to reach an agreed framework (MoWR 2005). The CBOs would work in partnership with the local government institutions to implement the programmes and for their integration with higher levels of the government.

28.3.2.3 Pakistan

Pakistan Environmental Protection Act, 1997, aims to protect, conserve, rehabilitate and improve the environment. The Act calls for sustainable development of natural resources through the participatory approach. It required the federal government to encourage formation of community organizations and village organization to meet its objectives through coordinated implementation of management plans (PEPA 1997).

National Environment Policy, 2005, provides the framework for protecting, conserving and restoring its natural environment. The policy encourages participation of the local communities in conservation and sustainable use of the biological resources and encourages the development and implementation of conservation plans with the community involvement. Recognizing the linkage between the poverty and the environment, the policy encourages enhanced participation of the community in environmental management via capacity building and skill strengthening. In order to improve the management of natural resources at the community level, the government, through the National Environment Policy, devolves necessary powers to the local government for effective management. The policy encourages the inclusion of participatory approach and practices into curriculum of environmental education to create awareness about the environmental management and community participation (MoE 2005).

National Wetland Policy, 2009, governs Pakistan's wetlands for sustaining the lives of its people as well as its biological diversity. Recognizing the linkage between wetland resources and the local community livelihoods, the policy calls for community-based management of the wetland resources through equitable resource utilization, good governance, integrated planning and decision-making, knowledge-based management of wetlands and stakeholder involvement (MoE 2009). In addition, special funds are also made available in order to promote and sustain the community management of wetlands.

National Forest Policy, 2010, provides a framework for forest conservation and management in order to increase the productivity and function of the forests so as to aid in the development of the community livelihoods, those the communities are depending (MoE 2010). The policy highlights the importance of community participation in forest conservation and provides for management of the protected areas by the local communities.

National Climate Change Policy, 2012, addresses the climate change-related issues in the governance of the natural resources, especially involving the community participation (MoCC 2012). The policy encourages establishment of community-level forest protection clubs for better management of the resources. Apart from the forest conservation, the policy wants to strengthen the community-level management and adaptation plan preparation for enhanced natural resource management.

28.3.2.4 India

National Forest Policy, 1988, emphasizes that the forestlands are not just the resources meant for utilization but important to the well-being of communities depending on them (MoEF 1988). In addition, the policy enunciates that the revenue generated from forestlands belong to the village, as the villages and the communities are entitled the right of ownership over the lands. This ownership right would drive the community to protect and conserve their revenue generating resources. Under the Forest Policy, the Joint Forest Management (JFM) was initiated in 1990, to conserve the forests jointly with the involvement of local communities (Murali et al. 2002). This co-management approach towards the forest conservation recognizes the value of community-based sustainable forest management. There are 84,632 JFM Committees spread across 28 states in India (Majhi 2016) inclusive of all the coastal states of the main land India and the Andaman and Nicobar Island.

National Conservation Strategy and Policy Statement on Environment and Development, 1992, identifies the significance and uniqueness of wetlands, which are being subjected to overexploitation, pollution and other severe damages due to natural causes. The policy recommends micro-level planning for resource development, which comprises of development of management plans involving community/village people (MoEF 1992). In addition, it recommends empowerment of *Panchayats* and *Gram Sabhas* to support community mobilization and participation.

National Environmental Policy, 2006, was framed and approved in response to the "clean environment" mandate in the Constitution in Articles 48 A and 51 A(g). The policy envisages environmental conservation in a cooperative and coordinated manner. The policy advocates the ICZM in order to sustain the coastal livelihood and improve the coastal economics (MoEF 2006). The policy recognizes the importance of multi-stakeholder partnership in conserving the natural resources and recommends planning and implementation of environment conservation plans at Panchayat levels in cooperation with community-based organizations and other associated stakeholders. In addition, it brings out the fact that the 73rd and 74th amendments of the Constitution provide the framework for local self-government institutions for managing local environment and natural resources (MoEF 2006). It recognizes the importance of traditional knowledge of the community on natural resources for strengthening and building knowledge capacity.

Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006, commonly referred to as the Forest Right Act (FRA), is considered a path breaking legislation that acknowledges the historical injustice meted out to India's forest dwellers, particularly the tribal people (MoTA 2006). The Act provides for allocation of land to traditional communities in all forests including core areas of National Parks and Sanctuaries. The legislation was promulgated to "recognize and vest the forest rights and occupation in forest land in forest dwelling" to tribal and other traditional forest dwellers "who have been residing in forests for generations but whose rights could not be recorded". In core areas, Forest Dwelling Scheduled Tribe (FDST) would be given provisional land rights for 5 years, within which they would be relocated and compensated. If the relocation does not take place within 5 years, they get permanent right over the land. The Act outlines 12 forest rights that include the right to live in the forest, the right to cultivate, use and enjoy minor forest produce and the right to protect and conserve their community forest resources. The *Gram Sabha* is empowered to initiate the process of determining the extent of forest rights to be given to each eligible individual or family. Those communities that depend upon the forest for survival and livelihood purposes but are not forest dwellers or Scheduled Tribes are excluded from the purview of the Act.

28.4 Challenges in Community-Based Management of Coastal Wetlands

The community-based management of coastal wetlands involves the process of decision-making and implementation of sustainable practices to conserve and manage the local ecosystems. The complexity of community-based management has created a shift from a general conservation strategy to a site-specific approach involving several issues to be addressed. The issues in the community-based management of coastal resources (wetlands) are summarized hereunder.

28.4.1 Conflict of Interests

The fundamental component of the community-based natural resource management is decision-making, but that process could be influenced by the differences in perspectives, opinions and the rights the people hold over the natural resources they depend upon in the area. Although there are no statutory provisions, the rights over the land are misinterpreted, leading to the conflicts of interest within the community. Since there can be different uses for the same natural resource, generally the conflicts arise due to the exclusion of certain resource users from being part of the decision-making, contradiction between local and introduced management plans, inequality in resource availability and access and poor policy and implementation (FAO 2000). The issue of conflict of interest would influence the process of electing members to the decision-making body, and over the time, this could lead to authoritative influences in managing the natural resources and even misappropriation or mismanagement of the resources. The conflict of interest in community-based resource management may arise among the people of the same community or between communities who share the resources.

28.4.2 Knowledge Gaps

Managing the complex and interlinked coastal wetland ecosystems requires good understanding and knowledge of each of the ecosystems. In the case of community-based coastal resource management, there could be a knowledge gap among the community members even though they have been living all their life in the coastal region. The environmental policies often emphasize uncertainties in controversial situation that limit the decision-making abilities to achieve best management practices. To avoid these uncertainties, more knowledge needs to be put in place during the decision-making to achieve the best management practices for coastal wetland ecosystems (Knol 2010).

28.4.3 Lack of Expertise

The local community members possess useful knowledge and information on the natural resources they depend upon. However, they may not possess adequate scientific knowledge to complement their traditional knowledge of the ecosystem to formulate effective conservation and management plan (Marshall 2011). The lack of expertise is not confined to the lack of knowledge on the ecosystems but also is prevalent on the process of decision-making, management of finance and in resolving intra- and intercommunity conflicts.

28.4.4 Mismanagement of Coastal Wetlands

The mismanagement of natural resources could result from the community taking advantage of the rights and freedom they have obtained over the natural resource (coastal wetlands). The absolute sovereignty gives them full access and control over the natural resources and their biodiversity, which could be taken to their advantage and exploited, thus making the community-based resource management inefficient and untrustworthy.

Managing the natural resources through community participation, at times, suffers from the lack of transparency in dealing with the finances and accounting. The community members may also lack the knowledge about the processes and procedures of accounting. Such drawbacks may lead to corruptive practices in the resource management, thus resulting in the reluctance of the funding agency to partner with and engage the community in managing the natural resources (Misati et al. 2012). This would lead to mistrust with the sponsor as well as among the members of the community and hold them back from participating whole-heartedly in the sustainable management of natural resources (coastal wetlands). The solution for this could be through proper and transparent communication to the members on the processes, procedures and social audits that empower the community to question and track fund receipt and disbursal.

28.4.5 Weak Institutional Structure

The institutional weakness is one of the major factors leading to unsound environmental planning affecting proper management of natural resources. The involvement of multiple agencies and institutions would facilitate the effective implementation and enforcement of wetland (coastal) conservation measures.

28.4.6 Poor Implementation

Even if the institutional structure is well organized and the policies lay out clear guidance for environmental conservation, the conservation plan will not be fruitful unless there is proper implementation. Poor implementation leads to gaps, offering space for resource mismanagement by the stakeholders making the entire programme meaningless. The poor implementation often turns out to be the graveyard of policy wherein the intentions of the policymaker are outsmarted by the political influence and administration in collusion with certain unscrupulous people in the community (Makinde 2005).

28.4.7 Overlapping Roles and Responsibilities

The multiple organizations and government agencies have different mandates and responsibilities when it comes to coastal wetland management. This multi-agency involvement in coastal resource conservation and management often leads to duplication of responsibilities and confusions, thereby developing gaps in the management framework. The confusion can result in lack of interest in implementation and monitoring of conservation plan, causing ineffective protection and unsustainable exploitation of the wetland resources. This, over the time, can cause distrust and ambiguity among the community members on the designed plan, tempting them to take advantage of the situation and mismanage and overexploit the resources.

