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H. S. Sen *Editor*

The Sundarbans: A Disaster-Prone Eco-Region

Increasing Livelihood Security

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I dedicate the book in memory of my ***Mother, Arati Sen****, a teacher in mathematics, a great knowledge-seeker and human, infusing through her silent acts, forthrightness and motivation for higher studies not only in me but also the greater family members and beyond, particularly the women, that went a long way*

Foreword

Sundarbans is the largest delta in the world and shared between Bangladesh and India on the coast of the Bay of Bengal. It is adjacent to the border of India's Sundarbans World Heritage site inscribed by UNESCO in 1987. It contains the world's largest mangrove forest and is possibly one of the most biologically productive of all-natural ecoregion. It is located at the confluence between Ganges and Brahmaputra and supports a wide range of flora and fauna including several species threatened with extinction. The mangrove forest is divided as 66% under Bangladesh and 34% under India. The delta has 0.1% of the global population with high population density. It covers 133,010 ha area including 55% forest land and 45% wetlands in the form of tidal rivers, creeks, canals and estuaries.

Being highly populous, the contiguous area, spread over the two countries, with large number of soil- and water-related constraints, suffers seriously from the productivity in agriculture and aquaculture being the two major professions threatening the livelihood security of the inhabitants. The problems limiting the productivity and its sustainability, as well as damage to wealth and properties, tend to become even more perilous because of climate change and frequent occurrence of storms and cyclones, which appear to become still more acute in time to come. The ecological balance of the area being essentially coastal is highly dynamic, sensitive and fragile in nature. The problems being transboundary in nature with several deteriorating factors, which are not only complementary in nature but also mutually dependent between the countries, affect the ecological balance and livelihood security of the populace. Although commendable progress in research has been made in individual countries, the validity of most may not be tenable spatio-temporally for the lack of a unified approach with both countries taken as a single unit. No attempt has been made so far in this direction with full regards to ecology and geopolitical sovereignty of both.

The book bearing the title *The Sundarbans: A Disaster-Prone Eco-Region – Increasing Livelihood Security* with Dr. H.S. Sen, having 26 years of experience of research and extension in Sundarbans, as the Editor, makes an attempt in the direction through threadbare discussion based on significant inputs on diversified areas received from experts in Bangladesh and India. I endorse such a publication and wish him every success in his endeavour for better planning by scientists and policy-makers of both countries.

Founder Chairman, Ex-Member of Parliament (Rajya Sabha), M. S. Swaminathan Research Foundation, Chidambaram, Tamil Nadu, India

M. S. Swaminathan

Preface

The Ganges delta, popularly known as Sundarbans, is one of the largest river deltas in the world. The rivers Ganges and Brahmaputra flow into the delta from the northwest and the north. The delta is distributed over major parts of Bangladesh and the southern part of West Bengal (India). At the extreme south, along the Bay of Bengal, the delta is roughly 360 km wide. Its total area is ca. one million hectares, roughly 55% of which is covered by forest, and it is distributed over both countries, with 60% in Bangladesh and 40% in India. With increasing population pressures, deteriorating hydrological conditions in the rivers and other anthropological factors, along with the trend of seawater rise vis-à-vis global warming, the majority of the area remains highly fragile and ecologically unsustainable. The productivity of agriculture and aquaculture, the principal sources of income for the majority of the population, is generally poor because of various constraints, which, along with ecological vulnerability, are responsible for the abject poverty and uncertain livelihood of the local inhabitants.

There is an urgent need to holistically assess the entire problem, which is essentially of a transboundary nature, so much so that the problems and solutions of the two countries are not only mutually dependent but also complementary; accordingly, this book attempts to devise a future roadmap for higher and sustainable productivity and improved livelihood status in this area. Obviously, any future steps for improvement should be of mutual benefit to both countries, more specifically the tide-dominated ecoregion. The latter acts as a sink for the entire river system, which originates thousands of miles upstream in India. Unfortunately, to date, no such attempt has been made in earnest, to the detriment of both countries. This being the crux of the issue, the present book addresses it by means of a multipronged approach.

The book encompasses analyses of various risk factors related to geohydrological, climatic, natural, biodiversity, socioeconomic and anthropological aspects of the Sundarbans ecoregion; further, it discusses strategies for disaster risk management and sustainability in natural resource management including agriculture, aquaculture and forestry for ecological sustenance, along with their impacts on livelihood security, and, lastly, suggests future pathways for improved socioeconomy using interventions in both farm and non-farm sectors and in a transboundary mode cutting across political borders. The book includes several chapters authored by eminent scientists and practitioners specializing in the respective areas in both countries. A chronological review of societal transformation and related approaches to various livelihood patterns followed over the ages, with subsequent chapters on modern-age professional practices in agriculture, land and water management, sweet and brackish water aquaculture and mangrove ecosystem management, is presented – and all of these aspects, along with non-farm activities like transboundary ecotourism, together with their respective impacts on the economic growth of the inhabitants and the improvement of their livelihood, are discussed. The book places considerable emphasis on characterizing Sundarbans in terms of its dynamic behaviour, on the one hand, including the continual changes in several islands due to erosion and accretion in the riverbanks under changing surface-water hydrology in rivers and tide-fed estuaries, and on suggesting estuary management interventions in order to augment the freshwater supply, improve drainage and reduce bank erosion. On the other hand, the book highlights the challenges involved in combating future adversities in the ecoregion. Recent climate change-induced disasters, along with the relief measures undertaken and their impacts on biodiversity and livelihood, are discussed. In a departure from the common trend, the book includes an inventory of algal dynamics and examines their role as climate change proxies in a separate chapter. Further, it addresses the use of remote sensing satellites as a state-of-the-art technology for disaster management and monitoring ecological disturbances and landmass changes.

On the whole, I am forced to agree with what Dr. Uttam Kumar Mandal and his associates determine in their chapter in this book, namely, that conditions in Sundarbans are gradually becoming untenable due to climate change, the deteriorating hydrological balance of its rivers and streams, unscientific anthropological interventions, etc. Climate change appears to be irreversible, making the whole situation highly complex and adding to a host of previous constraints on the ecoregion's soils and waters, thereby further limiting the productivity of agriculture and aquaculture. Nevertheless, the question before us remains, whether it is technically possible to achieve 'improvements in farm productivity' by addressing these challenges. Alternatively, we may choose to content ourselves with 'subsistence farming' and nonetheless ensure the local inhabitants' livelihood security. The solution in this direction, though difficult, is not impossible if a holistic approach is pursued. In this regard, it is of utmost importance, as Prof. M.M.Q. Mirza and associates urge, to integrate the climate change policies of the two countries, and possibly Nepal also, all of which share the Ganges-Brahmaputra-Meghna (GBM) basin, under the aegis of the South Asian Association for Regional Cooperation (SAARC), in order to address key concerns and vulnerabilities and discuss all related issues jointly. I strongly endorse the view that Bangladesh and India should work hand in hand to mitigate these miseries and find tangible solutions for improved and sustainable livelihood. The book seeks an answer in this direction.

West Bengal, India H. S. Sen

Acknowledgements

I began my engagement with Sundarbans in West Bengal, India, as a junior research worker at the Central Soil Salinity Research Institute (under the Indian Council of Agricultural Research, DARE, Government of India), Regional Research Station, Canning Town, West Bengal, India, in late 1971. The Research Station was regarded as the main centre for addressing the problem of coastal saline soils, which was affecting a number of Indian states, although our main focus remained with Sundarbans in order to characterize and suggest pathways to solve its (both then and now) massive and complex problems. In the absence of any scientific information, we started from scratch and, in the process, found ourselves working with various researchers and local inhabitants, including many working in agriculture and allied sectors in Sundarbans.

Amongst my colleagues in the academic world, I am deeply grateful to many, but will not venture to name them all, lest I leave out many important ones. Yet, I would be remiss in my duties if I did not pay my deepest respects to the late Dr. J.S.P. Yadav, a former director of the institute. Dr. Yadav was a true *doyen* in the field of agricultural science, and I drew my inspiration from him to always look ahead with a positive mindset. He was my mentor in every sphere of my academic activities. I am honoured to pay my heartfelt respects to him through this book. There were many amongst my contemporaries whose love and affection, and often criticism, constantly helped me to forge ahead. In this regard, I would like to above all recognize the silent yet subtle presence of my tried-and-true friend Dr. A.R. Bal, a plant physiologist who is now battling against a dreaded disease, and to express my heartfelt thanks for his constant and affectionate support.

During my long involvement with Sundarbans, spanning from 1971 to 2002, I encountered scores of people in the region's farming and non-farming sectors and was taken aback time and again by their at-times catastrophic economic and social conditions, living so close and yet so far from Kolkata, one of India's metropolises. During my initial stay, there were waterways, though primitive, connecting the major islands. During my first 15 years working in the region, these waterways disappeared, first slowly and then completely, due to a lack of management and complete disregard for the local ecology, resulting in the unabated sedimentation of the rivers.

The inhabitants of Sundarbans have observed this and other developments and have often swallowed the bitter pill with little protest, leaving their fate to destiny and perhaps assuming that these changes were inevitable. Through this book, I wish to pay homage to the inhabitants of both countries in the farming and non-farming sectors in Sundarbans, who have been battling against all odds, silently but undaunted, for hundreds of years; their fighting spirit is a source of inspiration that moved me to serve them to the best of my abilities, in the hope that good sense will someday prevail with the authorities concerned, helping them find a lasting solution for livelihood security based on ecological approaches.

I am also deeply indebted to the contributing authors, one and all, for their untiring efforts to prepare the chapters despite their busy schedules. This would never have been possible without their belief in the purpose for which this joint venture, bringing together authors from Bangladesh and India, was conceived and put into practice. In the same breath, I greatly appreciate and wish to acknowledge the valued support I received from Dr. Dipankar Ghorai, SMS and Programme Coordinator (Acting), Krishi Vigyan Kendra, ICAR-CRIJAF, Budbud, Bardhaman, West Bengal, throughout the compilation and editing processes. I also wish to thank my late mother, a mathematics teacher, who was my spiritual guide. She constantly inspired me through her silent acts of morality and integrity and encouraged me to take up higher studies. In turn, the other woman who I have to thank for the accomplishments in my research career is my wife, Dr. Paramita Sen, a researcher turned physics teacher, who always gave me her candid support and encouragement, often sacrificing her own personal and academic interests in the process. Her unflagging reassurance has been, and continues to be, an invaluable source of support.

Similarly, I have enjoyed the support and patience of my son, a medical practitioner, and my daughter-in-law, another mathematics teacher, without which this endeavour would never have been a success. Not to mention my 2-year-old granddaughter, Arshi, who, buzzing around all the time, often had to do without a hug from, and some quality time with, her grandpa (who she calls dada). I am thankful to them all for bearing with me throughout the last 18 months and for exempting me from the major domestic chores during the preparation of this book.

H. S. Sen

Contents

About the Editor

H. S. Sen is the former Director of the Central Research Institute for Jute & Allied Fibers (CRIJAF – a unit under the Indian Council of Agricultural Research under the Ministry of Agriculture, GoI), located at Barrackpore, West Bengal. He joined the research service after completing his MSc and PhD at the Indian Agricultural Research Institute, New Delhi, in 1971 and retired from regular service on superannuation on 31 January 2008.

During his career Dr. Sen was exclusively devoted to research, especially in the fields of water management and soil salinity related to coastal ecosystems during 1971–1976 and 1982–2002 at the Central Soil Salinity Research Institute, Regional Station Canning Town, which is located in the heart of the Sundarbans. His research on water management and soil salinity aspects on coastal Sundarbans covered a large number of areas on salt and water dynamics in soils, irrigation and drainage methods and applications, nutrient use efficiency under nitrogenous fertilizer use, and crop management under stressed environment. Between 1976 and 1982, he was involved in research in the field of water management under rice-oriented cropping systems at Central Rice Research Institute, Cuttack, Orissa. At CRIJAF, he was exclusively devoted to Research Management and Administration under the mandate "Productivity and Quality Improvement of Jute & Allied Fibers" with emphasis on Ecology and the Environment.

Lately, Dr. Sen has devoted his postretirement period to planning for future research strategies and livelihood securities in the tidal-dominated lower Ganges Delta covering India and Bangladesh. He has also authored a book on this topic and a chapter in a book on a similar topic. Recently, he has also authored several papers on the drying up of the Ganges and its consequences on the deteriorating ecology in the lower delta in India and Bangladesh. In addition, he gives attention to climate change and its impact on water management, along with suggestions for possible remedies thereof for sustained productivity, as well as the role of climate change on oceanic hazards damaging coastal ecosystems at a global scale. He has published over 165 research papers, has guided 5 students for the PhD, and has been a post-graduate teacher at the University of Calcutta for 26 years. He also serves as a regular reviewer of leading journals. In 1999, Dr. Sen received a National Award on rainfed management in the Sundarbans.