28.5 Conservation of Coastal Wetlands by Local Communities: Case Studies

28.5.1 India

Mangrove Rehabilitation and Conservation in Coastal Villages of Kendrapara District, Odisha, India – Bhitarkanika mangrove forest, in Kendrapara district in Odisha, is the second largest mangrove formation in the Indian subcontinent and a Ramsar site declared in 2002. The encroachment by human settlements along the forest boundaries, extensive shrimp farming, cattle grazing and deforestation by the local people have led to the loss of forest spread and density, calling for immediate action for mangrove forest management (APOWA 2013). With the intent of involving the local community in mangrove restoration and management, the Mangroves for the Future (MFF) project funded by International Union for Conservation of Nature (IUCN) initiated the mangrove restoration project with the consent and participation of the local community in 2012 in ten villages. The project established a community-based mangrove nursery, which eventually provided over 36,000 mangrove saplings for plantation, with the technical assistance of Action for Protection of Wild Animals (APOWA), an NGO. For managing the mangrove forests sustainably, an institution was established in each of the ten villages known as the Village Mangrove Council (VMC), which was headed by a president with its members represented by all groups of the village that includes women, men, youth, fishers and grass-root level Panchayat Raj elected members. The VMCs were responsible for the restoration, conservation and management of the mangroves, enabling the local community to take complete stewardship for the mangroves and reap their benefits. In order to educate and develop an understanding of the mangroves among the members of VMCs, capacity-building workshops were conducted in all the villages. The APOWA with the assistance of the VMC conducted mangrove conservation training and awareness programmes for the communities, including students, through school activities. The communities were also trained in alternative livelihoods such as mushroom farming, vegetable cultivation and Systematic Rice Intensification (SRI), to reduce the extent of their dependence on mangroves. The VMC-directed management of the mangrove forest in Bhitarkanika led to the strengthening of stakeholder participation in decision-making and a sense of ownership of their dependent forest resources resulting in sound and cooperative management of natural resources.

28.5.2 Sri Lanka

Community-based management to reduce stress over coral reefs in Sri Lanka – The Kalpitiya Peninsula, in the north-west coast of Sri Lanka, is gifted with many coastal resources, the second largest lagoon in Sri Lanka, with mangroves, sand dunes, seagrass meadows, salt marshes and Bar Reef. The Bar Reef of Kalpitiya, the most extensive reef complex in Sri Lanka, serves as the source of food and income for the fishers and the local community. The reef was declared as a marine sanctuary, and due to illegal fishing, destructive fishing practices and lack of implementation of regulations and other such issues, the area was closed for fishing (Reef Resilience 2014). In 2013, when the ban on fishing was lifted, there was a swell in fishing which led to the decline in stock and income per capita.

In order to address the issue and reduce the negative impact of fishing in the Bar Reef, the Marine and Coastal Resources Conservation Foundation (MCRCF) of Sri Lanka adopted the IUCN's Sustainable Livelihood Enhancement and Diversification (SLED) approach to improve the livelihood status of Kalpitiya community. As a result, the MCRCF chose to train the community people to adopt alternative income-generating businesses such as seaweed farming, tilapia farming, ornamental fish farming and homestead farming to reduce the fishing pressure on the reef area by collaborating with other organizations, such as MFF, the International Coral Reef Action Network (ICRAN) and Centre for Rural Empowerment and Environment (CREE). Consultants from those organizations from various streams such as agriculture and aquaculture including the seaweed cultivation enhanced the knowledge and skills of the local people on alternative livelihoods. These alternatives improved the livelihoods due to the diversified income sources. Educational programmes on the negativity of overfishing and destructive fishing practices were also offered to the community members to create awareness on reef conservation. The case of Kalpitiya community conveys that (a) effective stakeholder partnership is essential in management of natural resources, (b) consultations with experts in specific areas are needed to bridge the knowledge gaps those prevail in the community and get better solutions and (c) partnering with organization(s) is required for better planning and implementation.

28.5.3 Pakistan

Community-based mangrove conservation in Sonmiani Bay, Pakistan – The coastline of Pakistan that extends across the provinces of Sindh and Balochistan is a diverse wetland ecosystem, having coral reefs, mangroves, lagoons and salt marshes of which mangroves are the dominant ones. The Sonmiani Bay, located on the eastern coast of the Province of Balochistan, has a mangrove cover of about 7340 ha, i.e. about 3% of Pakistan's total mangrove cover. The bay has three villages, Dam, Sonmiani and Bhira, whose livelihood directly depends on the coastal resource, fisheries and mangroves. The women in the community are knowledgeable about the resource management but are deprived of the opportunities due to cultural reasons. The mangroves of the bay region support significant biological diversity, serving as shelter, habitat and breeding ground for marine organisms and migratory birds that are of economic importance. The mangroves are under stress due to the high community dependence and the industrial pollution from upstream along the Indus that affect fish productivity and coastal livelihood of the Sonmiani Bay (Shah and Josuff 2007).

With the motive of creating awareness on natural resource threats and educating the communities on the best practices in resource management over the wider area, the World Wide Fund for Nature (WWF)-Pakistan, with support from EU, implemented the project on Tackling Poverty in Pakistan's Coastal Communities through Sustainable Livelihoods. Through this project, the WWF-Pakistan established CBOs in the three villages of the Sonmiani Bay, Society for Social Development and Conservation of Nature (SSDCN) in Dam, Sonmiani Development Organization (SDO) in Conmiani and Mahigeer Tarquati Tanzeen (MTT) in Bhira. Through these organizations, the community members were given skill-based and issue-based training on environmental, social and developmental aspects like economic and women empowerment, loss of biodiversity, degradation of habitat and decline in fish productivity. In addition, the Forest Department of Balochistan collaborated with WWF-Pakistan to develop mangrove conservation activities for the community. Management plans for mangrove conservation were developed, involving the community members, and the same was accepted by the village communities. The mangrove conservation in Sonmiani Bay is an example of successful development and implementation of management plan through the co-management approach, involving the NGOs, government agencies and the local community.

28.6 Conclusion

The relationship and the bonding between the coastal environment and the local community are so strong that even without much scientific input, they understand every reaction or change in the environment. The communities are sensitive to the significance of the ecosystems they depend upon and also realize the associated threats. The historical insight into their local environment transferred from generation to generation is a valuable key in resource management. The traditional knowledge and the knowledge gained through their lifestyle closely linked to the coastal ecosystems provide the community an inherent capacity to evolve appropriate conservation approach and to be adaptive to the changes over time. The community initiatives can promote the participation of the local people in programmes that help to protect and restore wetlands in alliance with the state or central agencies, community groups, environmental organizations and other non-government organizations. The alertness to report the illegal actions, such as wetland filling or dredging activities, helps the government authorities to take appropriate and timely legal actions.

The traditional knowledge and the experiences will not be enough for managing coastal wetland resources due to the increasing stress caused by natural and anthropogenic activities. Hence, collective inputs of both traditional and scientific propositions are required to meet and abate the issues surrounding the loss of biodiversity. In order to achieve this, collaborative actions among government, community, scientists, other experts and NGOs in the designing and implementation of community management of resources are necessary. Involvement of an external knowledgeable stakeholder would not only assist in the design of an effective resource management plan but also facilitate the community in building an organized institution for implementation and monitoring of the plan. The local community should involve the representation of the local government to overlook the formulation and implementation of the plan for compliance with government regulations. The co-management, a relatively recent concept, evolved from the fisheries management is being slowly adopted in other marine resource management programmes, as well.

The community-based coastal wetland management is ideal for restoring and conserving biological diversity and ecological services offered by the ecosystems. This method gives a feeling of ownership among the communities, which makes them more responsible in their usage and exploitation of resources. However, that has to be done under a proper management structure and guidance by external expert partners during planning and implementation processes. It is also important to ensure cooperation and coordination among all the stakeholders, especially the local community, which would help the process to sustain in the long run.