Part I
Sundarbans – A Dynamic Ecosystem Meddling with Environment

Sundarbans in wilderness (Courtesy R. N. Mandal)

Chapter 1
The Sundarbans: A Flight into the Wilderness

H. S. Sen and Dipankar Ghorai

Abstract The Sundarbans is an agglomeration of about 200 islands, separated by some 400 interconnected tidal rivers, creeks and canals spanning across two neighbouring countries of India and Bangladesh. It is the habitat of world's largest contiguous mangrove forest and abode for the enigmatic Royal Bengal Tiger. The area, over time, has been continuously truncated in size and at present it is approximately three-fifths the size of what existed 200 years ago (about 16,700 km^2), the rest having been cleared and converted for agriculture and allied activities. Of the present expanse of 10,217 km^2, 4262 km^2 (41.7%) is in India. About half of the area in India (2320 km^2) is land mass. The rest 5955 km^2 (58.3%) is in Bangladesh. The eco-region has huge ecological significance in terms of the deluge of ecological services and functions for human welfare. But unbridled and naive anthropogenic avarice is taking a heavy toll of Sundarbans' resources in both the countries ripping people of the region off their precious livelihoods. There is a need for concerted efforts by all players transcending the international border for its ecological sustenance. A succinct overview of Sundarbans comprising of its structure, its historical progression, its ecological and economic value, its challenges and livelihood of people in it is chronicled in this introductory piece for the book.

Keywords Sundarbans · Livelihood · Community based tourism · Challenges · Recurvature of storm · Ecological value

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1.1 Introduction

To subdue Nature, to bend its forces to our will, has been the acknowledged purpose of Mankind since human life began, but the time has come for a revision of our conception of the benefits and responsibilities of holding dominion over all other created things. (The Royal Bank of Canada Monthly Letter, Vol 41, No. 4 (May 1960))

History asseverates that evolution of *Homo habilis* to *Homo sapiens* has been a perpetual struggle of taming the untamed. First, it was struggle for existence, then it became necessity in order to colonize, and finally, to this present day, to an astounding avarice for exploitation – a tale of Nature accommodating Man changing to Man exterminating Nature. The consequences may be gravely disconcerting, at least the indications are so. All of World's pristine, and thus far virgin, ecosystems, or eco-regions, have been invaded to gain social and economic mileage mindlessly, altogether ignoring their enormous ecological values – as a result of which many of those are on the verge of extinction or endangered, to put mildly. It is time for Man to reinstate the wilderness of the wild, lest they may go into oblivion.

THE SUNDARBANS, spanning over two neighbouring countries of India and Bangladesh is one such example of endangered eco-region. Etymologically, Sundarbans means "Beautiful Forest". The name, SUNDARBANS, itself, conjures images of a mystic forest, predators and hostile environments. Populated by both animals and half-starved humans, Sundarbans is a place that has continued to be a perpetual battle ground of nature and man. Danda (2007) portrays Sundarbans as a microcosm for examining global dilemma for development, ecology, and competing values. The dilemma arises out of constructing built capital for welfare for the 4.5 million people living in the region thereby compromising ecology.

The Sundarbans eco-region is part of the world's largest delta, formed from the sediments brought down by three great rivers, the Ganges, Brahmaputra and Meghna. The eco-region is unique in the world and is *uniquely fragile, too*! The eco-region is unique by virtue of its most extensive mangrove forest in the world exposed to freshwater and seawater mix. Its uniqueness also pertains to being shelter to one of the most enthralling and endangered creatures in the world – the Royal Bengal Tiger and that the mangroves of Sundarbans acting as a natural buffer against the coastal erosion and seawater ingress into one of the most densely populated regions of the world. But the paragon of its uniqueness is, arguably, ascribed to the incalculable loss of human and built capital which would have otherwise happened had the Sundarbans mangrove not acted as a natural shield against the ever-increasing tropical cyclones and storms in the Bay of Bengal and Indian Ocean and arresting it from entering the mainland with their full throttle.

The Sundarbans is a conglomeration of about 200 islands, separated by some 400 interconnected tidal rivers, creeks and canals. The area, over time, has been continuously reduced and at present it is approximately three-fifths the size of what existed 200 years ago (about 16,700 km^2), the rest having been cleared and converted to agriculture (Hussain and Acharya 1994). Of the present expanse of 10,217 km^2, 4262 km^2 (41.7%) is in India. About half of the area in India (2320 km^2)

is land mass. The rest 5955 ha (58.3%) is in Bangladesh. The landscape is one of low-lying forested alluvial islands (56 in the Indian sector), mudbanks with sandy beaches, and dunes along the coast (Hussain and Acharya 1994). The forest swamp is extensively embanked and empoldered and is an essential buffer for inland areas against the ravages of frequent cyclones from the Bay of Bengal. The nutrient-rich waters also provide the most important nursery for shrimps and spawning grounds for crustaceans and fish along the whole coast of eastern India.

Sundarbans features, as per classification of WWF, two distinct eco-regions – '*Sundarbans freshwater swamp forest (IM 0162)*' and *'Sundarbans mangroves (IM 1406)'*. The Sundarbans Freshwater Swamp Forests eco-region is nearly extinct. Hundreds of years of habitation and exploitation by one of the world's densest human populations have exacted a heavy toll of this eco-region's habitat and biodiversity. Because, it sits in the vast, productive delta of the Ganges and Brahmaputra rivers and their annual alluvial deposits make the eco-region exceptionally productive. Therefore, most of the natural habitat has long been converted to agriculture, making it almost impossible to even surmise the original composition of the eco-region's biodiversity (https://www.worldwildlife.org/eco-regions/im0162). The Sundarbans Mangroves eco-region is the world's largest mangrove ecosystem. Named after the dominant mangrove species *Heritiera fomes*, locally known as Sundari, this is the only mangrove eco-region that harbors the Indo-Pacific region's largest predator, the Royal Bengal Tiger. Unlike in other habitats, here tigers live and swim among the mangrove islands, where they hunt scarce prey such as chital deer (*Cervus axis*), barking deer (*Muntiacus muntjak*), wild pig (*Sus scrofa*), and even macaques (*Macaca mulatta*). Quite frequently, the people who venture into these impregnable forests to gather honey, to fish, and to cut mangrove trees to make charcoal also fall victim to the tigers (https://www.worldwildlife.org/eco-regions/im1406).

The Bangladeshi and Indian parts of the Sundarbans, while in fact adjacent parts of the uninterrupted landscape, have been listed separately in the UNESCO World Heritage List as Sundarbans and Sundarbans National Park, respectively.

Over the centuries, Sundarbans had been, and is being, continually morphed to come to its present make up – physically as well as demographically. Physically through the unceasing accretion – erosion process of its river system and demographically through incessant in- and out-migration of people of diverse ethnicity, invasion of foreigners and colonial condign. Let us contemplate upon its history, briefly.

1.2 Sundarbans: A Brief History over Time

The history of Sundarbans can be traced back to the ages of Puranas. Mythologically, the Sagar island of Sundarbans was said to be the abode of Sage Kapila who incinerated 60,000 sons of King Sagar for some misdeed of theirs and it was Sagar's grandson, Bhagiratha, who placated Sage Kapila and brought the Ganges to earth to revive his ancestors. Historically, several travellers as well as historians like, Satish Chandra Mitra, Kalidas Dutta have eloquently described Sundarbans in their accounts of Bengal Allusion to the famous coastal trading town of 'Chandraketugarh' can be found in the accounts of ancient Greek and Roman writers – dating back to the post-Gupta period, between fourth century BCE and sixth century AD (Mandal 2016).

1.2.1 The Muslim Time

The Muslim period (1204–1574) saw the rise of Sundarbans as a humanized colony. Following the Muslim invasion of Bengal in the twelfth century, from the early part of thirteenth century, Sundarbans witnessed infiltration of large number of Muslims rendering the area a Muslim dominated one. Unlike the native Hindus, whose primary occupation was fishery, the Muslims were agriculturists and following their suit the Hindus also took to agriculture as their primary livelihood with forest making way for agricultural land. Agriculture flourished also due to the fact that, unlike fishery produce, agricultural produce can be processed and stored for future use.

Joao de Barros, the acclaimed Portuguese historian, was the first to map the Sundarbans. Among the Muslim settlers, Khanja Ali was the most prominent, who along with his followers reclaimed large part of mangrove forest to build a sizable Muslim agricultural colony, although after his death the area relapsed into forests (Mandal 2016).

1.2.2 The Time of Baro-Bhuyans (The Twelve Zamindars)

Afterwards, Maharaja Pratapaditya, the most prominent among the Baro Bhuyans of Bengal, ruled the area from 1560 to 1611. He hired various tribal creeds to clear the forests for agricultural purposes. Maharaja Pratapaditya restored to various developmental activities like building of roads, forts, township and temples with an eye for holistic development of the area. Sadly, after his demise the forest crept back into place giving shelter to various miscreants and local dacoits.

With passage of time, the region saw mass scale plundering by the Arakan invaders along with Dutch and Portuguese traders. They continuously engaged themselves in human trafficking to far off places like Goa, Cochin, Ceylon and Batavia (now Jakarta in Indonesia) where they had established their colonies. This ensued rapid decline in population of the Sundarbans. Francois Bernier, the famous French traveller, has referred to these horrendous episodes of pillage and human trafficking in his book – "*Travel in the Mogul Empire*" (Bernier 1914).

1.2.3 The Colonial Times

Time went on. It was the colonial periods when Sundarbans started to revert back to its past glorified self. Britishers acquired the proprietary rights over the area from the Mougal Emperor during the later half of eighteenth century. Claude Russel, the then Collector-General of 24 Parganas started to make way for agriculture, again, by clearing the forests in 1770s. This was preceded by mapping of the area by the Surveyor-General in 1764.

During 1780s, Tillman Henckell, the then Magistrate of Jessore, established several government outposts in Sundarbans and set up number of salt manufacturing units along the coasts. Then began the land distribution among the *Talukdars* which was speeded up with the introduction of Permanent Settlement System in 1793. Rapidly lush mangrove made room for agricultural land and that was when anthropogenic doings, *or rather 'undoings'*, started to take toll on natural balance of the eco-region that continued several years afterwards and, with more apposite means of livelihood being available, people began to pour in, thereby shifting the natural equilibrium to irreversibility.

But, Nature retaliates – the fact was soon learnt by Viceroy Lord Canning in hard way. Viewing the multitude of promise for colonization in the Sundarbans, Canning started to build infrastructures, like roads, railway tracks; and even a port to support Calcutta port by the river Matla in the 1860s. But within 5 years of its completion, the entire port was annihilated in a super-cyclone and concomitant surge in Matla in 1867 (Mandal 2016).

Yet, the bigger damage was done. Sundarbans, by then, with its bountiful of resources and plethora of opportunities, caught the eye of many and with passage of time, during the late nineteenth century and early twentieth century, more influx of people of all creed and cast took place and more forest solemnly made way for their settlement.

1.2.4 The Time After Independence

The post-independence period encountered even greater in-migration into Sundarbans, especially in the aftermath of 1952 famine and subsequent liberation of Bangladesh in 1971. During this time the region also witnessed one of the most horrific political oppressions in human history, known as the Marichjhanpi massacre. Thousands of poor Bengali refugees, who came to India after Bangladesh Liberation War in 1971 and were relocated in prison like camps of Orissa and Madhya Pradesh, supported the Left Front in the state election as they promised to give them land in West Bengal if they won.

So, after the Left Front came to power in 1977, they came to West Bengal. A large portion among them settled in Marichjhanpi island of Sundarbans which was a deforested, but unpopulated island at that time. However, the left front was not happy with the influx of refugees in Bengal anymore. In Marichjhanpi, after giving several warnings to the new settlers to leave, the police surrounded the island, cut its communication with outside world and destroyed the food stock, thus leaving people to die of starvation and diseases. On 31st of January, 1979, police opened fire on the settlers. Thousands were gunned down, forced to drown or beaten to death, women and children were assaulted and killed. The few, who were still alive, were driven out of the island and sent back to their old camps (Mandal 2016).

Thus, Sundarbans, although much impoverished, withstood the wrath of time and, finally better sense prevailing, it was recognized as a Ramsar site of ecological importance in May 21, 1992 seeing its huge ecological and positional importance.

Although much impoverished, the Sundarbans, in its rich ethnological backdrop, still envisages gargantuan value – ecological, economic, human and socio-cultural like all other coastal wetland and forests all over the world. Below is an annotation that delves into pricing this most exquisite biome.

1.3 Sundarbans: Valuing the Invaluable

Ever since the field of *'Ecological Economics'* took flight in the 1940s, there had been deluge of works in this field to estimate the value of ecosystem services and functions globally. The economic value of natural capital and ecosystem services is accepted by mainstream environmental economics, but is emphasized as especially important in ecological economics. Ecological economics basically work on following methodologies,

- Allocation of resources
- Weak versus strong sustainability
- Energy accounting and balance
- Ecosystem services
- Cost shifting for externalities
- Ecological-economic modeling

A number of eminent ecological/environmental economists have evaluated various major ecosystems worldwide. Notable among these are Odum (1971), Westman (1977), Ehrlich and Mooney (1983), de Groot (1987), Costanza (1997), and many others. Ecological economists begin by estimating how to maintain a stable environment before assessing the cost in dollar terms (Costanza et al. 1998). Ecological economist Robert Costanza led an attempted valuation of the global ecosystem in 1997. Initially published in Nature, the article surmised the value of global ecosystem services to \$33 trillion with a range from \$16 trillion to \$54 trillion (in 1997, total global GDP was \$27 trillion) (Costanza et al. 1998). Half of the value went to nutrient cycling. The open oceans, continental shelves, and estuaries had the highest total value, and the highest per-hectare values went to estuaries, swamps/floodplains, and seagrass/algae beds. The work was criticized in many corners, but the critics acknowledged the positive potential for economic valuation of the global ecosystem (El Serafy 1998; Opschoor 1998, https://en.wikipedia.org/wiki/Ecological_economics).

BUT!! And Yes, this is a capital 'but'. The question remains – *whether all the 'Externalities' or 'Avoided cost (AC)', as they prefer to call it, which is defined as 'services those allow society to avoid cost that would have been incurred in absence of these services' (de Groot et al. 2002), can be taken into account while valuing ecological services?*

Mangrove ecosystems are recognized as providers of untold ecological services – providing optimal breeding, feeding and nursery habitat for ecologically and economically important fish and shell fishes (Verma et al. 2017), habitats for resident and migratory birds, valuable source of fuel, fodder, timber and other natural products, protect freshwater resources from intrusion of saltwater, protect coastal lands from eroding winds and waves by stabilizing them (Prasetya 2006), etc. All these services have been assessed for their economic benefits by large number of researchers all over the world for different mangrove ecologies – many of them amounting to billions of US$ per year for these intrinsic values (Sathirathai and Barbier 2001; Rog et al. 2016). But, we surmise, the most important function of mangroves is protection of human and built capital, or the 'avoided cost' as defined earlier. For example, the post-independence period, once after 1947 and then after 1971, saw massive in-migration of people into Sundarbans and subsequent large-scale deforestation of mangroves paving way for their habitat. Then came the Great Cyclone Bhola in November 12, 1970 that ripped nearly 0.3 million people of their lives. Again the 1991 tropical cyclone accounted for some 0.14 million human lives. While the loss of built capital and the intrinsic resources were put to well over a billion US$ in 2004–05 prices (Hossain et al. 2008), question remains *can the loss of human capital be estimated*?

What presently is being done by the ecological economists, is to assess the following three chief value parameters while evaluating one ecology,

1. Ecological value
2. Socio-cultural value, and
3. Economic value

Economic value, again, is measured in terms of,

1. Direct market valuation,
2. Indirect market valuation,
3. Contingent valuation, and
4. Group valuation (de Groot et al. 2002)

We maintain that there should be one '*Anthropogenic value*' parameter in addition to the abovementioned. *Exempli gratia,* in Indian context, if somebody tries to assess the economic value of the Himalayan eco-region, it is beyond human acumen to entwine all the 'externalities'. The Himalayas had shaped the past, is shaping the present, and will shape the livelihood of millions of Northern Indian population, its river systems, and its monsoon wind control. Therefore, it entails that for holistic ecological evaluation of the Himalayas, this '*Anthropogenic value*' have to be estimated, which is, unfortunately, beyond capabilities of man *simply because of the social capital of those billions of people, and is outside purview of monetary estimation*! Similarly, it is so in the present case – economic evaluation of Sundarbans. Apart from its huge ecological significance being the world's largest contiguous mangrove and habitat of the endangered Royal Bengal tiger, its positional advantage in unfathomable. The Sundarbans mangrove protects some of the world's most populated cities and towns, namely Kolkata, Dacca and others, from the ever-increasing wrath of tropical cyclones in the Indian ocean and Bay of Bengal by attenuating the storm surges and buffering wind thrust of the cyclones. Had it not been there, colossal loss of human and built capital would have occurred. While the cost of built capital is possible to estimate, the cost of human capital or '*Anthropogenic value*' is one '*externality'* of '*avoided cost*' that is beyond pricing. Therefore, we prefer the Sundarbans ecology be called, *ipso facto,* '*INVALUABLE'*.

Although, there had been few attempts in the past to measure Sundarbans's ecological and economic value, it was essentially '*intrinsic'*, and not '*holistic'*. For academic interest, we prefer to put here few lines regarding the '*intrinsic value'* of this all important eco-region worked out by two workers (Verma et al. 2017; Shams Uddin 2011) to give the reader an idea of the stupendous ecological and economic value it would have gathered had the '*Anthropogenic value*' could have been estimated by some means. Since there is no such literature available about the intrinsic economic evaluation of Sundarbans eco-region as a whole transcending the international boundary, Indian part and Bangladesh part will be dealt separately.

Very recently, one study (Verma et al. 2017) has extensively tried to price the Sundarbans tiger reserve in the Indian part. As has been done in case of other mangrove ecologies (Viswanathan et al. 2011; Rog et al. 2016), Verma et al. (2017) evaluated for Sundarbans total of 25 ecological services and functions, namely, employment generation, agriculture, fishing, fuelwood, fodder/grazing, timber, non-wood forest produce (NWFP), gene-pool protection, carbon storage, carbon sequestration, water provisioning, water purification, soil conservation/sediment regulation, nutrient cycling/retention, biological control, moderation of extreme events, pollination, nursery function, habitat/refugia, cultural heritage, recreation, spiritual tourism, research and education, gas regulation and waste assimilation. As per their estimation he stock benefits accrued to US$ 10,089 million per year.

As for the Bangladesh part, Shams Uddin (2011) has similarly evaluated the same. He categorized the services into three broad categories, namely provisioning services (timber, fish, fuel wood, thatching materials, honey and wax, crab), cultural services, and regulatory services. Total economic benefits for these services, as per his estimates, stands at US$ 43 million per year.

These are the only two available studies that have tried to price the Sundarbans eco-region in the light of its ecological services and functions in the two neighbouring countries. Notable point from these two studies is the large variation in the quantum of economic benefits derived. Although of the 10,000 km^2 area of the Sundarbans eco-region, Bangladesh accounts for some 3/5th, yet economic benefits derived for that part is abysmally low compared to Indian part (Shams Uddin 2011).

Other workers, who tried to value the mangrove ecologies over the world (Santhirathai and Barbier 2001; Hussain and Badola 2010, etc.), have used different metrics and valuing parameters resulting in wide variation in quantum values among their works. Hamel and Bryant (2015) and Boithias et al. (2016) categorized such uncertainties in assessment of ecological services. They maintain that varying number of services under consideration, selection of valuation metrics, stakeholders credibility and response, etc. are the root causes of the uncertainties in such kind of studies. From these, it can be surmised that *no single study should be adequately well-versed in deriving even the 'intrinsic value' of Sundarbans, leaving alone the 'Anthropogenic value'*.

Then, there are stiff challenges, both anthropogenic and climatic, those are gulping in the natural resource base of the ecosystem, thereby decreasing its intrinsic value, slowly yet steadily. Unless stringent measures are adopted to combat the human maleficence and to adapt to the climatic vagaries, the Sundarbans may not live to see another day in 100 years from now. Let's explore the challenges that the ecosystem is facing.

1.4 Challenges Typical of the Ecosystem

Coastal ecosystems are inimitable in view of their frailty as compared to terrestrial ecosystems, and yet in their indispensability in preserving the terrestrial ecosystems being the first line of defence against hazards of oceanic origin. More often than not, these are more precious in terms of their natural, built, human and social capitals over land ecosystems; and yet more often than not these are subjected to ill considerate, unbridled and indefatigable anthropogenic avarice for gaining *entrée* to these capitals. The human malfeasance over and above enhancement in climate change-induced degenerative – and often cataclysmic – marine influences in form of tropical and extratropical cyclones, tsunamis, hurricanes, etc. are only adding to the woes in so far as the stability of the coastal ecosystems – and their very existence as well – is concerned (Ghorai and Sen 2015; Sen and Ghorai 2017).

Global climate change will alter temperature and precipitation regimes, oceanic and atmospheric circulation, rate of rising sea level, and the frequency, intensity, timing and distribution of hurricanes and tropical storms (Ghorai and Sen 2015; Seneviratne et al. 2012), the magnitude of which and their subsequent impacts on coastal wetlands will vary temporally and spatially. The ecological effects of tropical storms and hurricanes indicate that storm frequency, intensity, and their variations can alter coastal wetland hydrology, geomorphology, biotic structure, energetics, and nutrient cycling (Mitchener et al. 1997). The more these storms eat out the coastal wetlands, the more will be the exposure, and hence the vulnerability, to future such occurrences (IPCC 2012). Tropical (occurring in tropical oceans) and extratropical cyclones (occurring near the poles), in particular, pose a significant threat to coastal populations and infrastructure, and marine interests such as shipping and offshore activities. Added to these are tsunamis and earthquakes, besides giving severe blows to particularly coastal wetlands time to time, take heavy toll of human capital as well.

1.4.1 Sundarbans Mangroves and Climate Shift: Weathering the Storms?

The mangrove ecology is extremely important for human and other biotic communities in multifarious ways. These include providing habitat that serves as reservoirs, refuges, feeding grounds, and nursery grounds for many useful and unusual organisms; feedstuff for many aquatic organisms and commercial species of shellfish, shrimps, and fish of lagoons and the near-shore ecosystems such as seagrass beds and coral reefs through partially decomposed leaf detritus (Sukardjo et al. 2013).

In addition to their biotic functions and their role as natural bio shield, mangroves, being endowed with extensive rooting structures that slow water movement to trap sediments, also absorb and dissipate the energy of the waves (Nguyen et al. 2013; Takle et al. 2006), slowing their ingress inland. This is particularly important as high waves or storm tides can take heavy toll of human, natural, and built capital along the coastlines. Mangroves absorb water wave energy as a result of reversing and unsteady flow of water around the vegetation. In other words, mangroves protect the coast from wave erosion by dissipating wave energy through drag and inertial forces (Mazda et al. 1997). Mazda et al. (1997) have experimentally proved this at the muddy coast in Vietnam. The protective role of mangrove was proven by Badola and Hussain (2005) in India's Bhitarkanika mangroves where they found minimal damage (US$33/ha), in the 1991 tropical cyclone, in the village, among the three equidistant villages selected for the study, which has a protection of mangroves. In the other two villages, the respective figures were US$ 44 per ha in the village that did not have any protection and US$ 154 per ha in the village that had a dyke, but failed. The high cost for the village that had a dyke is attributed to the swift currents after the dyke breached. Similar attenuation of wave energy by mangroves in case of tsunamis is also established (Vermaat and Thampanya 2006; Wolanski 2007).

1.4.2 Sundarbans Mangroves and Climate Shift: Withering in?

A general trend of mangrove forests decline is being observed all over the world. About 90% of the global mangroves are growing in developing countries and they are under the condition of critically endangered and nearing extinction in 26 countries (Kathiresan 2008). The world mangrove experts are of the opinion that the long-term survival of mangroves is at great risk due to fragmentation of the habitats and that the services offered by the mangroves may likely be totally lost within 100 years (Valiela et al. 2001; Alongi 2002). In general, the anthropogenic stress on mangrove is predominant, especially in the best developed mangroves that grow along humid sheltered tropical coastlines, such as delta areas of Ganges-Brahmaputra, Irrawaddy and Niger as well in the coastlines of the Malacca Straits, Borneo and Madagascar. Some estimates put global loss rates annually at one million ha, with some regions in dangers of complete collapse (Kathiresan and Bingham 2001). The rate of loss in the recent past has reached alarmingly high rates. To cite two examples, the Philippines lost 3155 km^2 of mangroves from 1968 to 1990 that was 70.4% of the initial stand, at a rate of 143 km^2 per year or 39 ha per day (Kathiresan 2008).

Although climate change augmented relative sea level rise is posing the greatest threat to the mangrove ecology, increased intensity and frequency of storms have the potential to increase damage to mangroves through defoliation and tree mortality. In addition to this, storms can alter mangrove sediment elevation through soil erosion (Baldwin et al. 2001), soil deposition, peat collapse, and soil compression (Cahoon et al. 2006). One study by US Geological survey (Doyle 1997) used hurricane and mangrove simulation models, namely HURASIM and MANGRO, respectively, in forecasting the fate of mangrove forests along the coasts of Florida which revealed that occurrence of major storms every 30 years in twenty-first century may be the most important factor controlling mangrove ecosystem dynamics and in case storms become more intense over the next century, they may further alter the structure and composition of the Florida mangrove landscape. Hurricane Georges passing over Dominican Republic in 1998 afflicted 48% mortality in 4700 ha mangrove area (Sherman and Fahey 2001). Many other have reported flagrant mortality rates of different mangrove species owing to category 3 and 4 cyclones worldwide (Cebrian et al. 2008; Smith et al. 2009; Kauffman and Cole 2010).

Besides man-made pressures, the mangroves are degraded by environmental stress factors (Gilman et al. 2008; Giri et al. 2011). Cyclones, hurricanes and tsunamis are the three major environmental factors that is taking a significant toll on mangrove ecosystem all over the world (Gilman et al. 2008). Wind damage, storm surge and sediment deposition are the tree primary mechanisms through which cyclones and hurricanes impact mangroves (Smith et al. 2009). Very high winds rip off and tumble stems defoliate trees and severely debilitate their delicate root structure (Smith et al. 1994; Doyle et al. 1995). As a storm surge comes ashore taller stems may be uprooted and knocked over, yet when covered by the surge, shorter stems may be protected from the hurricane's winds (Smith et al. 1994). Storm surges carry suspended sediment that is deposited on the forest floor as the surge recedes (Risi et al. 1995). Craighead and Gilbert (1962) and Ellison (1998) reported that very fine sediments deposited from hurricane storm surges resulted in mangrove mortality. The deposited materials interfere with root and soil gas exchange leading to eventual death of the trees. The damage inflicted by each of these mechanisms often varies according to species of mangrove (Woodroffe and Grime 1999).

During the last two-and-a-half centuries, the Sundarbans mangrove ecosystem has been affected by human impact, slow onset of climatic change and extreme weather events (Ghosh et al. 2015). Protection of mangrove forests is extremely complex and multiscalar because of the interaction of climatic threats, path-dependent development regimes and environmental governance (Ghosh et al. 2015).