References

Agarwal A, Gibson CC (1999) Enchantment and disenchantment: the role of community in natural resource conservation. World Dev 27(4):629–649

APOWA (2013) Community stewardship in conservation, restoration and sustainable management of mangroves in Orissa. https://www.mangrovesforthefuture.org. Accessed 29 July 2015

Berkes F (2010) Devolution of environment and resources governance: trends and future. Environ Conserv 37(4):489–500

CEA (2006) National Wetland Policy and Strategies. http://www.ramsar.org/sites/default/files/documents/library/national_wetland_policies_-_sri_lanka.pdf. Accessed 28 July 2015

CITES (2013) Resolution 16.6 – CITES and livelihood, Sixteenth meeting of the Conference of the Parties, Bangkok, Thailand, 03–14 March 2013 https://cites.org/sites/default/files/eng/res/16/E-Res-16-06.pdf. Accessed 14 July 2015

CNRA (2010) The future of natural resource management – A white paper and action plan. http://www.resources.ca.gov/docs/IRM_Action_Plan12-10.pdf. Accessed 21 July 2015

FAO (2000) Conflict and Natural Resource Management, Rome, Italy http://www.fao.org/forestry/21572-0d9d4b43a56ac49880557f4ebaa3534e3.pdf. Accessed 29 July 2015

GoS (1981) Coast Conservation Act, 1981. http://faolex.fao.org/docs/pdf/srl11456.pdf. Accessed 24 July 2015

ICSU (2015) Sustainable development goals and targets. http://www.icsu.org/publications/reports-and-reviews/review-of-targets-for-the-sustainable-development-goals-the-science-perspective-2015/sdgs-report-supplement-goals-and-targets. Accessed 13 July 2015

Knol M (2010) Constructing knowledge gaps in barents sea management: how uncertainties become objects of risk. Maritime Stud 9(1):61–79

Luyet V, Schlaepfer R, Marc BP, Buttler A (2012) A framework to implement stakeholder participation in environmental projects. J Environ Manag 111:213–219

Majhi B (2016) Joint forest management programme in India and community participation. Int J Res Econ Soc Sci 6(3):322–332

Makinde T (2005) Problems of policy implementation in developing nations: the Nigerian experience. J Soc Sci 11(1):63–69

Marshall K (2011) Critical review of international literature relating to integrated and adaptive natural resource management, with particular reference to effective stakeholder engagement in catchment management. http://www.demonstratingcatchmentmanagement.net/wp-content/uploads/2011/11/Marshall-Review-Nov2011.pdf. Accessed 13 July 2015

Misati J, Nyangena J, Ndetei R (2012) Towards a policy frame-work for community-based natural resources management in freshwater eco-systems: a case study of Lake Naivasha Basin, Kenya. Conference Proceedings. http://elearning.jkuat.ac.ke/journals/ojs/index.php/jscp/article/view/852/763. Accessed 29 July 2015

MoCC (2012) National Climate Change Policy, Government of Pakistan. http://www.mocc.gov.pk. Accessed 26 July 2015

MoE (2005) National Environmental Policy. Government of Pakistan. Available at http://environment.gov.pk/NEP/Policy.pdf. Accessed 26 July 2015

MoE (2009) Pakistan National Wetlands Policy, Pakistan Wetlands Programme. Available at http://waterinfo.net.pk/sites/default/files/knowledge/National%20Wetlands%20Policy%202009.pdf. Accessed 25 July 2015

MoE (2010) National Forest Policy, Government of Pakistan. http://sindhforests.gov.pk/admin/MediaLibrary/National%20Forest%20Policy%202010.pdf. Accessed 25 July 2015

MoEF (1988) National Forest Policy 1988, Government of India. http://www.moef.gov.in/sites/default/files/introduction-nfp.pdf. Accessed 27 July 2015

MoEF (1992) National Conservation Strategy and Policy Statement on Environment and Development, Government of India. http://www.moef.gov.in/sites/default/files/introduction-csps.pdf. Accessed 27 July 2015

MoEF (2006) National Environmental Policy, 2006, Government of India. http://www.moef.gov.in/sites/default/files/introduction-nep2006e.pdf. Accessed 27 July 2015

MoTA (2006) Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 http://tribal.nic.in/WriteReadData/CMS/Documents/201306070147440275455NotificationMargewith1Link.pdf. Accessed 2 Apr 2016

MoWR (1999) National Water Policy, Government of the People's Republic of Bangladesh. http://wptest.partnersvoorwater.nl/wp-content/uploads/2011/07/WARPO2004_National-Water-Policy.pdf. Accessed 25 July 2015

MoWR (2005) Coastal Zone Policy, Government of the People's Republic of Bangladesh. http://www.warpo.gov.bd/pdf/czpo_eng.pdf. Accessed 25 July 2015

Murali KS, Murthy IK, Ravindranath NH (2002) Joint forest management in India and its ecological impacts. Environ Manag Health 13(5):512–528

NOAA (2015) National Marine Sanctuaries – Community-based management – Module 3. Available at http://sanctuaries.noaa.gov/management/pdfs/comm_based_mod3_curr.pdf. Accessed 15 July 2015

Ostrom E (1990) Governing the commons: the evolution of institutions for collective action. Cambridge University Press, Cambridge

PEPA (1997) Pakistan Environmental Protection Act, 1997. http://www.environment.gov.pk/act-rules/envprotact1997.pdf. Accessed 26 July 2015

Ramsar (1999) Resolution VII.8 – People and Wetlands: The Vital Link, 7th meeting of the Conference of the Contracting Parties to the Convention on Wetlands (Ramsar, Iran, 1971), San Jose, Costa Rica, 10–18 May 1999 http://www.ramsar.org/sites/default/files/documents/library/key_res_vii.08e.pdf. Accessed 13 July 2015

Reed MS (2008) Stakeholder participation for environmental management: a literature review. Biol Conserv 141:2417–2431

Reef Resilience (2014) Sustainable livelihoods enhancement and diversification to reduce pressure on the Bar Reef ecosystem. Available at http://www.reefresilience.org/case-studies/sri-lanka-sustainable-livelihoods/. Accessed 29 July 2015

Ruiz-Mallén I, Corbera E (2013) Community-based conservation and traditional ecological knowledge: implications for social-ecological resilience. Ecol Soc 18(4):12

Shah AA, Jusoff K (2007) Mangrove conservation through community participation in Pakistan: the case of Sonmiani Bay. Int J Syst Appl Eng Dev 1(4):75–81

UN (1971) Convention on Wetlands of International Importance especially as Waterfowl Habitat. Concluded at Ramsar, Iran, on 2 February 1971: No. 14583. https://treaties.un.org/doc/Publication/UNTS/Volume%20996/volume-996-I-14583English.pdf. Accessed 13 July 2015

UN (1972) Report of the United Nations Conference on the Human Environment, Stockholm, 5–16 June 1972. Available at http://www.un-documents.net/aconf48-14r1.pdf. Accessed 14 July 2015

UN (2002) Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August – 4 September 2002. www.unmillenniumproject.org/.../131302_wssd_report_reissued.pdf, Accessed 14 July 2015

UN (2012) Report of the United Nations Conference on Sustainable Development. Rio de Janeiro, Brazil, 20–22 June 2012. http://www.uncsd2012.org/content/documents/814UNCSD%20REPORT%20final%20revs.pdf. Accessed 15 July 2015

UNCED (1993) Agenda 21 *:* programme of action for sustainable development; Rio Declaration on Environment and Development; Statement of Forest Principles: The final text of agreements negotiated by governments at the United Nations Conference on Environment and Development (UNCED), 3–14 June 1992, Rio de Janeiro, Brazil. United Nations Dept. of Public Information, New York

Values Associated with Village Tanks and Some Instances of Enviro-Legal Activism for Wetland Conservation

29

Abdul Jamil Urfi

Abstract

Village ponds and irrigation tanks perform several useful ecological and hydrological functions. They also act as repositories of unique biodiversity. Their role in the conservation of wildlife and birds is highlighted in this chapter. The efforts being made by public-spirited people who have filed public interest litigations (PILs) for the conservation of these waterbodies are also discussed. Some of the key principles to emerge from the Stockholm Declaration of 1972, *viz*., precautionary principle, polluter pays principle, public trust doctrine, intergenerational equity, and sustainable development, have been invoked by Indian courts in settling the PILs filed for the preservation of village tanks, which are outlined here. A representative case of enviro-legal activism, in context of water tanks, is that of "Avilala" and "Peruru" village tanks of Tirupati town in South India. This chapter concludes by emphasizing upon regular ecological monitoring and environmental education for long-term sustenance of wetland ecosystems.

Keywords

Irrigation tanks • Public interest litigation • Village ponds • Wetland birds • Wetland values

A.J. Urfi (✉)
Department of Environmental Studies, University of Delhi, New Delhi 110007, India
e-mail: ajurfi@rediffmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_29

29.1 Introduction

For a country like India, where the bulk of its annual rainfall is obtained from the seasonal monsoon, conservation of water is extremely crucial. This function is quite effectively performed by village ponds and tanks, which store water from precipitation, surface runoff, or stream inflow, for domestic needs of the community, cattle bathing, growing aquatic crops and vegetables, etc. Many village ponds and tanks simultaneously serve as repositories of biodiversity and wildlife, particularly migratory and resident waterbirds, reptiles, amphibians, and plants. While village ponds and tanks were once numerous and well maintained, now due to the spread of urbanization and increased pollution levels, many of them have been destroyed and the land claimed for development. The several wetlands and tanks of ornithological significance which are mentioned in Usha Ganguli's monumental work on the birds of Delhi region (Ganguli 1975) provide a good illustration of this. Revisiting some of the wetlands mentioned in her book, one discovers today that in most cases these waterbodies have either been lost, encroached upon, polluted, or become infested by aquatic weeds.

Interestingly, many tanks or waterbodies, which are encountered in urban premises today, are the ones, which were once village tanks around, which urbanization has spread its tentacles in the form of new buildings and infrastructure. A case in point is Vastrapur *talavadi* (the local term for a village tank) in the city of Ahmedabad – a large village pond, once performing several useful ecological and hydrological functions, but now surrounded by built-up areas, high-rise buildings, and hotels (Fig. 29.1). The same can be said for several tanks, which dot the

Fig. 29.1 A view of Vastrapur *talavadi* in Ahmedabad during 2012. Note the concreted banks, high rises in the background, and boats for recreation. What was once a village pond, for storage of rain water, is now an island in a sea of concrete

cityscapes of Bengaluru and Mysore in Karnataka, and several other Indian cities. The fate of water tanks is more or less similar across cities and urban agglomerations in South Asia.

In this chapter, issues of wetland values and wetland conservation in context of village ponds and irrigation tanks are taken up. Emphasis is made on the biodiversity of ponds and irrigation tanks, with special reference to heronry birds. Rather than merely making a wish list of possible actions in the vague hope that the concerned authorities will follow up in the interests of environmental protection, sometimes it is much more fruitful to take recourse to legal remedies. Therefore, on a more positive and optimistic note, the chapter highlights some of the conservation initiatives taken by public-spirited citizens, taking recourse to legal action through public interest litigation (PIL) suits. The well-known enviro-legal cases covered here are placed in the larger context of conservation of village ponds and tanks for the purpose of a broader narrative. Though many of the cases taken up here are specific to India, they are likely to be useful to readers from other parts of South Asia as well as Southeast Asia, where conditions are somewhat similar.

29.2 Biodiversity Values: Aquatic Birds in Village Ponds and Tanks

Many village tanks are refugia for rare and endangered wildlife. For instance, a thriving population of the Indian Mugger or Marsh Crocodile (*Crocodylus palustris*) besides several species of mud turtles has been recorded from Traj village pond in Kheda district of Gujarat (Urfi 2002). An interesting feature of many of these waterbodies is heronries, *viz*., nesting colonies of such waterbirds as darter, cormorant, heron, egret, ibis, spoonbill, pelican, and stork (Fig. 29.2). The heronries usually exist on clumps of trees growing on islands in the middle of village tanks and ponds and are a common feature in Karnataka, Gujarat, Tamil Nadu, and many other Indian states. Some of the Indian heronry birds of conservation significance, which have been listed in the BirdLife Conservation International (2001), are Oriental Darter (*Anhinga melanogaster*), Painted Stork (*Mycteria leucocephala*), and Black-headed Ibis (*Threskiornis melanocephalus*) often occurring in mixed colonies at village tanks (Tiwary et al. 2014). Thus, efforts for their conservation can be a strong reason for taking care of these habitats and also for the larger benefits that they provide for the local communities. Village pond heronries also present a unique opportunity for conducting environmental education and outreach programs (Urfi and Nareshwar 1998).

29.3 Enviro-Legal Activism: Relevant Background Concepts

In spite of their biodiversity values and ecological significance, most village tanks across India are under threat, facing problems from different directions. For instance, while pollution and disturbance are important causes, illegal and rampant

Fig. 29.2 Village tanks are repositories of unique biodiversity. The village pond near Traj village in Kheda district, Gujarat, which has a thriving population of Mugger, a nesting colony of openbill stork and several other types of birds including jacanas and teals. Photo taken by author during 1998 (Source: Urfi 2011)

urbanization on the shore is causing destruction of foraging habitat in the vicinity of the nesting colonies inside the premises of tanks (Fig. 29.3). In the Delhi region where our research group has been conducting field studies for the past several years, some of these problems have been documented. For instance, at Chhata village tank, locally known as Surajkund Tank, the water is severely polluted with trash, discharge from drains carrying municipal sewage from the neighboring households, plastic bottles, and other garbage (Fig. 29.4). Much of the pond is covered with water hyacinth (*Eichhornia crassipes*) leading to a reduction in the surface area of water and preventing sunlight from penetrating the column of water beneath. Each village tank has specific problems, but the above summary presents a brief account of the general nature of the problems and the conservation challenges.

In recent years, PIL by public-spirited citizens has emerged as a powerful tool to push the authorities into action and take necessary steps for the conservation of environment. Perhaps the same strategy can be adopted for village ponds. An outline of some relevant legal concepts is provided here.

Prior to the 1976 Amendment, the Indian Constitution did not have any major provisions for dealing with issues of environmental degradation except for a few acts such as *The Factories Act of 1948*, *River Boards Act of 1956*, and the *Prevention of Cruelty to Animals Act of 1960*. While there were only a few provisions for checking pollution, it was the Stockholm Declaration (1972), which led a major paradigm shift worldwide, resulting in introduction of a number of important principles in the environment protection lexicon. Taking advantage of these

Fig. 29.3 A view of Shilaj village pond near Thaltej, Ahmedabad (during 2012). This pond has (or used to have) a heronry, with nests of storks, ibises, herons, and cormorants. Consequent to the real estate building boom in and around Ahmedabad over the past few years, several housing societies are coming up. Inset shows the board of one of the developers near Shilaj pond. Note that the builder is cashing in on wetland values (peace, tranquility, esthetics, etc. in the proximity of a waterbody) to sell flats in the housing society

Fig. 29.4 The picture shows pollution and dumping of garbage and solid waste in a village tank. An open drain is seen. The waterbird colony can be seen in the background. Photo by NK Tiwary and BB Sharma (during 2013)

developments, environmental activism took off in a major way as concerned citizens started filing PIL cases and applying pressure on civil authorities to perform their duty with respect to safeguarding the environment. Some of the important principles that emerged during this period were:

1. *Precautionary principle*: The basis of this principle was the “Assimilation Capacity” rule (Principle 6 of the Stockholm Declaration), which assumed that natural systems such as rivers, lakes, and atmosphere had a certain capacity to assimilate the impacts of environmental degradation and pollution. There was also a general belief in the society, administrators, etc., that it was within the capacity of scientists to not only estimate when an upper limit of the assimilation capacity of natural systems had been reached but also to offer mitigation strategies. The belief about the great powers of modern science and optimism in it, prevalent in modern society especially following the great discoveries of modern science in the early parts of the twentieth century, led credence to general belief that the problems of environment could be solved by science. Certainly, by employing technological and scientific methods, it could be possible to estimate the levels of pollutants in a river or a lake and then come to some conclusion as to whether the system could withstand higher pollution loads or not. Though the idea behind the “Assimilation Capacity” rule, based on a belief in science, was simple, it was also recognized that for coming to any conclusion the right type of information or data was required, which in a sense was also a limitation. Therefore, this principle was to later change into what came to be called the “precautionary principle,” which held that “lack of full scientific certainty shall not be used as a reason for postponing cost - effective measures to prevent environmental degradation.” So “inadequacy of science” is the real basis of the precautionary principle, and if in any particular instance, appropriate data are not available to reach any conclusion about the assimilation capacity, then prevention of further degradation should be followed.
2. *Polluter pays principle*: This means that one who pollutes must bear the costs of cleaning up, remedying the damage. It evolved out of the rule of “absolute liability,” though some believe that the principle has degenerated into “pay and pollute.”
3. *Public trust doctrine*: The origin of this doctrine can be traced back to an ancient Roman law as “Doctrine of the Public Trust” and essentially rests on the idea that common resources such as air, sea, waters, and forests belong to all, and it would be wholly unjustified to make them the subject of private ownership. In most cultures, predating the advent of modern Western civilization, individual ownership of common resources such as air, water, and land was unthinkable. It was always given that such resources could not possibly be owned by anyone but they belonged to all. Therefore, acquiring a monopoly over such resources and making a profit out of it was not acceptable.
4. *Intergenerational equity*: It means that the moral obligation of the present generation is to manage the earth in a responsible manner without jeopardizing the aesthetic and economic welfare of future generations.

5. *Sustainable development*: According to the document emanating from "World Commission on Environment and Development" (WCED) or the Brundtland Commission Report (1987), sustainable development is defined as development that meets the needs of the present without compromising the ability of the future generations to meet their own needs.

   Thus, post-Stockholm saw the enactment of several new laws by the Indian Parliament and the emergence of important principles, which began to constitute the core of important pronouncements in the law courts. The Supreme Court of India also took a lead in environmental activism cases.

29.4 Preservation of Tanks: Activism by Public-Minded Citizens and Organizations

Though several decided cases have set the trend for environmental litigation and activism in India, the ones that are relevant in context of village tanks are summarized below. Many of these cases are standard teaching material in law schools across India.[1]

29.4.1 Avilala and Peruru Village Tanks of Tirupati Town

"Intellectuals Forum, Tirupati vs. State of Andhra Pradesh" (AIR 2006 SC 1350) is a landmark case and relates to protection and conservation of two ancient village tanks in the state of Andhra Pradesh, said to be in existence since 1500AD. The facts of this particular case are as follows: Avilala and Peruru village tanks are situated in the suburbs of Tirupati[2] town. Although these tanks had been in existence for a long time, there had been considerable encroachments of these waterbodies, largely due to the oversight by the authorities, because of which they had become thoroughly degraded and much reduced in size. Consequently, the tank beds were totally destroyed and could not perform their ecological functions (recharge of aquifers, storage of water, etc.). Since the land belonging to these tanks began to be considered prime property, there were considerable pressures from developers, mainly the "Tirupati Urban Development Authority" (TUDA) and the "Andhra Pradesh (AP) Housing Board," to claim more areas in these tanks for development projects. In spite of several representations made to the local authorities to improve the condition of the village tanks, no action was taken and therefore the appellants, all public-spirited citizens, filed two writ petitions challenging the government order by which the district collector of Chittoor was directed to hand over the land belonging to the tanks to the developers, AP Housing Board, Tirumala Tirupati

[1] The ones taken up here are included in the LLB course (paper "Environmental Law") offered by the University of Delhi, India. Description of cases available in relevant teaching material, e.g., Tandon et al. (2013).