Over the past five decades, Sundarbans mangroves are frequently hit by cyclone resulting in the complete destruction of mangrove vegetation in some places. Within a very short period of time the Sundarbans mangrove forests have encountered five major unusual cataclysmic events, i.e. cyclone in 1988 and 1991, the Asian tsunami in 2004, cyclone Sidr in 2007, and cyclone Nargis in 2008. Haq (2010) have put the damage due to cyclone Sidr in 2007 to one-third of the mangrove population in the Bangladesh part of Sundarbans. These disturbances have caused massive amount of damage to the standing vegetation of the Sundarbans mangrove forest and plantation in coastal afforestation. The damage, in turn, leads towards uncertainty in typical mangrove vegetation recovery (Azad and Matin 2012).

1.4.3 Challenges for Bangladesh Sundarbans: Recurvature?

The disproportionately high storm surges in Bangladesh coast is a matter of great concern. One study by Murty and El-Sabh (1992) showed that Bangladesh accounts for 40% of worlds total storm surges while rest of the world including Asia and other continents accounts for 60%. Khan (1992) ascribed this to the following causes,

1. The phenomenon of recurvature of tropical cyclones in the Bay of Bengal,
2. Shallow continental shelf, especially in the eastern part of Bangladesh,
3. High tidal range,
4. Triangular shape at the head of the Bay of Bengal,
5. Almost sea-level orography of the Bangladesh coastal land,
6. High density of population and coastal defence system.

Among these, the phenomenon of recurvature of tropical cyclones in the Bay of Bengal is the single most cause of the disproportional large impact of storm surges on the Bangladesh coast. Khan (1992) noted,

> *Extra-tropical cyclones, such as those that occur in Canada and Europe, generally travel from west to east. On the other hand, tropical cyclones such as those that occur in the Bay of Bengal, are expected to travel from east to west, as would be expected from considerations of the general circulation of the atmosphere. However, in the Bay of Bengal, tropical cyclones most often do not travel towards the west or northwest, but they turn towards the north or even Northeast. This turning back, referred to as Recurvature is still not fully understood. If the phenomenon of Recurvature does not happen, then Bangladesh would rarely be affected by tropical cyclones and the storm surges that result from them.*

In the light of the above, there should be increased emphasis on managing mangroves of Bangladesh Sundarbans. Government of Bangladesh should enforce stringent rules so as to protect the mangroves from any kind of anthropogenic malfeasance and, if need be, vast-scale mangrove plantation programme and relocation of human establishment, away from the vulnerable areas like, Chittagong, Cox Bazar etc., to more stable zones, as has been proposed by Sanchez-Triana et al. (2014) for the Indian part, should be taken up in order to preserve these precious ecosystem as well as human capitals.

These above-mentioned challenges are not only challenging the existence of the Sundarbans, but they are challenging the livelihood of 4.5 million people and all other creatures in it - the very right to live in under a wide spectrum of eco-services. Starting, in terms of human, with agriculture to fishing, boatman, forest resource collector, traders, and what not! Let us peek into the livelihood kaleidoscope of Sundarbans people for a while.

1.5 Sundarbans: The Livelihood Kaleidoscope

Nature is the birth-giver to all living beings existing on earth. Though we are living in an age of cyborgs, we cannot detach ourselves from the environment we live in. Livelihood refers to the means and sources of living which we use in our everyday life. There are multiple sources of livelihood in the Sundarbans, predominantly in the agriculture, fishing and aquaculture, forestry, and tourism sectors.

1.5.1 Livelihood in the Indian Sundarbans

1.5.1.1 Agriculture

In Indian Sundarbans, agriculture is chiefly inhibited by excess of water in the monsoon, and then lack of it in the dry periods! (Sen and Oosterbaan 1992). Nearly 60% of the total working population depends on agriculture as a primary occupation, either as cultivators (23.6%) or as agricultural laborers (36.1%) (Sánchez-Triana et al. 2014). More than 80% of total farmers in the region farm in marginal areas. The average landholding among farmers is just 0.36 ha. More than 75% of the inhabited portions of the Sundarbans are used for agriculture. The cropping pattern is largely a single crop of rainfed paddy (*aman*) cultivated during the *kharif* season (rainy season). During the *rabi* season (dry season), cropping is made difficult due to the lack of irrigation facilities in the Sundarbans. Soil salinity limits crop productivity in the region. An analysis of more than 10,000 soil samples taken from eight blocks of the Sundarbans found that 32.4% of the samples had high salinity levels (Sánchez-Triana et al. 2014). Besides, there are problems of drainage congestion particularly during monsoon.

1.5.1.2 Fisheries and Aquaculture

It was found that approximately 11% of households in the Sundarbans listed 'fishing' as one of the family occupations (Sánchez-Triana et al. 2014). This percentage goes up to 60–70% in areas with easy access to rivers. A separate study found that the estimated total number of inland fisher families in South 24 Parganas and North 24 Parganas was 52,917 and 50,897, respectively (GoWB 2005). The main areas of traditional fishing are Sagar, Fraserganj, Bakkhali, and Kalisthan islands. The significant inland fish landing regions in the Sundarbans include Canning, Hariabhanga, and Gosaba (Chatterjee 2011).

1.5.1.3 Forestry

The Sundarbans ecosystem is the basis for many of the livelihood activities that have traditionally formed the backbone of rural living, and a significant number of households depend on the forest for their livelihood and sustenance through activities such as honey collection, fishing, and timber collection. Over 32,000 households in the Sundarbans have at least one member exploiting the forest regularly for various purposes (Sánchez-Triana et al. 2014), such as collecting fuelwood, sustenance, cash income (from the sale of honey), medicinal requirements, and harvesting timber for construction of houses and boats (Roy 2011). Forest dependence is largely a result of low levels of education and skills, which prevents people from accessing better-paying jobs, and the lack of alternative income-generating opportunities in the region. Agriculture has low income-earning potential in the region, and conversion of agricultural land into prawn farms has forced many to turn to the forest for livelihood purposes. One study by Singh et al. (2010) shows that the contribution of Non-Timber Forest Product (NTFPs) is quite high as it contributes almost 79% (Rs. 80,000 per family) on an average to the annual income of the collector's family. Of course, not every family of the village goes for NTFP collection but nonetheless their number is significant. The major NTFP that are being collected includes firewood, prawn, fishes, crab, honey and bee wax.

1.5.1.4 Tourism

Forest-based tourism is regarded as an effective tool for sustainable conservation of forest resources and its biodiversity. It plays both conservation and revenue earning roles. Conservation roles are played in two ways: by keeping intact, and somewhere by improving, the existing forest resources to attract the tourists and secondly by involving the poor forest dwellers, who were removing trees and other non-timber products for their livelihood, in different income generating activities within the ecotourism area (Mazilu and Marinescu 2008).

Although tourism in the Sundarbans has ample opportunities, still it remains an option for very limited number of people in the Sundarbans. Guha and Ghosh (2007) reported that only 8.2% of villagers in Pakhiralaya, a tourism hotspot in Indian Sundarbans, participated in local tourism. Tourism development in the area is rapidly expanding, both as a reaction to the success achieved by pioneer developments such as the Sundarbans Tiger Camp, and as a result of increased demand for visiting the Sundarbans Tiger Reserve and the Sundarbans National Park. From 2003 to 2009, the number of tourists increased by roughly 101%, from 59,681 to 120,495 (Guha and Ghosh 2007). The majority of the visitors to the Tiger Reserve and National Park are domestic, suggesting that the domestic market can provide a solid base for gradual tourism development, allowing for eventual expansion into the international market as the tourism product of the region improves. However, domestic tourists are low-budget travelers and are not always aware of the ecological sensitivity of the area (Guha and Ghosh 2007).

1.5.2 Livelihood in Bangladesh Sundarbans

1.5.2.1 Agriculture

People of Bangladesh Sundarbans thrive on all the above livelihood options, including agriculture, in more or less commensurate with its area as Indian Sundarbans (Mukul et al. 2010). Similar to the Indian part, rice is the principal crop of the region. Agriculture in Bangladesh Sundarbans is also constrained by increased soil and water salinity, chiefly attributable to the diversion of Ganges at Farakka water, especially in the southwestern region (Khan 1993; Mirza 1998). One estimate (Hannan 1980) had put the total loss of agricultural produce to nearly 0.64 million tonnes in 1976 of which salinity alone accounts for some 21%. Anon (1993) reported annual loos of US$ 675 million in agricultural sector as a consequence of Farakka barrage. Apart from salinity; sedimentation, waterlogging, cyclone damage, accumulation of toxic elements from allied agricultural activities and port discharge are also adding to the woes in so far as agriculture is concerned (Mirza 1998).

1.5.2.2 Fisheries and Aquaculture

Apart from agriculture, of course, Bangladesh hugely thrives on mangrove forest aquaculture and fisheries. In recent years, commercial polyculture with fresh, marine and brackish water species is carried out on small scale (Azad et al. 2009). About 260 freshwater and 342 marine water fishes are found in this part of the Sundarbans (Hussain and Acharya 1994). But the resource is declining alarmingly over the last two decades affecting the estimated 3.5 million fishers, most of whom are penurious, directly or indirectly (Hasan and Naser 2016). Hasan and Naser (2016) reported steep decline in number of 79 freshwater and marine fishes in the area. This is endorsed to overfishing and mangrove habitat degradation (Islam and Haque 2004). Also, natural calamities like earth quake, heavy downpour, storm and cyclone also have a sizable impact on the fishery livelihood (Hasan and Naser 2016). Overall, the fact that fishing in the Bangladesh Sundarbans is a subsistence livelihood has been revealed by Alam and Basha (1995) who had put the average annual income of fishers in the region to BDT 2442 in 1994 which was 70% lower than the per capita annual income of Bangladesh.

Coastal aquaculture in Bangladesh consists mainly of two shrimp species (*Penaeus monodon* and *Macrobrachium rosenbergii*). Currently, there are about 16,237 marine shrimp (*P. monodon*) farms covering 148,093 ha, and 36,109 fresh water shrimp (*M. rosenbergii*) farms covering 17,638 ha coastal area. More than 0.7 million people are employed in the farmed shrimp sector and in 2005–2006 the export value of shrimp was 403.5 million US$ (Azad et al. 2009). Although the subsequent discussion is not strictly pertaining to the livelihood issue, we through a short annotation to this effect is expedient keeping in sight the broader picture of ecological sustenance of Sundarbans mangrove ecology.

1.5.2.3 Shrimp Farming Sustainability Concerns: What Reality Counts? Putting the First Last?

Although shrimping is a much vaunted livelihood option (Kamp and Brand 1994; Kendrick 1994) for people of Bangladesh Sundarbans, economically, and politically as well – so much so that often Bangladesh policy makers are forced to remain oblivious of its ill-effects on environment, and Sundarbans mangroves, in particular, in this case, despite the fact that large scale unscientific shrimping is con to environment sustainability had been indicated by various workers (Rosenberry 1993; Bundell and Maybin 1996; Be et al. 1999). Islam and Braden (2006) argued that modern shrimp farming is clearly ecologically unsustainable because of its operational requirements vastly exceeding the carrying capacity of surrounding ecosystems.

The environmental and social impacts of shrimp farming include large-scale degradation of mangroves, alteration of wetlands, land subsidence, salinization of ground and surface water, pollution of agricultural lands and coastal waters by pond effluents and sludge, introduction of exotic species or pathogens into coastal environment, loss of wild larvae and subsequent loss of goods and services generated by natural common property resources (Azad et al. 2009; Rahman et al. 2013).

Reportedly, more than one-third of mangrove across the world has been lost due to un-relented fisheries, and mariculture alone accounts for more than half of that (Azad et al. 2009). Shahid and Islam (2003) reported that about 10,000 ha of mangrove in the southeastern part of Bangladesh has been lost, thanks to shrimping.

Increasing soil acidity pertaining to aquaculture is another problem that needs counting. Aquaculture ponds in mangrove areas give rise to highly acidified soils as a result of exposure to air. This result in high level of aluminum in a form that is highly toxic to other aquatic life (Azad et al. 2009). If fact, many shrimping ventures were forced-closed due to this problem worldwide thereby putting livelihood of connected people in jeopardy (Lin 1989).

Another concern is salinization of soil and aquifers. Primavera (1998) showed that the use of large volumes of underground freshwater to generate brackish water by adding heaps of salt from outside for shrimp culture led to the lowering of groundwater levels, emptying of aquifers, land subsidence, and salinization of adjacent land and waterways in Taiwan and other southeast Asian countries. The discharge of saltwater from shrimp farms also causes salinization in adjoining rice and other agricultural lands. In Bangladesh, Rahman et al. (2013) reported increase in salinity of non-saline areas to the tune of 500% as a result of shrimping. They also reported large scale defoliation of mangrove trees as a result of pumping back the polluted and toxic water of the farms to the immediate mangrove surroundings for stacking freshwater for the next cycle.

Lastly, rampant shrimping is associated with grave socioeconomic implications as well. Lack of planning of coastal land use is the root-cause of the social problem. Because of the high profitability, powerful urban residents, including political leaders, relatives of bureaucrats, bankers and businessmen have caught hold of the coastal lands through lease from Bangladesh government which was con to the 1989 land reforms act of Bangladesh, where it was mandated that these land should be allocated to the penurious landless people of the region (Deb 1998). Loss of small indigenous species (SIS) of fish is another concern related to rampant shrimping. It is established that SIS of fish play an important role in nutrition and employment of rural impecunious mass (Thilsted et al. 1997; Islam and Braden 2006). Shrimping has ripped these people in penury, especially in the southeast region, as most of the farms have been constructed in the *beels* resulting in reduction of spawning and nursery grounds of SIS.

The above introspection entails that *shrimping reality in Bangladesh Sundarbans really counts* and, therefore, is *causa sine qua non* that the men who matters must prioritize the issues while chalking robust policy for maintaining the benignity and sustainability of this pulchritude ecology.