[2] The town is spelled differently in some documents, *viz.*, Tirupati in TUDA.

Devasthanams (TTD), and a local trust. Several other individuals also filed affidavits supporting the cause taken up by the appellants such as the Indian Medical Association cited evidence how the alarming increase in toxins (particularly fluorides) was creating health problems to the local people.

A counter-affidavit was filed by the government justifying its own decision on the grounds that since huge amounts of money had already been invested toward the development of land, it was all supposedly for the cause of promoting "public interest." However, since the respondents had taken the plea that the actions of the government were in pursuance of urgent needs of the development, this brought into the question on the kind of development. In deciding this case, the court invoked the principle of sustainable development. India is a party to Rio Declaration on Environment and Development (Earth Summit 1992). Principle 4 of the declaration states "In order to achieve sustainable development, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it."

At this juncture, it will be instructive to recount a number of previously decided cases, both in India and in other countries, on the basis of sustainable development and public trust doctrine, since they have a bearing on the present case. Some of them are the following:

- In "Essar Oil Ltd vs. Halar Utkarsh Samiti" (2004, 2 SCC 392), the Supreme Court observed "The objective of all laws on environment should be to create harmony between the two since neither one can be sacrificed at the altar of the other." Thus, an attempt was made to strike a balance between the interests of economic development and conserving the environment.
- In "Indian Council for Enviro-Legal Action vs. Union of India" (1996, 5 SCC 281), a similar view had been taken by the Supreme Court, invoking the principle of public trust doctrine and citing a case decided in the USA, i.e., "Illinois Central Railroad Co vs. People of the state of Illinois" (1892, 146 US 37:36 L Ed 1018). In this particular case, the US Supreme Court had held "…natural resources, which include lakes, are held by the state as a 'trustee' of the public…." Thus, the interests of the general public were kept in mind, and it was recognized that the duty of the state is to provide protection to natural resources.
- In yet another case from the USA, *viz*., "National Audubon Society vs. Superior Court of Alpine Country" (33 Cali 419), the Supreme Court of California held ".. the public Trust is more than an affirmation of the State Power to use public property for public purposes. It is an affirmation of the duty of the state to protect the people's common heritage of streams, lakes, marshlands, and tide lands, surrendering the right only in those rare cases when the abandonment of the right is consistent with the purposes of the trust."

  In several cases decided by the Supreme Court of India, we see that the public trust doctrine has been incorporated as a part of the Indian law. For instance, in "M. C. Mehta vs. Kamal Nath," also known as the *Span Motels case*, (1997, 1 SCC 388), the Supreme Court held "The State as a trustee is under a legal duty to protect the natural resources." A similar position was also taken in

"M.J. Builders (P) Ltd. vs. Radhey Shyam Sahu" (1999, 6 SCC 464) by the Supreme Court.

Thus, in the *Avilala* and *Peruru* village tanks case, the Supreme Court ruled in favor of protecting the village tanks for their numerous benefits to ecology and local communities. Further, the apex court imposed restrictions on new construction activities around the tanks, cleaning of supply channels and drains, creation of percolation tanks, measures for rain water harvesting, etc.

29.4.2 Bichhri/H: Acid Case

There are other cases that touch upon the conservation of waterbodies, imposing checks on pollution, etc. in the context of waterbodies (including riverine and coastal). The case "Indian Council for Enviro-Legal Action vs. Union of India" or the "*Bichhri/H – Acid Case*" (AIR 1996 SC 1446) is also relevant in context of conservation of village tanks. Some facts of the case are in Bichhri village near Udaipur (Rajasthan) due to chemical industries, the pollutants were severely hampering the "right to life" guaranteed by Article 21 of the Constitution. The Supreme Court invited experts from various institutes to submit their reports on this issue. After a perusal of the reports and due deliberations, the court observed:

1. Chemical industries were the main culprits and they could be characterized as "rogue industries."
2. Fundamental right to life is violated. Industries are allowed to run in blatant disregard of law to the detriment of life and liberty of citizens living in the vicinity.
3. Polluter pays principle shall apply.

29.4.3 Other Cases of Interest

The "'Vellore Citizens' Welfare Forum vs. Union of India" (AIR 1996 SC 2715) is also of relevance in this context. The facts of the case were as follows: Certain tanneries in Tamil Nadu were discharging effluents and impacting waterways, agricultural fields, and the environment in general in an adverse manner. The Supreme Court observations in this regard were "precautionary principle" and "polluter pays principle" that are part of the environmental laws of the country and essential features of "sustainable development." Under Section 3 of the Environmental Protection Act, 1986, the central government was directed to constitute an authority which would compute the compensation under reversing the ecological damage and payment to individuals.

"M. C. Mehta vs. UOI" (1997, 3 SCC, 715) or the *Badkhal & Surajkund Lakes* case is also relevant since it relates to waterbodies, *viz.*, two small lakes in the Aravalli hills on the outskirts of Delhi. New construction activities were being planned in the vicinity of the lakes which would spoil the scenic charm of the place, disturb peace and tranquility, and have other adverse impacts. Invoking the "precautionary principle," the Supreme Court took the view that construction activities within a radius of 1 km around the lakes should be banned.

29.5 Conclusion and Recommendations

- The village tanks provide a number of functions such as storage of rain water (for domestic needs, irrigation, cattle bathing, etc.), functioning as repositories of biodiversity, important hydrological functions such as recharge of aquifers, etc. The resources should be used in a wise and sustainable manner, and the unchecked urbanization in the immediate vicinity and disposal of untreated sewage into the tank pose numerous problems for their survival. It will be worthwhile to monitor village ponds of ornithological significance and keep a track of changes taking place at these sites.
- Local naturalists and birdwatchers can help in generating awareness about their conservation significance and ensure their protection.
- Many of the environmental problems that we see at the village tanks are due to negligence on part of the concerned authorities. Enlightened residents of the village as well as environment protection groups can play an important role by initiating education projects and installing educational interpretation waysides signages, which can focus not just on the heronry birds but also on other aspects. For example, near the Chhata village pond, there are also the ruins of an old, Mughal period building with several *chhatris* (awnings), due to which the settlement probably derives its name, and these need to be conserved and interpreted also. Efforts for developing outreach programs and environment education are virtually nonexistent for most sites. A proper system for providing on-site information by installation of waysides and other interpretation facilities is urgently required.
- Resorting to legal activism, such as filing a PIL, can help in putting pressure on local authorities to keep the village tanks clean and free from pollution and discharge their duties with respect to protecting the environment. Courts have relied upon constitutional provisions and several important principles which emerged in the aftermath of the Stockholm Conference and Brundtland Commission Report. However, no follow-up has been made to assess the present condition of the waterbodies over which legal victories were won.
- There is an urgent need to formulate a nationwide policy on conserving village tanks, urban tanks, and other such waterbodies for the many useful functions (particularly aquifer recharge) that they perform. Care and consideration of waterbodies become even more important given the widespread fear that in upcoming years the water will be a very scarce resource and battles are likely to ensue over sources and distribution of water.

Acknowledgment The University of Delhi and the Department of Science & Technology (DST "purse grant" to the University of Delhi), India, are thanked for the award of research grants to the author.

References

BirdLife Conservation International (2001) Threatened birds of Asia: the birdlife international red data book. BirdLife International, Cambridge

Brundtland Commission Report (1987) Our common future or the Brundtland Commission Report. World Commission on Environment and Development (WCED). http://www.un-documents.net/our-common-future.pdf. Accessed 11 Jun 2015

Convention on Climate Change and the United Nations Convention on Biological Diversity. http://www.un.org/geninfo/bp/enviro.html. Accessed 11 Jun 2015

Earth Summit (1992) United Nations Conference on Environment and Development (UNCED), Rio de Janeiro, 3–14 June 1992 .Agenda 21, the Rio Declaration on Environment and Development, the Statement of Forest Principles, the United Nations Framework

Ganguli U (1975) A guide to the birds of the Delhi area. Indian Council of Agricultural Research, New Delhi

Stockholm Declaration (1972) Declaration of the United Nations Conference on the Human Environment, Stockholm, 5 to 16 June 1972. http://www.unep.org/Documents.Multilingual/Default.asp?documentid=97&articleid=1503. Accessed 11 Jun 2015

Tandon U, Relan MA, Shabnam, Pushpa Kumar L, Kumar N, Singh A, Kumar V, Lata K (2013) L.L.B. V Term. Environmental Law (Cases Selected and Edited). Faculty of Law, University of Delhi, New Delhi

Tiwary NK, Sharma BB, Urfi AJ (2014) Two new nesting colonies of Painted Stork *Mycteria leucocephala* from northern India. Indian Birds 9:85–88

Urfi AJ (2002) A heronry at Traj in Kheda district, Gujarat. J Bombay Nat Hist Soc 99:113–114

Urfi AJ (2011) The painted stork. Ecology and conservation. Springer, New York

Urfi AJ and Nareshwar M (1998) Interpreting a village pond heronry. NewsEE (CEE) 4/3:5

Participatory Wetland Management: A Solution to Conservation Challenges in the Sundarbans Biosphere Reserve

30

Nisha Maria D'Souza, N.M. Ishwar, Isheeta Sumra, and Pradeep Vyas

Abstract

The nature of human dependencies on wetland goods and services is various and complex. Despite being vital societal assets, wetlands continue to degrade. Over the last couple of decades, the concept of participatory management of wetlands, particularly mangroves, in India has gained momentum in scope and application. The basis of community-based resource management is the recognition that humans are part of the ecological system and not separate from it. Through the Mangroves for the Future (MFF) initiative, International Union for Conservation of Nature (IUCN) aimed to assess the effectiveness of the participatory management approaches undertaken toward mangrove wetland management, particularly in the Sundarbans Biosphere Reserve, West Bengal, India.

Keywords

Biosphere reserve • Mangrove • Participatory management • Sundarbans

N.M. D'Souza (✉) • N.M. Ishwar
IUCN, International Union for Conservation of Nature, India Country Office, New Delhi, India
e-mail: DsouzaN@iucn.org; nm.ishwar@iucn.org

I. Sumra
Independent Consultant, New Delhi, India
e-mail: isum2619@gmail.com

P. Vyas
Sundarban Biosphere Reserve, Government of West Bengal, Kolkata, India
e-mail: sbrdir@gmail.com

B.A.K. Prusty et al. (eds.), *Wetland Science*,
DOI 10.1007/978-81-322-3715-0_30

30.1 Introduction

Healthy wetlands support ecological and human well-being, delivering services for people, livelihoods, and businesses. The Ramsar Convention (1971), the foremost international treaty for conservation and sustainable utilization of wetlands, uses a broad approach in defining wetland ecosystems. It covers a larger number of inland wetlands (such as swamps, marshes, lakes, and peat lands), coastal and near-shore marine wetlands (such as coral reefs, mangroves, seagrass beds, and estuaries), and human-made wetlands (including rice paddies, dams, reservoirs, and fishponds). Virtually all-existing wetlands have been influenced and altered by human use. Conservative global estimates suggest that almost 30% of natural wetlands have been lost in the last three decades alone.

India, by virtue of its geomorphological and climatic variability, has a rich diversity of wetlands spanning over 58.2 million ha (MoEF & CC 2015). In India, wetlands are not delineated under any specific jurisdiction. Nevertheless, the formal responsibility for the implementation of the regulatory framework for wetland conservation rests with the Ministry of Environment, Forest and Climate Change, Government of India. Wetland conservation, however, is indirectly influenced by other governmental departments (and policies and legislations) relating to energy, industry, fisheries, agriculture, transport, and water resources.

Conventional approaches to wetland conservation in India have been along the line of the protected area regulations. Wetlands within protected areas (PAs) are regulated by the Wildlife Protection Act (1972), while wetlands outside of protected or notified areas are regulated by the relevant provisions of the Environment (Protection) Act (1986). Typically, the responsibility for on-ground execution and management has been with the state apparatus. However, over the years, the functioning of the state apparatus has become highly compartmentalized with little coordination among different ministries and departments. Additionally, the link between wetlands and the services they provide toward food, water, and livelihood security is one that not all land managers and decision-makers understand. It has been widely realized that the relationships between wetland communities and their environments are extremely complex and the long-term integrity of PAs in low-income nations depends on the support of the local communities.

Extensive studies by International Union for Conservation of Nature (IUCN) and partners across South Asia have demonstrated that local knowledge with respect to wetlands is integral to effective wetland management and should be understood, acknowledged, and strengthened. In Bangladesh, climate change is having a disproportionately large impact on wetlands, and communities are constantly exploring adaptive measures to alleviate the impacts. For instance, in more than 100 wetlands (*Haors*), communities have developed their own fish sanctuaries whereby harvesting is conducted on a rotational basis; together with the agricultural ministry, they are also exploring and changing the variety of rice crops and the conventional floating rice beds to conserve water. In Sri Lanka, the private sector, local communities, and government departments are partnering to capitalize on filtration abilities of wetlands to address industrial waste pollution. All wetland-associated stakeholder groups play a fundamental role in applying knowledge and skills in wetland management. Many manage their knowledge through a variety of common as well as specific ways that can be categorized into internal mechanisms (e.g., passed through generations, contained within directives and community-based organizations) and external mechanisms (e.g., nonprofit organizations and governments). It is necessary that stakeholders be supported in developing their capacities to collect, edit, and present their knowledge systematically for effective wetland conservation and management.

Over the last couple of decades, the concept of participatory management of wetlands in India has gained momentum in scope and application. The basis of community-based resource management is the recognition that humans are part of the ecological system. Participatory management is generally defined as *a partnership in which government agencies, local communities and resource users, and perhaps other stakeholders, such as NGOs, share the authority and responsibility for management of a specific area or set of resource.* There are five basic principles that are required for this: (1) empowerment (the transfer of economic and political power from few to the impoverished many and the operationalization of community management and control), (2) equity (community as a whole benefit), (3) sustainability (i.e., intergenerational equity based on the carrying and assimilative capacity of the ecosystem), (4) systems orientation (the community functions in the context of other communities and stakeholders), and (5) gender considerations (women are involved in the control and management of community resources, and their practical and strategic needs are addressed) (Addun and Muzones 1997).

In India, participatory management of wetlands, particularly for mangroves, has met with considerable success. The Joint Mangrove Management (JMM) program was piloted by the MS Swaminathan Research Foundation (MSSRF) and State Forest Departments in India, between 1996 and 2004 in seven mangrove wetlands of Tamil Nadu (Muthupet and Pichavaram), Andhra Pradesh (Krishna and Godavari), Odisha (Devi and Mahanadi), and West Bengal (Sundarbans). It was included in the National Mangrove Action Plan (Selvam et al. 2012). The program is now being replicated in Gujarat. Apart from ensuring access to mangrove resources, particularly fishery resources, a number of other livelihood strengthening and poverty reduction activities are also conducted through the initiative. This incentivizes communities to participate actively in mangrove management. The initiative has allowed for effective channeling of central and state government resources toward mangrove restoration and management programs. During the last two decades, the country's mangrove cover has increased by 616.56 km^2, emphasizing the catalytic role of the JMM program (FSI 2013). The consensus is that location-specific, science-based, community-centered, and process-oriented approaches are necessary for sustainable management of wetlands. Such approaches should be promoted through multi-stakeholder community-NGO-government-private sector partnerships that allow for equal opportunities for participation in decision- and policy-making processes.

30.2 Participatory Management in the Sundarbans: A Case Study

Vast expanses of the Sundarbans are arguably wilderness areas in their most literal form. Spread across the border between India and Bangladesh at the confluence of three major rivers, Ganges, Brahmaputra, and Meghna, it is the world's largest delta (~80,000 km^2). The Sundarbans hosts the greatest continuous extent of mangroves globally and a unique and unparalleled wetland biodiversity, with distinction as the only existing mangrove tiger habitat (Shunmugaraj et al. 2011). It is an example of an endangered ecological system that is highly populated and both fragile and economically valuable.

The Indian Sundarbans (ISB) was designated a biosphere reserve in 1989 by the Government of India and subsequently brought under the United Nations Educational, Scientific and Cultural Organization (UNESCO) Man and the Biosphere Programme (MBP) in 2001. Around 4264 km^2 of the ISB was designated reserved forest under the Indian Forest Act, 1927. Within this area, intensive protection has been provided to the Sundarbans National Park (SNP) and three wildlife sanctuaries, Sajnekhali (362 km^2), Lothian Island (38 km^2), and Haliday Island (6 km^2). As one of nine original tiger reserves under Project Tiger, the Sundarbans Tiger Reserve (STR) was established within the SNP in 1973 and covers over 2585 km^2 of critical tiger habitat. In recognition of its immense value, UNESCO declared the SNP a World Heritage Site in 1987; discussions are underway to include it as a Ramsar Site of National Importance.

Indian Sundarbans is characterized by extreme poverty, which contributes to and arises from the vulnerability of the human population to natural threats. Over the past century, sea level rise (SLR), salinization of soil and water, cyclonic storms, and flooding have plagued local communities living in the area. Natural stresses are compounded by human-induced stresses, including reductions in freshwater flows to the delta and an expansion in unsustainable tidal aquaculture.

Of the 108 islands within the Sundarbans, 54 are currently inhabited with a population of approximately 4.2 million living in 1060 villages (2011 Census of India). The region is spread over two administrative districts, namely, South 24 Parganas (13 blocks) and North 24 Parganas (six blocks). Post-independence, the region witnessed a sudden influx in population due to migration from neighboring states and Bangladesh. The Sundarbans therefore has a high population density, averaging 800 people per km^2. Studies show that settlement areas have increased from 1226 to 1666 km^2, while agricultural land has reduced from 2149 to 1619 km^2 between 2001 and 2008 (WWF 2010). This conversion raises important questions relating to food and water security in the region. However, the study (WWF 2010) has also recorded an increase in aquaculture farms from 603 to 649 km^2, which could be a result of market pressures or a response to increasing salinity ingress into agricultural lands.