1.5.2.4 Forestry

Alike India, Bangladesh Sundarbans mangrove forest resources provide ample livelihood opportunities, although subsistence, to the penurious 2.5 million people of the locale. For example, one study by Chowdhury and Ashrafi (2008) in the Soranokhola upazilla revealed that 49% household depends on the forest resources to varying degree. The same study also noted that 60% of the resource extractors prefer agriculture and trade as alternate profession (Chowdhury and Ashrafi 2008). According to daily need of people forest resources is divided into food (various types of fishes, honey, crab, etc.), fuel wood (trees and tree parts) and shelter building materials (Golpata, Goran, etc.) (Chowdhury and Ashrafi 2008). Getzner and Islam (2013) calculated that 90% of share of cash income (600–800 Euro per year) comes from harvest and sale of forest produces and only 10% from other sources for about 200 sampled households in south western part of Sundarbans.

1.5.2.5 Tourism

There is vast scope of Community Based Tourism (CBT) opportunities in Bangladesh, and especially, in the Sundarbans (Alauddin et al. 2014; Islam et al. 2013). CBT involves meaningful participation both by visitor and host to generate economic and conservational benefits for the local community (Mazilu and Marinescu 2008). Since 1966 the Sundarbans have been a wildlife sanctuary, and it is estimated that there are now 400 Royal Bengal tigers and about 30,000 spotted deer in the area. This is indeed a land for the sportsmen, the anglers and the photographers with its abundance of game, big and small, crocodile, wild boar, deer, pythons, wild-birds, and above all the Royal Bengal Tiger, cunning, ruthless and yet majestic and graceful (Alam et al. 2009). But Human – Tiger Conflict (HTC) remains a major reason for underdevelopment of tourism in the Bangladesh Sundarbans. Inskip et al. (2013) were of the view that interactions between the problems experienced by villagers, including HTC, result in a complex 'risk web' which detrimentally affects lives and livelihoods and ultimately perpetuates poverty levels in the Sundarbans communities.

So, there goes, for the zealous readers of this book, a laconic apercu of Sundarbans – its' life and times. In one line it may be summarized that the wilderness of the wild "Beautiful forest" should be ensured as "There is no prettiness to invite the stranger in here" (Amitava Ghosh *in* Journey to the Sundarbans: The Beautiful Forest of Mangroves) and in this tone we may sum up now.

1.6 Conclusions

NATURE speaks a language of her own and Man, being her creation, need to interpret her properly and interact accordingly. But, sadly, man is no longer a mere tenant in nature, he is transmuting it. From *ab ovo* of his existence with increasing intensity, human society has been environing nature and made all kinds of incursions into it.

At present the interaction between man and nature is determined by the fact that in addition to the two factors of change in the biosphere that have been operating for millions of years – the *biogenetic* and the *abiogenetic* – there has been added yet another factor which is acquiring decisive significance – the *technogenetic* (https://www.marxists.org/reference/archive/spirkin/works/dialectical-materialism/ch05-s03.html). As a result, the previous dynamic balance between man and nature and between nature and society, as a whole, has shown ominous signs of breaking down. The problem of the so-called replaceable resources of the biosphere has become particularly acute. It is getting more and more difficult to satisfy the needs of human beings and society even for such a substance, for example, as fresh water. The threat of a global ecological crisis looms large over humanity like the sword of Damocles.

The above overture is not mere verbosity. It is prerequisite for an ardent reader to grapple the quiddity of an ecology like The Sundarbans. It had been invaluable in the past and it will remain irreplaceable in the future – unless Man's overwhelming avarice and Nature's languid, yet unwavering, fury has other intentions.

Over the decades, there has been scads of literature on Sundarbans – its *pro bono* quintessentially, its resources, its problems, its people and livelihood, its conflicts, its policies, and so on and so forth. But, there has been no literature on Sundarbans that transcended the international borders and simulacrum it as *e pluribus unum.* As such, there is a great need for one compendium that would enumerate its worth as a single system and address all the issues concerning it from multiple angles to safeguard the environment and for the common good of billions of people in terms of livelihood security in the two neighbouring countries.

This book is an attempt towards that end.

The book comprises of several chapters authored by renowned scientists specializing in the respective areas of both countries. It encompasses wide variety of areas dealing on geo-hydrology, biodiversity, river and groundwater hydrology, climate, E-flow of river network, salt water intrusion inland, and the government policies to project upswing of E-flow and its possible impacts on soil, biodiversity and other domains or enterprises. A chronological review of societal transformation and related approaches towards various livelihood patterns followed over ages, with subsequent chapters on modern-age professional practice of agriculture, land and water management including flood and drainage congestion with suggestions on possible relief measures, sweet and brackish water aquaculture, mangrove ecosystem management – all these, along with non-farm activity like transboundary eco-tourism, with impacts on economic growth of the inhabitants for improvement of the livelihood are discussed. The book places considerable emphasis in characterizing Sundarbans for its dynamic behaviour, on one hand, with continual modification of several islands due to erosion and accretion in the river banks under changing surface water hydrology in rivers and tide-fed estuaries, thereby suggesting engineering interventions on estuary management for augmenting freshwater supply, improved drainage and reduced bank erosion, and on the other hand, presenting engineering challenges to mainstreaming of climate change to combat future adversities in the eco-region. The climate change induced recent disaster events along with relief measures undertaken and their impacts on biodiversity and livelihood in the past have been discussed with emphasis. In a departure from the common trend, an inventory of algal dynamics and their role as climate change proxies have been presented in a separate chapter. Use of remote sensing satellites, as a state of the art technology, for disaster management, ecological disturbance and landmass changes, has been presented through an interesting discussion.

Sundarbans is gradually becoming inhospitable with time in view of climate change, deteriorating hydrological balance of the rivers and creeks, unscientific anthropological interventions, etc., all acting individually or through their interactions. Climate change, in particular, appears to be irreversible in nature, making the whole situation very complex adding to a host of constraints in soils and water normally experienced in the eco-region, thereby limiting the productivity of agriculture and aquaculture. Adaptation strategy, however, has been suggested to mitigate climate risks for the future in Sundarbans. Nevertheless, the issue before us remains, whether or not, it is technically possible to look for 'improvement in farm productivity' by tiding over the challenge with time. Alternatively, we may be content with 'subsistence farming', and yet ensure livelihood security, means of which have to be worked out in the lines suggested. The solution in this direction is, though difficult, not impossible if a holistic approach, with both countries taken together, is undertaken.

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Succession of embankments due to erosion and poor hydrological conditions in river (Courtesy A. A. Danda)

Chapter 2
Sundarbans a Dynamic Ecosystem: An Overview of Opportunities, Threats and Tasks

Shafi Noor Islam

Abstract The Sundarbans, spreading over 10,000 km^2 area, is one of the largest productive deltas in the world, and is located in the Ganges-Brahmaputra-Meghna river basin over parts of Bangladesh and India. The coastal mangrove wetland is playing a potential role in balancing the ecology, community socio-economy, and livelihoods of the community. It is a hotspot of mangrove biodiversity with 373 faunal and 324 floral species. The ecosystem is dynamic, fragile and complex owing to several climate-, soil-, and water- related stress factors. Climate change and several anthropogenic interventions have transformed the natural landscape with significant changes in the social matrix. The salinity intrusion of water is the most sensitive and serious threat for mangrove ecosystem in the coastal region, more in Bangladesh. Since the diversion of Ganges freshwater at Farakka Barrage in India since early 1975, salinity levels have increased drastically in the coastal region in Bangladesh. The reduction of Ganges flow has made disastrous effects on agriculture, fisheries, hydro-morphology, drinking water and mangrove coastal ecosystem. All these factors, individually and collectively, pose serious threats to livelihood and food security for the coastal community in Sundarbans, and what's more, to the ecological balance. E-flow assessment methodologies are discussed in this chapter with reference to attempts made in Bangladesh. It is believed that the present coastal mangrove wetland ecosystem conservation and planning policy is inadequate. In this backdrop, the article suggests in this introductory chapter thrust on future policies for better management, monitoring and conservation of the Sundarbans in a transboundary mode towards improved livelihood.

Keywords Sundarbans mangrove · Wetland · Ecosystem · Biodiversity · Salinity intrusion · Agricultural crop production · Food security · Management and conservation

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2.1 Introduction

The coastal wetlands in Sundarbans, spreading over 10,000 km^2 area across Bangladesh and India, are playing a potential role in ecological balance and local socio-economic improvement. The coastal mangrove is the most dynamic and potential eco-region in the world. The Sundarbans is the largest mangrove forest in the world which has been declared as World Natural Heritage Site (WNHS) by UNESCO in Bangladesh in 1997, and as World Heritage Site in 1987 in the Indian counterpart of the mangrove forest. It is hotspot of biodiversity with 373 faunal and 324 floral species (Milliman et al. 1989; Khan 1993; Hughes et al. 1994; Gopal and Wetzel 1995; Islam and Gnauck 2008). Over 3.5 million coastal people are directly dependent on the Sundarbans heritage site goods and services (Islam and Gnauck 2008, 2009a, b; Islam et al. 2017).

The Sundarbans is the largest unique mangrove ecosystem of the world. The significance of this unique ecosystem is greatly felt due to its unique biota and source of multiple resource bases for the regional economy. The Sundarbans Reserve Forest (SRF) in Bangladesh comprises of 6017 km^2 and in India it encompasses 4000 km^2 area. Within the SRF, there are three wildlife sanctuaries located in the southern part of Bangladesh. The SRF area is recognized as internationally important as the Ramsar Site and as a repository for globally significant biodiversity and dynamic sensitive ecosystem (Richards 1990). Moreover, it has a unique position not only for forestry but also in terms of deltaic landscapes, eco-tourism, culture and heritage. The natural beauty and the universal value of the forest property have given us natural heritage. The importance of the site is its floristic composition, economic uses.

However, it is a dynamic, fragile and complex ecosystem largely influenced by different stress-related factors in the fields of soil, water and climate, further interacting with each other. The anthropogenic interventions in the Sundarbans have transformed natural landscapes through the process of fire, hunting, agriculture, shrimp farming, along with climate change and industrial pollution (Hughes et al. 1994; Gopal and Wetzel 1995; Islam and Gnauck 2008). The present management and conservation strategy is inadequate. Therefore, it is virtual and essential to conserve Sundarbans World Natural Heritage in twenty-first century of interest to both Bangladesh and India. In this backdrop, the article suggests thrust on future policies for better management, monitoring, and conservation of the Sundarbans towards improved livelihood and food security.

2.2 Ecosystem Concept

The ecosystem concept can apply from a micro level to the global scale, and energy is playing a central role in an ecosystem. Energy flows one-way through an ecosystem that is from sunlight to producer, through food chain, and ends up as heat dissipated in the atmosphere. In contrast, natural materials and mineral nutrients either flow one-way or cycle within an ecosystem (Fujimoto 2000). On the other hand, ecologists consider ecosystems to be the basic units of ecology and of the earth's surface. An ecosystem is thus a space where species interact with the physical environment (MEA 2003).

The ecosystems can be defined as a relationship between biotic and abiotic characteristics.

The meaning of ecosystem means the functions of biotic and abiotic factors, like

$$\text{Ecosystem} = f(\text{biotic and abiotic characteristics}) \tag{2.1}$$

or, on the other hand,

$$\text{Ecosystem} = f(\text{s}, \text{cl}, \text{a}, \text{pm}, \text{o}, \text{mo}, \text{r}, \text{w}, \text{e}, \text{t}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots) \tag{2.2}$$

where, 's' is soil, 'cl' is climate, 'a' is air, 'pm' is parent material, 'o' is organism, 'mo' is microorganism, 'r' is relief of topography, 'w' is water, 'e' is energy, and 't' is time, etc.

The equations (Eqs. 2.1 and 2.2) represent the scientific expressions and understanding of the definition of ecosystem. In Eq. 2.2 the potential elements which ensure the functions, like soil, climate, air, parent material, organism, microorganism, relief of topography, water, energy, or time are the potential factors that characterize an ecosystem in a particular region, and the area, where Sundarbans, the important natural heritage site, represents one such (Miah and Bari 2002). Over and above, the Sundarbans ecosystem is characterized by a very dynamic and complex environment due to the effect of tidal flooding and cyclones (Islam 2003; Erdogan and Kuter 2010), besides various stress-related factors. This, as a consequence, reflects on various species – their population and symbiotic relationships creating an equilibrium at a given time – under continual drift over time.

2.3 Geographical Setting and Dynamics Changes

The Sundarbans stretches over 10,000 km^2 and located at the south-western extreme of Bangladesh and south-east of the state of West Bengal in India (Hussain and Acharya 1994). The area is situated in the Ganges trans-boundary catchment area, and lies between latitude 21° 31′ N and 22° 30′ N and between longitudes 89° E and 90° 18′ E (Katebi 2001). Out of this approximately 70% are lands and 30% are water bodies.