The majority of the population in the Sundarbans lives below the poverty line, subsisting on single-crop agriculture on reclaimed mangrove land, made possible by the development of earthen embankments to keep the brackish tidal water at bay. Over 50% of the agricultural laborers are landless or marginal farmers; the daily income of the local people involved in agriculture is as low as INR 5–12 per day (Shunmugaraj et al. 2011). Apart from rain-fed agriculture, resource-dependent livelihoods such as fishing, honey collection, and woodcutting are undertaken in the region. The extreme poverty and dense population, coupled with increasing population growth and development rates, have exerted significant pressure on the natural mangrove ecosystem. Conversely, although dependence on non-timber forest produce (NTFP) is extremely high in the ISB, it is observed that the majority of communities are engaged in agricultural labor, despite it being low yielding due to high soil salinities (ten quintals per hectare for main crop) (Singh and Pandey 2010).

Investments in infrastructure development such as roads, embankments, dams, diversions, and power facilities while bringing visible benefits at the local level are also creating multiple risks to the ecosystem. These pressures in the Sundarbans have already led to the extinction of several faunal species (Chaudhuri and Choudhury 1994). Finding appropriate solutions to the demands of human development processes in the Sundarbans seem to be an uphill battle. There is an ongoing conflict in the area between the survival strategies of distressed people and protection of the environment in its natural state.

30.2.1 Setting the Scene

There are three administrative units in the Sundarbans Biosphere Reserve (SBR), namely, the STR, North 24 Parganas Division, and South 24 Parganas Division. Within each of the administrative units, and for management purposes, the areas are further divided into ranges, beats, and *mouzas* (villages).

Forest management, particularly in the Indian Sundarbans, is a multidimensional process that encompasses ecological, technical, socioeconomic, and institutional aspects of management and minimizes human-wildlife conflict. This process, apart from government management, needs greater participation from local communities. In recent years, there has been a paradigm shift from centralized, controlled, and custodial forest management to democratic, devolving, community-based natural resource management. The participatory management model has led to a shift in forest management priorities, from revenue generation to resource development, from single benefit to multiple benefits, from monoculture to multiple cropping, and above all from unilateral decision-making to participatory process (Debnath and Naskar 1999).

A Joint Forest Management (JFM) governance system was introduced for the effective management of the ISB. Under this scheme, the State Forest Department has formed a number of Joint Forest Management Committees (JFMCs), an institution representing the village communities living in and around the reserve forests of the ISB. To date there are 65 JFMCs, 51 Forest Protection Committees (FPCs), and 14 Eco-development Committees (EDCs) registered in the Sundarbans. However, the long-term viability of the JFMCs appears doubtful until issues of poverty alleviation, empowerment, sustainable development, and forest regeneration are addressed satisfactorily.

The JFM institutions referred to as FPCs are led by the local communities in a step toward mobilizing and motivating them to conserve the natural resources, thereby ensuring their participation in planning, executing, monitoring, and evaluating conservation interventions. The funds for these activities come from centrally sponsored schemes of the Government of India, including Conservation and Management of Sundarbans, Conservation and Management of the SBR, Project Tiger, and Wetland Project. The Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) is also being implemented to provide employment and income sources to the rural poor of the Sundarbans. The members of the FPCs are selected by the Divisional Forest Officer (DFO) in consultation with the Bon-o-Bhumi Sanskar Sthayee Samiti (BoBSSS) of the local Panchayat Samiti. Each FPC has an executive committee that consists of six elected members, who are responsible for protection of the forests and for ensuring smooth harvesting of forest produce by the Forest Department. Additionally, the FPC is entrusted with the duty of ensuring that the usufructuary rights are not misused by any of the members.

Similarly, the local communities living around the protected areas of the Sundarbans have EDCs, which manage wildlife and biodiversity conservation, wildlife poaching, and unscientific harvesting of medicinal plants. The members are selected in the same way as in the FPCs, although 30% of the members of the executive committees must be females.

30.2.2 Study Process

30.2.2.1 Project Conception

The IUCN's interventions in the Sundarbans derived their basis from initial learning developed through a short-term project aimed at assessing the effectiveness of introduced livelihood programs in the region. The following was highlighted in the assessment:

- Following cyclone Aila, the local communities have a deeper appreciation of the protective role of mangroves. As such, they are willing to participate in mangrove plantation activities, and it is recommended that social forestry intervention be explored and taken forward in this respect.
- Through the project, it was realized that the self-help groups (SHGs) were efficient in providing women with the financial support they needed. Sixty-two percent of women interviewed from all the surveyed SHGs in the 24 Parganas claim to have benefitted socioeconomically in one way or the other from being SHG members. The rest of the SHGs said that they found no change in their socioeconomic status at all.
- The JFMCs are responsible for spreading awareness about the harmful effects of fuel wood collection and in reducing the incidence of this among local communities. However, in 40% of the JFMCs in the 24 Parganas, this trend was not visible.

- It is apparent from the study results that goodwill has already been developed between the local communities and JFMCs in the STR. However, the same cannot be said for the 24 Parganas; a lot of grievances from the JFM members toward the Forest Department were reported. It was observed that within the STR, several additional confidence-building activities were undertaken in addition to intensive alternate livelihood programs. The study recommended that the same approach be adopted by the 24 Parganas administration to win over the local communities.

Based on these observations, a larger project was conceptualized to engage in a more efficient and robust JFM process. As such, IUCN (through the MFF initiative) and the SBR, Government of West Bengal, were the leaders in this and provided oversight, while World Wide Fund for Nature (WWF) India undertook the study for assessing the effectiveness of JFMCs in conservation of natural resources in the Sundarbans.

30.2.2.2 Study Methodology

The survey was conducted in 17 JFMCs (25% of the existing JMFCs in the region), selected through a process of stratified sampling. Stratified purposive sampling illustrates characteristics of particular subgroups of interest; it involves dividing the purposefully selected target population into strata (e.g., above average, average, and below average) with the goal of discovering elements that are similar or different across the subgroups. The stratification was based on the following criteria:

1. Incidences of human wildlife conflict
2. Alternative livelihood programs
3. Awareness toward conservation
4. Eco-development activities

The project interventions were implemented in two ranges of the South 24 Parganas Forest Division and ranges in the STR. The South 24 Parganas Forest Division is currently within the jurisdiction of the SBR and includes both reserved forests and human inhabitations. Matla and Raidighi were chosen because they face the highest incidences of human-wildlife conflict in the area and are most in need of infrastructure and supplementary livelihoods to prevent their dependency on the forests (within which subsequent wildlife attacks ensue). The South 24 Parganas Division is managed by a joint director, assisted by a division forest officer, two assistant deputy forest officers (ADFOs), three rangers, and six deputy rangers. They currently work in 18 JMFCs. The project area also includes the STR. A field director, assisted by a deputy field director, two assistant field directors, seven range officers, and six deputy rangers, manages the STR; they collectively look after 25 fringe villages to the north of the STR.

The JFMCs were analyzed for their effectiveness, based on the following factors that affected the JFMC functioning:

- The procedure for membership to a JFMC, its functioning, the development of its micro-plan, and activities were assessed. *Awareness* is the basis of any successful program designed to function with active community participation. This parameter was therefore considered important in the effectiveness assessment.
- *Level of participation of women and youth* in electing the JFMC executive body, in the general body, and their membership in the executive body were assessed.
- Extent of *participation of the ex officio member secretary* of the executive body of the JFMC greatly influences the effective functioning of the JFMC. This factor studied the involvement of the Secretary in the activities of the JFMC and the community's perception of the Secretary.
- The micro-plans were assessed to establish whether community *needs are being addressed*. The economic and social benefits to the community from activities undertaken by the JFMC were similarly examined.
- *Financial transparency:* The levels of awareness among community members concerning the financial affairs of the JFMCs were assessed, including awareness regarding the funds sanctioned to the JFMC and the actual expenditure incurred.
- Well-maintained and easily accessible *records* support transparency in the functioning and progress of the JFMC.
- JFMCs were assessed on the activities they carried out to *protect* the natural mangrove forests and resources.
- Strong *leadership* makes for a successful JFMC; the involvement of the head of JFMCs and the relationship between members and leaders were assessed.

Primary data were collected through interviews conducted in the selected 17 JFMCs. Focus group discussions were conducted with the members of JFMCs and officials from the West Bengal Forest Department, who shared their perception of the JFMCs and their functioning, which helped in collecting comprehensive data on the JFMCs. Secondary data was collected from project reports, annual reports, micro-plans of the JFMCs, and relevant government resolutions. The 17 JFMCs were scored out of 80 points (10 points for each of the abovementioned factors).

30.2.3 Results

A performance matrix was developed based on the results, and in general, it was found that:

- General awareness of the composition and rules of JFMCs was found to be low in all the selected JFMCs. Only 12% of the JFMCs members were aware of the existence of micro-plans for their JFMCs.
- The level of participation from the local communities was found to be low in all the surveyed JFMCs. Incentives need to be provided to encourage participation of all members, and member secretaries should ensure that all members participate in a satisfactory manner. For instance, it was observed that communities

located around the fringe areas of the STR were largely more proactive about registering under JFMCs, compared to those at the 24 Parganas South Division. This can be attributed to the benefits JFMCs, and in particular EDCs, bring to the community; 25% of the government profits generated through ecotourism-related activities and transport entry are given to EDC members within the STR for various activities. However, there are very limited ecotourism initiatives being implemented in the 24 Parganas South Division, with no incentive mechanism in place.

- The participation of the member secretary varied through the JFMCs. Samsernagar FPC (score: 10/10) had good participation by the member secretary, while Nagenabad FPC, Ambikanagar FPC, and Deulbari FPC (score: 4/10) scored very low in this factor.
- Most of the JFMCs studied scored very high when it came to addressing the needs to the local community. However, financial transparency is an area that needs attention; the majority of JFMCs scored very poor in this area. Members were largely unaware of the availability of funds and how much was being spent on implemented activities. Capacity building of JFMCs in financial accountability is required.
- While many JFMCs were managing their records well, some JFMCs like Baghnapara FPC, Nagenabad FPC, Ambikanagar FPC, and Deulbari FPC (score: 0/10) scored zero in this. Capacity building of JFMC members is much needed to improve their performance under this factor.
- The level of protection offered to the forest and its resources varied widely among the JFMCs – while eight JFMCs scored a 10/10, Nagenabad FPC, Ambikanagar FPC, and Deulbari FPC scored a 0/10. Given the high level of natural resource dependability in the Sundarbans, effective conservation cannot be maintained without community participation, for which JFMCs were originally designed. Forest officials need to understand why some JFMCs are more motivated and inclined toward natural resource protection and others are not. For instance, in some villages, it was observed that the community clearly identify themselves as the primary stakeholders and beneficiaries of joint management efforts. As a result of this, the sense of ownership of the resource was visible, which was reflected in the level of protection they afforded the forest and its resources.
- Overall, most JFMCs scored well on leadership-related aspects. It is important that the JFMCs have an influential and proactive leader. Such leaders should be identified within the community and encouraged to participate in JFMC activities.

30.2.4 Recommendations for Strengthening the JFMC Model

30.2.4.1 Improving Accountability and Transparency

The roles and responsibilities of every member of the JFMC should be defined and well explained in local language during the general meetings. Members should be capacity built to carry forth their responsibilities, and refresher trainings should be conducted periodically. There should be a clear understanding among the members on forest management and protection and access and benefit sharing. The executive body members should address associated issues in the executive body meetings and in general body meetings and report to the Forest Department with respect to capacity building and training needs. The minutes of JFMC meetings should be publicly displayed and disseminated so that each community member is made privy to this information.

Records of the following must be maintained by the JFMC without fail:

- Micro-plans
- Forest management plans – section-wise village perspective development
- Records of all activities undertaken
- Membership registers
- Asset registers
- Meeting and resolution registers
- Receipt and payment registers
- Asset provided by Forest Department register
- Benefit to individual families
- Cash/bankbook
- Journal book/general ledger
- Register of drafts/checks – outgoing and received
- A letter from the department regarding the registration/recognition of JFMC

30.2.4.2 Promoting Transparency

The account rules, disbursement of wages, and distribution of forest produce (NWFP) should be clearly explained and discussed with the members of the JFMC to the mutual agreement of both parties.

30.2.4.3 Training and Capacity Building

All the executive body members should be trained and educated concerning community mobilization and leadership skills and communications, in implementing the rules of the JFMC, and in provisions provided by various government departments for financial and administrative support to JFMC activities. It is equally important that participatory planning and management courses be provided for Forest Officials on the ground, in order that they too are able to contribute effectively by adding value to and strengthening JFMC efforts.

30.2.4.4 Encouraging Experience Sharing

Meetings should be organized frequently (at least once every 3 months), and each member is given the opportunity to voice their opinions. Experience sharing visits should be encouraged. This will further help JFMCs align their activities toward greater conservation impacts.

30.2.4.5 Extending Tenure of Executive Committee to Improve Long-Term Performance

It was recommended that the tenure of the executive committee be extended from 1 to 3 years, to ensure continuity and consistency in decision-making and implementation of interventions for village-level development activities. This recommendation has been acted upon by the Forest Department and it has issued an order for tenure extension.

30.3 Conclusion

As the Anthropocene progresses, humans stand at a critical juncture in history, where biodiversity and habitat losses are accelerating due to exploitation, climate change, population growth, and unrestrained development. The resilience of wetland ecosystems needs to be increased to ensure that the services they provide continue to be available to all stakeholders. Identifying vulnerable human and ecological communities, and increasing their resilience, is an immediate priority of most state governments in India. However, limited human power and infrastructure, development pressures, extreme poverty of the surrounding communities, various inhibiting ecological factors (including lack of accessibility to some regions), and the disproportionately heavy impact that climate change is expected to have on wetlands challenge their effective management. The need to improve adaptive management and develop appropriate conservation approaches for wetland systems has gained momentum. As such, a participatory approach is necessary so that the responsibility of wetland management is shared among stakeholders, for their benefit.

Throughout the study, it was realized that there are several benefits to the JFMC initiatives that often remain unnoticed. For instance, as an offshoot of the awareness-building interventions by JFMCs on mangrove conservation and wildlife-human conflicts in villages on the fringes of the STR, local NGOs have been able to identify several families who have lost members to wildlife conflicts. Some of the families have lost their sole breadwinners and are struggling to make ends meet. For a variety of reasons, they have not received financial compensation from the Forest Department, the policy in such cases. The lists provided by the local NGOs of these affected families have been shared with the Forest Department who is taking the necessary steps to provide appropriate compensation. The work of the local NGOs through the JFMCs will continue to monitor human-wildlife conflicts and periodically report to the Forest Department. The active efforts of the Forest Department and JFMCs to look after the families who have suffered due to human-wildlife conflicts have served to build trust with the communities. This in turn has made local communities more responsive to the conservation interventions being piloted and implemented by the Forest Department.

The effectiveness of participatory management efforts in the case of wetlands across India remains inconsistent, as evident from the above case study. However, it is clear that where they are operationally strong, participatory management interventions are having visible positive impacts on wetland biodiversity and wise use of resources. Though not limited to, an integrated and holistic participatory wetland management approach includes:

- Capacity building and awareness generation of stakeholders in the concepts of participatory management.
- Autonomy of the local communities in decision-making and monitoring and enforcement of locally made rules. If this is challenging, responsibility could be transferred to an appropriate agency, which recognizes that wetlands are common property resources, and manages them as such (in a decentralized manner). It is essential, however, that there is trust among all stakeholders.
- Carefully planned and executed entry-point activities (including short- and long-term incentives), to meet the immediate needs of the people and to assist in building trust between communities, the State Forest Departments, NGOs, and private sector partners.
- Meeting the interests of equity and gender considerations so that all wetland stakeholders benefit equally from the conservation efforts.
- Systems for knowledge exchange and capacity building must be established. Understanding of the wetland ecosystem biodiversity and the services it provides among all stakeholders and adopt systems to measure ecosystem health must be developed. Stakeholders in restoration and rehabilitation of wetland habitats should be developed.
- Continuation of investment and resources for management of wetlands.

There is extensive literature on the challenges and success of participatory approaches to management of wetlands. Approaches need to be contextualized in order to yield maximum benefit; there is no ready-made blueprint for successful wetland management.

Acknowledgments This study comprises a component of the alternative livelihood opportunities for vulnerable mangrove resource users in the SBR project, jointly implemented by MFF initiative, IUCN, and SBR, Government of West Bengal. The authors are grateful to Mr. Anurag Danda and the WWF India Sundarbans program team for implementing project activities.

References

Addun RP, Muzones DM (1997) Community-based coastal resource management (CBCRM): Tambuyog's experience in the Philippines. In: Community involvement in wetland management: lessons from the field. Wetlands International, Kuala Lumpur, pp 219–230

Chaudhuri AB, Choudhury A (1994) Mangroves of the Sundarban, vol 1: India. IUCN, Bangkok, p 247

Debnath HS, Naskar KR (1999) A comparative study on the mangroves and associated flora in the Ganga delta (Sundarban) and Bay Islands (Andaman and Nicobar). In: Sundarban Mangal. Naya Prokash, Calcutta, pp 277–292

Forest Survey of India (2013) India State of Forest Report, Ministry of Environment and Forest, Government of India, Dehradun

MoEF & CC (2015) Wetland Inventory, Ministry of Environment, Forest and Climate Change (MoEF & CC), New Delhi. http://www.moef.nic.in/sites/default/files/Wetland%20Inventory.pdf. Accessed in Sep 2015

Selvam V, Ramasubramaniam R, Ravichandran KK (2012) Genesis and present status of restoration practices in saline banks in India. In: Sharing lessons on mangrove restoration, mangroves for the future, IUCN, New Delhi

Shunmugaraj T, Tune Usha, Sanjeevan VN, Subramanian BR (2011) The ecosystem, biodiversity and resource information system in Sundarban. In: Towards conservation and management of mangrove ecosystems in India. IUCN, New Delhi

Singh VS, Pandey DN (2010) What makes joint forest management successful? Science-Based Policy Lessons on Sustainable Governance of Forests in India, RSPCB, Occasional Paper No. 3

WWF (2010) Temporal change detection study of Sundarban: 2002–2008. World Wide Fund for Nature (WWF) India, Kolkata