The Ganges-Brahmaputra and Meghna river systems and drainage basin is 1.76 million km^2 in area (Fig. 2.1) (Islam 2006). The Sundarbans stretches from the Hoogly on the west in India to the Meghna, the estuary of the Ganges and

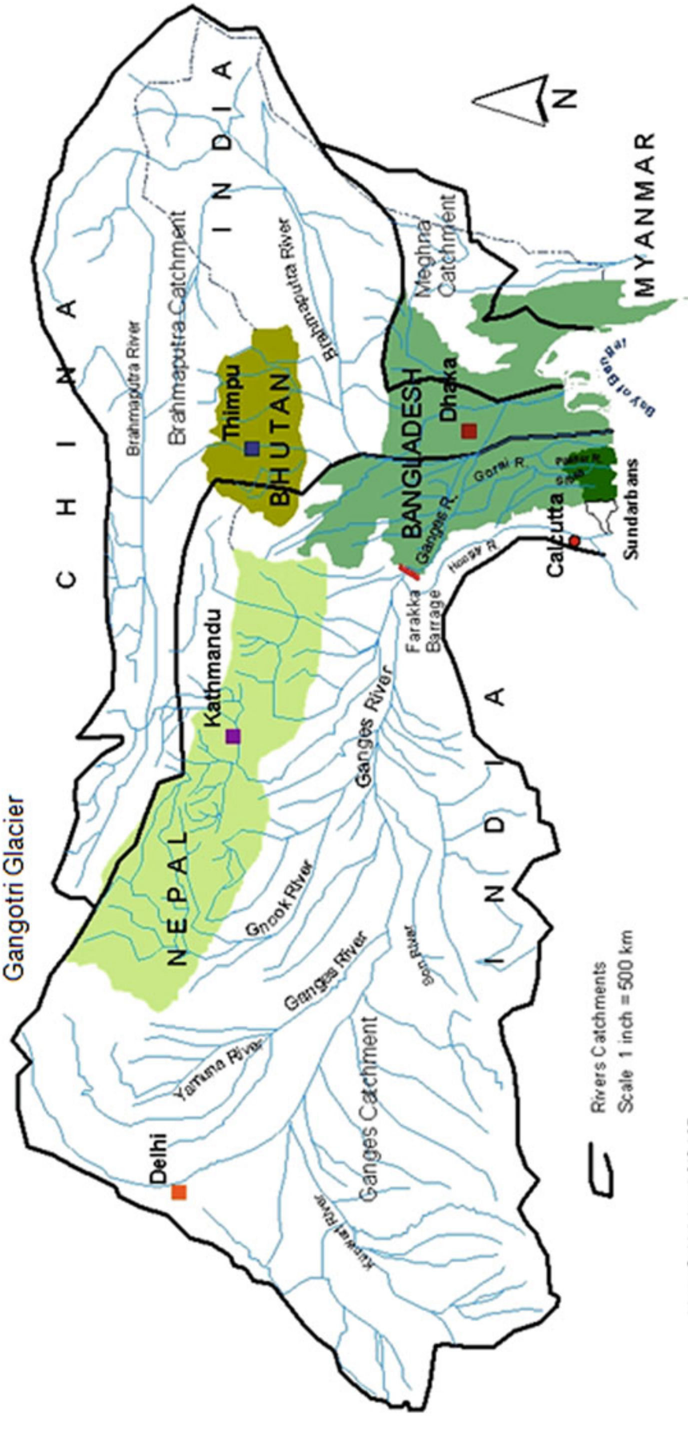

Fig. 2.1 The Geographical location of the Sundarbans in the Ganges-Brahmaputra-Meghna river in the catchment area. (Source: Islam and Gnauck 2008)

Brahmaputra, on the east, located in Bangladesh. It covers the southern portions of the districts, viz. South 24 Parganas in India, to Khulna and Barishal in Bangladesh (Islam 2003). There is evidence to suggest that due to geomorphological processes the Bengal Basin is tilting, diverting fresh water through the Ganges-Brahmaputra river system to the east. It was thus only natural that the eastern part of Bengal was marked by its greater agricultural produce and greater population growth compared to the western part. This was made possible by the silt deposit because of the shift in the river system (Islam and Gnauck 2008; Islam 2016).

The Indian part of the delta is thus being denied fresh water from upstream, resulting in increased salinity (Islam and Gnauck 2008; Islam 2016). The entire region is subject to violent storms, particularly during the monsoon months, as the Bay of Bengal frequently sees the development of cyclonic depressions (Islam and Gnauck 2008) making livelihood fragile and uncertain.

2.4 Characteristic Features

2.4.1 Coastal Geo-hydrology

The entire Sundarbans area, comprising of many islands, is deltaic active and hydrologically dynamic. The coastal morphology is further characterized by different features like, vast networks of rivers and channels, heavy water discharge carrying sediment, strong tidal waves, cyclone and surges. The three divisions in Bangladesh are (i) Eastern region, (ii) Central region, and (iii) Western region, and in Indian part it is named as the south-eastern region. The central region runs east from the Tetulia River to the big Feni River estuary, including the mouth of the combined flows of the Ganges-Brahmaputra-Meghna (GBM) Rivers (Akter et al. 2010; Islam et al. 2017). This is the reason that this region is characterized by heavy sediment input, formation of new *chars* (sedimented raised bed), and river bank erosion, and accretion. The western region covers the coastline westward from the Tetulia River to the international boundary located at the Harinbhanga River (Fig. 2.1). This region is mostly covered with dense mangrove forests having a reduced river bank erosion. The rivers of the region are mostly stable; land accretion does not occur massively (Jalal 1988). Figure 2.2 shows the Sundarbans mangrove wetlands and the river system in the mangrove forest areas in both countries. The southeastern part of the Sundarbans in West Bengal (India) starts from Harinbhanga river in the east to Hoogly River in the west. In between, the Gosaba, Matla and Suparnakhali river systems are playing a potential role to protect the coastal landscape and balance the Sundarbans coastal deltaic ecosystem (Fig. 2.2). The central region in Bangladesh has deltaic characteristics. The GBM rivers discharge at the rate of about 1.5 million $m^3 s^{-1}$ during the peak period (Hasan and Mulamoottil 1994). The fluvial and tidal landscapes and related features are created by four mighty rivers (Ganges – Brahmaputra – Meghna and Hoogly river) in the Ganges coastal deltaic wetlands regions between Bangladesh and India (Islam 2003; Islam and Gnauck 2007a, b). All the

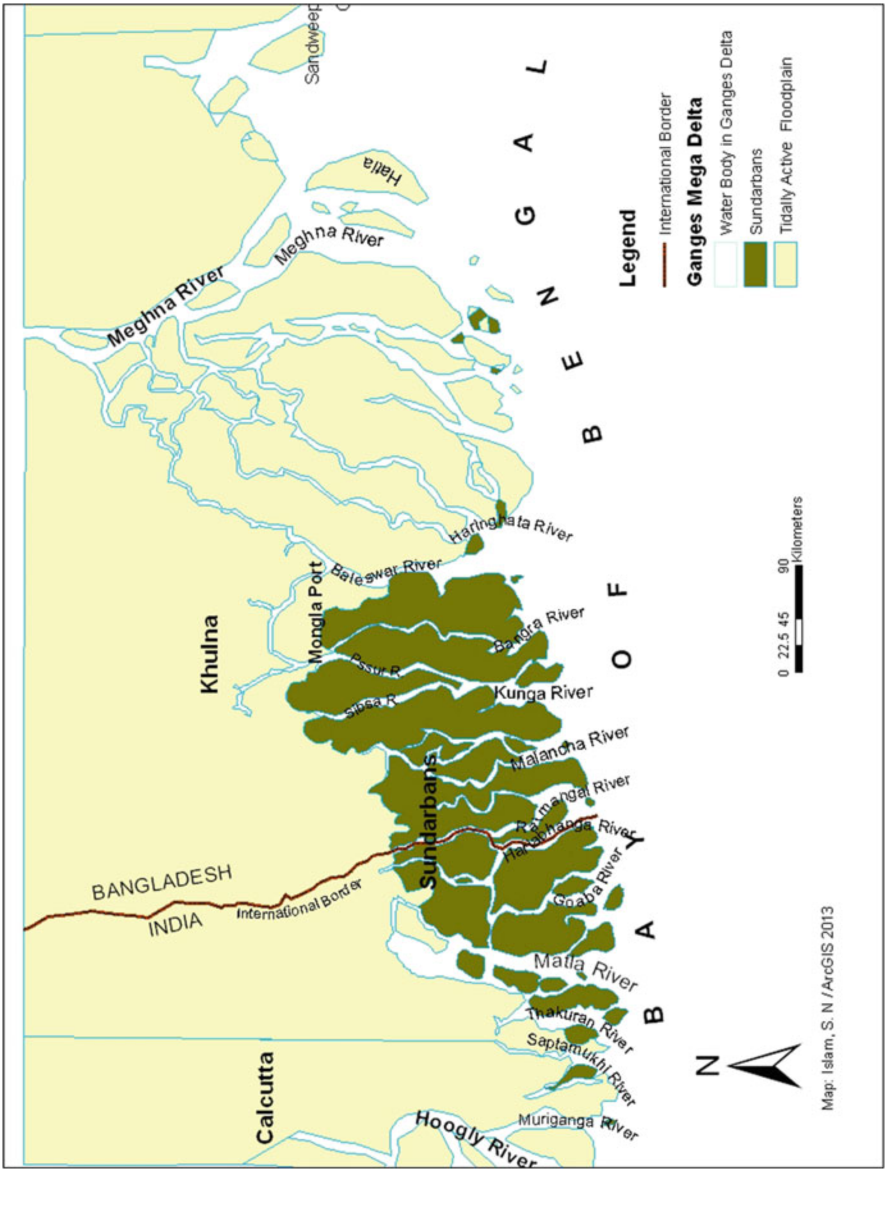

Fig. 2.2 The Sundarbans coastal mangrove delta and river system. (Source: The figure prepared by author through ArcGIS 10.2 in 2013)

rivers have its origin in the Himalayas and carries an estimated annual sediment load of 2.4 billion tons (Elahi et al. 1998) and having a profound effect on the floodplains. Silt deposition in the forest poses a threat to the river flow but supports vigorous growth of mangrove vegetation. The silt deposition causes a rise of the forest floor but due to irregular flow of tidal water, mangrove regeneration does not take place properly. Area is densely populated and plays important economical role – wood production and agricultural cultivation with allied activities.

2.4.2 Groundwater Hydrology and Tidal Features

Ground water issue is a potential factor in hydrology studies where water is a valuable natural resource to man and other living beings (Rahman and Ahsan 2001). Under natural conditions, freshwater flow toward the sea limits the landward encroachment of seawater. The surface water disturbs the dynamic balance between freshwater and seawater, which, in turn, allows seawater to intrude into the usable parts of aquifers (Rahman 1988; Hossain 2001; Iftekhar 2006). Ground and surface water quality is dominated by both natural and anthropogenic influences, where the former is governed by the local climate, geology, etc., and the latter by the construction of dams and embankments, irrigation practices, indiscriminate disposal of industrial effluents, etc. (Rahman and Ahsan 2001).

The amount of the Ganges water flow into Bangladesh is remarkably affected by the amount of water drawn at the Farrakka Barrage in India since 1975. The Ganges flow in 1962 was 3700 $m^3\ s^{-1}$, whereas it was 364 $m^3\ s^{-1}$ in 2006 and 370 $m^3\ s^{-1}$ in 2010 (Goodbred and Kuehl 2000; Islam and Gnauck 2009a). The Ganges water flows is also related to the condition of groundwater hydrology. The river water flows and rainwater on the surface dominate and balance the groundwater condition in the Sundarbans region, and the reduction in flow rate has resulted in increase in high rate of saline seawater intrusion in the upstream areas. Such diversion of upstream waters resulted in falling groundwater tables and greater salinity in downstream for Bangladesh especially in the Sundarbans region. Some portion, almost 16% of the flows of the Gorai River, meets the Haringhata-Baleswar estuary system at Madhumati river and the other 85% flows to join the Passur Basin at Nabaganga River. The last part of the Gorai River joins the sea as Baleswar River (Islam and Gnauck 2008, 2009a, b; Islam et al. 2017).

Water salinity intrusion of the whole Sundarbans region is dependent on hydrological condition and its changing behaviour. Water level inside the Sundarbans is highly fresh and dependent on the upstream river inflows and on the tidal oscillation at the coast (Siddiqi 2001). Tides in the Bay of Bengal are semi-diurnal exhibiting two high water and two low water levels per day. The variations in water level and tidal amplitude experienced at the coast are also propagated inland during each tidal cycle. It has been observed that the tidal range in the northern fringe of the Sundarbans mangrove forest is higher than that in the southern bay. The lowest record of tidal range was 2.74 m and the highest in the east is higher than that in the southern Bay, while the highest range was 5.12 m (Islam and Gnauck 2009a, b; Islam et al. 2017).

The maximum inundation period during the spring tide is around 3–4 h, the average velocity of micro-current varies from 10 to 20 cm s^{-1}. Both siltation and erosion occur at the end of monsoon. The maximum net siltation and erosion at the end of monsoon were found to be around 50 and 19 mm, respectively (Islam et al. 2017). The hydrological changes in the Sundarbans region will pose a new threat for the mangrove ecosystem, its goods and services. There is close correlation with hydrological cycle and the mangrove ecosystem in any region of the mangrove world.

2.4.3 River Hydrology

The Bengal delta is the world's largest delta comprising of 100,000 km^2 of riverine flood plain and deltaic plain (Goodbred and Nicholls 2004). The high tide energy results in tide dominated deltas, like the Meghna estuary, where distributaries with linear river mouth bars are present (Miah 1989). Sediment deposition occurs only by river flushing in the river-dominated delta, while in tide-dominated deltas, sediments are reworked and redeposited (Goodbred and Nicholls 2004). Every year about 1×10^{12} m^3 of freshwater is brought into the Meghna estuary by the three major rivers the Ganges, the Jamuna and the upper Meghna (Nishat 2006). These rivers are major source of water supply to the wetlands and make the balance of wetlands ecosystems. The largest rivers in Asia are created from the Himalayas and Tibetan pleatue (Jalal 1988). As a whole, the Bramaputra (Jamuna) river carries water flowing at the rate of 60,000–100,000 m^3 s^{-1} and about 600 million tons of sediment particles, major part of which are sand and clay in each year (Jalal 1988; FAP 24 1996; Islam and Gnauck 2008, 2009a, b; Islam et al. 2017). The reduction of the Ganges freshwater in the upstream area is the root cause of salinity intrusion in the south-western region which is affecting the Sundarbans coastal mangrove and saline wetlands in both countries in Sundarbans (Nishat 2006).

2.5 Threats to the Ecosystem

2.5.1 Soils: Delineation of Problems and Risk Factors

The reduction of Ganges fresh water in the upstream area is the main reason of salinity intrusion in the south-western part of Bangladesh and some part of south-eastern West Bengal (India). Therefore, the result of increased salinity has damaged vegetation, agricultural cropping systems, and changing the cultural landscapes in the Sundarbans region. The impact of soil starts with the destruction of surface organic matter and of soil fertility for mangrove plants production (Islam and

Gnauck 2007a, 2009a). The changes alter basic soil characteristics related to aerations, temperature, moisture and the organisms that live in the soil. Figure 2.3 demonstrates the soil and water salinity intrusion pattern in the Sundarbans and surrounding areas where soil delineation impacts are very high in agricultural cropping system and drinking water supply and management (Islam and Gnauck 2009a, b).

The core elements of ecosystem such as soil, water, vegetation and wildlife are strongly affected due to fresh water shortage and human influences. Water scarcity of the Ganges flow is challenge for coastal food security and mangrove wetland ecosystem protection, and for further improvement of coastal saline environment. Figures 2.3 and 2.4 are displaying the real scenarios of the Sundarbans mangrove deltaic sensitive ecosystem.

There are many reasons for the mangrove degradation in the Sundarbans Deltaic region. More sensitive and critical issues are human uses of mangroves, fishery development, hyper-salinity, salt pans, salt ponds, and sediment deposition, like sea sand from low lying sand dunes, sea beaches and sand bars, which are transported or drifted into the forest areas by over-wash fan sediment deposition particularly by storms and tidal waves (Wolanski et al. 2009).

2.5.2 Threats to Biodiversity

The delta front sand bodies with different shapes and sizes are unable to hold the surge waters of advancing storm waves that can transport the bulk of sediment from seaward face to inner of the delta plains (Farley et al. 2010). The sediment lobes submerge the forests, wetlands surface, and tidal creeks at a steady rate with increased frequency of storm events in the deltaic coast at present (Wolanski et al. 2009). Mangroves occur in the waterlogged, salty soils of sheltered tropical, and subtropical shores. They are subject to the twice-daily ebb and flow of tides, fortnightly spring, and neap tides, with seasonal weather fluctuations. They stretch from the intertidal zone up to the high-tide mark (GOB 2001; PDO-ICZMP 2005). These forests are comprised of 12 genera comprising of about 60 species of salt tolerant trees. With their distinctive nest of stilt and prop-like roots, mangroves can thrive in areas of soft, waterlogged, and oxygen-poor soil by using aerial and even horizontal roots to gain a foothold (Islam et al. 2017). The roots also absorb oxygen from the air, while the tree leaves can excrete excess salt. Most species typically have relatively widespread distributions, low diversity floras, but overall alpha diversity is very high when terrestrial and aquatic species are considered, very low beta diversity, and low eco-region endemism, while some highly localized species exist with strong zonation along the gradients; showing thereby several distinct mangrove habitat formations. Alterations of hydrography and substrate have considerable impact, although restoration potential is high; mangroves are susceptible to pollution due to particularly oil and other petroleum compounds; and alteration of salinity levels can have dramatic impacts on mangroves. In Sundarbans a

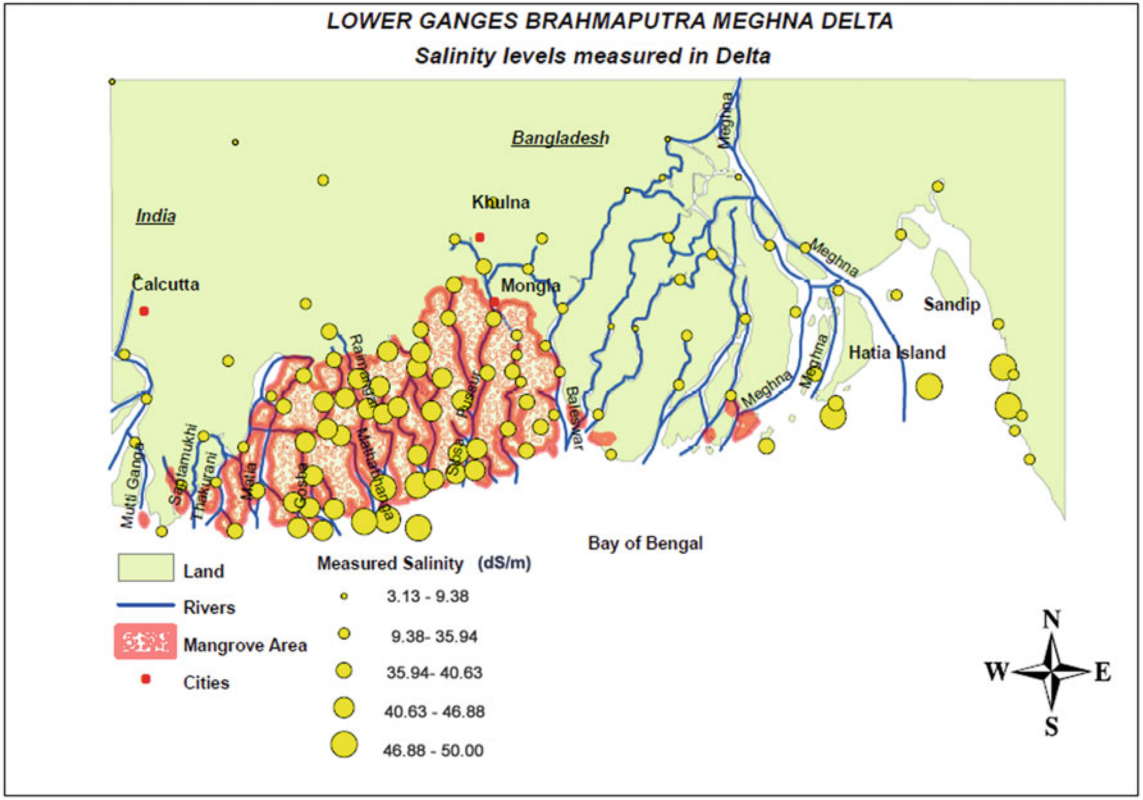

Fig. 2.3 Salinity measured in Sundarbans mangrove and the Ganges-Brahmaputra-Meghna deltaic coastal region in 2015. (Source: Salinity intrusion model was developed by author through ArcGIS 10.2 in 2013)

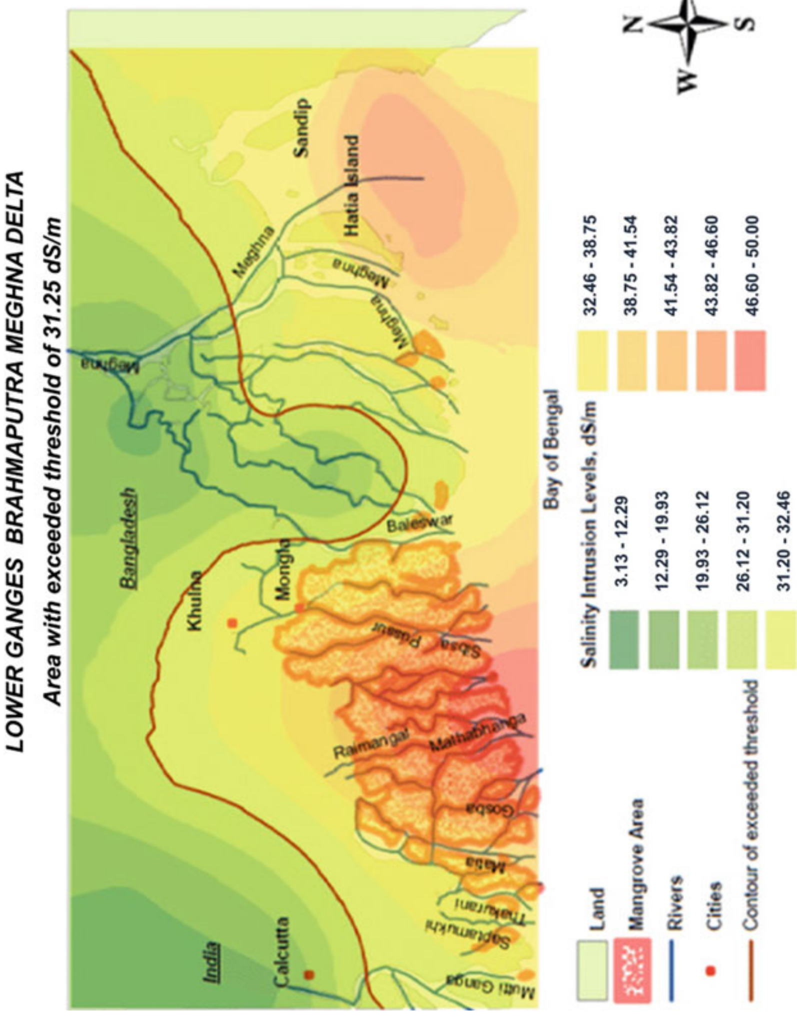

Fig. 2.4 Lower Ganges-Brahmaputra-Meghna-River delta: area which exceeded threatened limit of 31.25 dS m^{-1}. (Source: Salinity intrusion model prepared by author through ArcGIS10.2 in 2013)

large number of mangrove seeds is regularly drifted into the unfavourable sandy substrate after the events of storms, tidal waves, south-west monsoon brace, and HAT (Highest Astronomical Tides) phase currents along the shores of the Bay of Bengal, which is creating another type of threat for mangrove biodiversity (Islam 2016; Islam et al. 2017). The habitats, biotops and ecosystem also serve as habitat for especially four dominant tree species of the Sundarbans. But the existence of these and many more native species is endangered (Islam et al. 2019). So the native species are approximately decreasing significantly by the year 2100 due to sea level rise (88 cm) in the Sundarbans area compared to the year 2001. Species Biswas found 23 invasive which belong to 18 families and 23 genera. These species are highly invasive, six species are moderately invasive and the remaining are potentialy invasive (Biswas et al. 2007; Islam et al. 2019).

2.5.3 Global Warming and Future Projection

Climate change and sea level rise, induced by global warming, also influence the ecological stability of the coastal zone; and the situation becomes serious when the climate change phenomenon is compounded with various natural and anthropogenic factors, and, as a result, the natural resource base of the zone is on a declining trend. This affects the productivity of agricultural and allied fields including fishery. Failing ecosystem productivity further degrades the coastal deltaic ecology, and quality of life of the local communities (Dasgupta 2001). As a result of global warming, relative Sea-Level Rise (SLR) movement has an immediate and direct effect on the coastal inter-tidal ecosystems, particularly on vegetation. A rise of relative SLR decreases the influences of terrestrial processes and increases the influence of coastal marine processes (Islam 2001). The world's great deltas are the most densely populated, and most vulnerable of coastal areas are threatened by sea level rise (Broadus 1993). Global warming, sea level rise, and vulnerability of coastal wetland ecosystems are factors that have to be considered to draw long-term management strategy for dealing with the coastal mangrove wetland issue (Fedra and Feoli 1999). The impacts of climate change in any given region depend on the specific climatic changes that occur in that region. Local changes can differ substantially from the globally averaged climate change (Harvey 2000). In Bangladesh it has been projected by IPCC (2007) that 3 mm per year sea level rise may occur before 2030 and might cause 2500 km^2 land (2%) to be inundated. About 20% of the net cultivable area of Bangladesh is located in the coastal and offshore island (Fig. 2.5), which is under threat due to the above-mentioned causes.

A very recent study on the Ganges deltaic coastal area in Bangladesh by IPCC report shows that the mean tidal level at Hiron Point is showing an increase of 4.0 mm per year which is higher than the global rate. Soils in this area are affected by different degrees of salinity (Rahman 1988; IPCC 2007). About 203,000 hectare very slightly, 492,000 hectare slightly, 461,000 hectare moderately, and 490,200 hectare strongly salt affected soils are assessed in south-western part of the coastal area (Fig. 2.5). The climate change impact issue is a new threat for the coastal area of Bangladesh. In Sundarbans, sea level rise would further result in saline water moving into the delta which would be the major threat for mangrove and coastal wetland ecosystems (IECO 1980). It was projected in respect of different SLR that for 10 cm rise 15% of the land in Sundarbans will be inundated and will affect 17% of the population rendering them homeless. A detailed account of climate change and probability of inundation of land has been projected in a separate chapter by Danda and Rahman in this book.

The Fig. 2.5 shows that 3 m SLR would cause much worse scenario for Bangladesh when almost one-third of land could be inundated by saline water. The reduction rate of mangrove areas will be from 50% to 75% and would be more harmful for coastal ecosystems in the estuaries (IPCC 2007). Besides, other environmental problems will arise in the coastal belt such as, water pollution and scarcity, soil degradation, deforestation, solid and hazardous wastes, loss of bio-diversity, estuary landscape damage, and river bank erosion, all of which will create a lot of new challenging problems for human livelihood in the coastal region.

2.6 E-flow of the Catchment River Network Including its Water Quality

The flows of the world rivers are increasingly being modified through impoundments in dams and weirs, besides abstractions for agriculture and urban water supply, drainage return flows, maintenance of flows for navigation, and structures for flood control (MEA 2003). These interventions have caused significant alteration of flow regimes mainly by reducing the total flow and affecting the variability and seasonality of flows. It has been estimated that more than 60% of the world rivers are fragmented by hydrological alterations. This has led to widespread degradation of aquatic ecosystems by MEA or Millennium Ecosystem Assessment (2003). Available literatures have been reviewed for searching out available techniques for assessing e-flow requirements. In the previous studies, the key information and recommendations of different techniques under different environmental values were described with their limitations, advantages and cost effectiveness. These have been applied for e-flow assessment (EFA) in different river systems in Bangladesh. This study assists to propose a best practice framework for the application of techniques to EFA (Akter et al. 2010).

Akter (2010) stated based on the reports of Tharme (2000, 2003) that "there is no specific guideline for assessing e-flow. However, several methods, approaches and frameworks are being applied in different countries including Australia, South Africa (SA), United Kingdom (UK) and United States of America (USA) depending on their river function. Mainly it depends on stakeholders' decision on the desired character and health condition of a certain ecosystem". In the most recent review of international e-flows assessments, Akter (2010) recorded 207 different EFA methodologies applied over 44 countries (Tharme 2000, 2003). Several

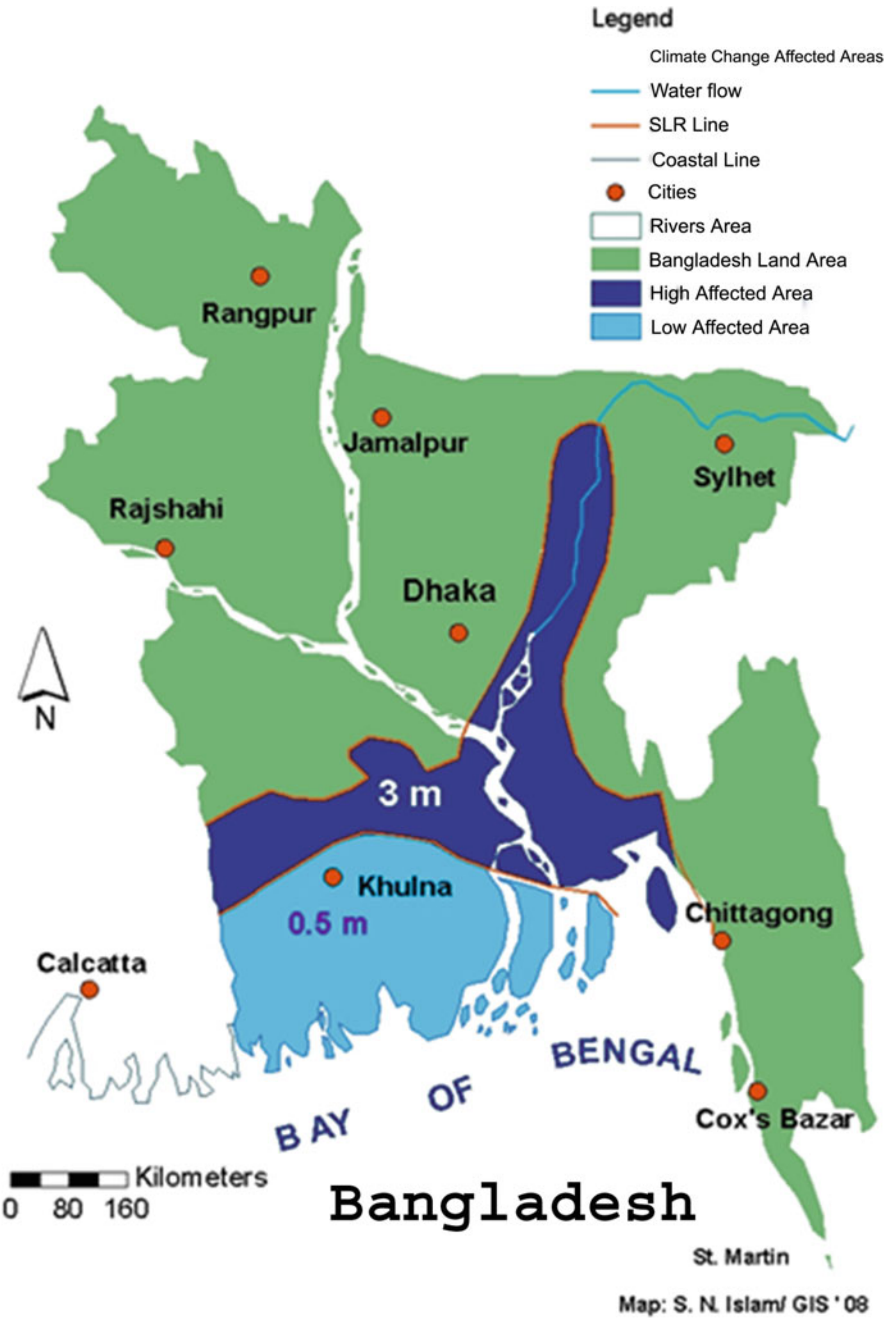

Fig. 2.5 Climate change impacts in the coastal region of Bengal Delta and Sundarbans region. (Source: Akter et al. 2010, open access)

categorizations of these methodologies exist. Many EFA methods have been applied in Australia and modified according to circumstances. Reviews can be found in 2009 (Tharme 2000, 2003; Akter 2010). Above researchers have set out these methods under the headings of geomorphology and channel morphology, wetland and riparian vegetation, aquatic invertebrates, freshwater and estuarine fish, water dependent wildlife, and water quality (Tharme 2000, 2003; Akter 2010).

2.6.1 Methodologies of Measurement of E-flow in Various Countries

Developments in EFAs in South Africa have advanced dramatically during the past decade (Akter 2010). Akter (2010) presented an overview of the historical and local evolution of e-flow methodologies. Methodologies are considered the most appropriate for South African conditions, where there are some constraints. Those constraints are historical, hydrological, ecological with 11 geomorphological data on the river systems of concern; limited finances; extreme time pressures with future water-resource development projects; and limited manpower and expertise. Akter (2010) stated, based on Tharme (1997), that a multi-scale approach to EFAs for South Africa, comprising of a three-tier hierarchy of methodologies with professional judgment, is exercised at all levels. Akter (2010) recommends further advancement of the Building Block Method (BBM) for its most effective use at this level, for instance, by incorporating ecologically relevant hydrological indices into the hydrological component and by biotope-level modeling. It is noteworthy that Downstream Response to Imposed Flow Transformations, DRIFT, developed subsequently, incorporates early elements of both these features (Tharme 2000, 2003). With rivers of high conservation priority, it would be appropriate to apply elements of a suitable, internationally recognized habitat simulation methodology within or in conjunction with a holistic methodology, like the BBM or DRIFT, where the flow requirements of key, ecologically important or rare species need to be addressed (Tharme 2000, 2003; Akter 2010). This would represent the final, most resource-intensive level of the proposed hierarchy. Considerable effort would need to be expended, however, in order to select the most appropriate techniques from the wide range available, and to train and guide researchers in the development and application of these techniques in a local context (Tharme 2000, 2003; Akter 2010).

Before Farakka Barrage construction (1934–1975), the mean of yearly maximum, minimum and mean flow were calculated as 73,000 $m^3 s^{-1}$, 1190 $m^3 s^{-1}$ and 11,692 $m^3 s^{-1}$, respectively; whereas, after Farakka Barrage construction (1976–2005), those values were calculated as 77,438 $m^3 s^{-1}$, 261 $m^3 s^{-1}$ and 11,195 $m^3 s^{-1}$, respectively (Chowdhury and Haque 1990). The detail impact analyses are discussed and given in Table 2.1.

The relative elevation of the coastal south-west region of Bangladesh and south-east region of West Bengal of India have been widely reported by different studies to assess the required E-flow in the regions and the same was validated through direct

Table 2.1 Percentage of mean annual flow (MAF) in Ganges River (Akter 2010, p. 89, open access)

Percentage of MAF m^3/s	Pre-Farakka (1934–1975)	Post-Farakka (1976–2005)
200% (flushing flow)	23,029	22,715
60–100% (optimum range)	6909–11,514	6815
60% (outstanding)	6909	6815
50% (excellent)	5757	5679
40% (good)	4606	4543
30% (fair and degrading)	3454	3407
10% (poor)	1151	1136

measurements (Akter 2010). On 25 May 2009, Cyclone *Aila* struck West Bengal in India and south-west region of Bangladesh as a relatively weak category 1 storm, causing embankment failures, tidal flooding and the displacement of over 100,000 inhabitants of the coastal regions, like Koyra, Shyamnagar and Dacope in Khulna region (Akter 2010). A detailed account of the nature and extent of damage has been presented by Paul and Chatterjee in a separate chapter in this book. At the Polder 32 in Dacope in Khulna, *Aila* cyclone caused five major breaches of the embankments that protected the island's western margin despite a storm-surge height just 0.5 above the spring high-tide level (Akter 2010). The exact mechanism of failure at these locations remained unknown, while the other four of the five failures occurred at the mouths of former tidal channels blocked by the embankments. All breach sites had experienced ~50–200 m of river bank erosion in the decade before the storm. In contrast, the adjacent Sundarbans, ∼100 cm higher, was inundated only during spring high tides (∼37% of all tides) to a mean depth of just 20 cm for 1.7 h day^{-1} (Akter 2010). The high rates of sedimentation following embankment breaches exemplify the efficiency with which the Ganges–Brahmaputra fluvio-tidal system can disperse sediment to areas of accommodation, particularly where land has been starved of sediment for extended periods of time (Islam 2007a). To understand the origin of elevation offset between the polder landscape and Sundarbans, it may be necessary to establish an account to work out for differences among local, relative water levels, and the natural and human-altered landscapes (Turner et al. 2001; Tress et al. 2005).

2.7 Government Policies to Upswing the E-flow and Projected Impacts on Soil Properties, Crops Growth, Fisheries, Forestry and Biodiversity

The salinity trends are higher in the Sathkhira, Khulna, Bagerhat, Borguna, Jhalokhati, Potuakhali, Bhola and southern part of Noakhali districts in Bangladesh. The trends are higher in the south-western region of Bangladesh and comparatively less saline intrusion occurred in the eastern region of the coastal region. These trends are also affecting the whole coastal urban ecosystems (Islam 2001, 2006; Akter et al. 2010). The available drinking water and its quality are not enough to meet the demand of the urban citizens. The surface and groundwater in the coastal region is affected by high saline water intrusion. This is deteriorating the quality of drinking water (Adel 2001). Due to the penetration of saline water the soil is also becoming highly saline and soil fertility is getting low. Therefore, the urban flora and fauna are also facing trouble to receive quality water for vegetation growth and survival of fauna in the urban areas (Chowdhury and Haque 1990).

2.7.1 *Water and Soil Salinity in the Wetlands*

The wetland areas in the coastal region of Bangladesh are affected due to high rate of water and soil salinity intrusion. In general, the annual pattern of salinity changes in the Sundarbans region is also related with the changes of freshwater flow from upstream rivers. The adverse effects of increased salinity on the ecosystem of the Sundarbans mangrove wetlands are manifested in the drying of tops of Sundari (*Heritiera fomes*) trees, retrogression of forest types, slow forest growth, and reduced productivity of forest sites (DoF 2003). The peak soil salinity level was found to be about 40.63 dS m^{-1} in 2001 and 2002, and minimum soil salinity was found to be about 7.81 dS m^{-1} during the post-monsoon period of the same years, when huge fresh water supply was available, which mean that fresh water flush out high amount of salts in soil (IWM 2003). The salinity levels crossed the salinity threshold value for the mangrove wetlands ecosystems in the coastal region. Some mangrove species have dried and displaced due to high salinity penetration and intrusion into the coastal area in Bangladesh.

The soil salinity in the southern part of the Sundarbans mangrove forest remains less than 7.81 dSm^{-1} during monsoon and starts to increase at a steady rate to 23.44 dS m^{-1} during the dry season (IWM 2003). Salinity in the western part in not reduced to low salinity range even during monsoon period; salinity increases at a steady rate during the dry periods. Almost 265 km^2 area under *Heritiera fomes* type of forest is affected moderately and 210 km^2 area was severely affected, which is one of the main threats for a sustainable mangrove forest management and its ecosystems (Islam and Gnauck 2008, 2009a, b).

The highest soil salinity levels measured were ECs 41.2 dS m^{-1} at Nilkamal, ECs 40 dS m^{-1} at Mirgang, and ECs 24 dS m^{-1} at Munchiganj point in the north-western Sundarbans mangrove coastal wetlands region. The increasing salinity levels are major threats for both biotic and abiotic factors of mangrove wetland ecosystems in the region (Islam and Gnauck 2009b).

The severity of salinity problem in the coastal wetlands increases with the desiccation of the soil (Fig. 2.6).

The coastal region covers an area about 29,000 km^2 or about 20% of Bangladesh. The coastal areas of the country cover more than 30% of the cultivable lands of the country (Jabbar 1979). About 53% of the coastal areas are affected by salinity. Salinity causes unfavorable environment and hydrological situation that restrict the normal crop production throughout the year (Iftekhar 2006). Soil salinity, besides on the soil surface, is a major concern for surface water in many coastal urban towns

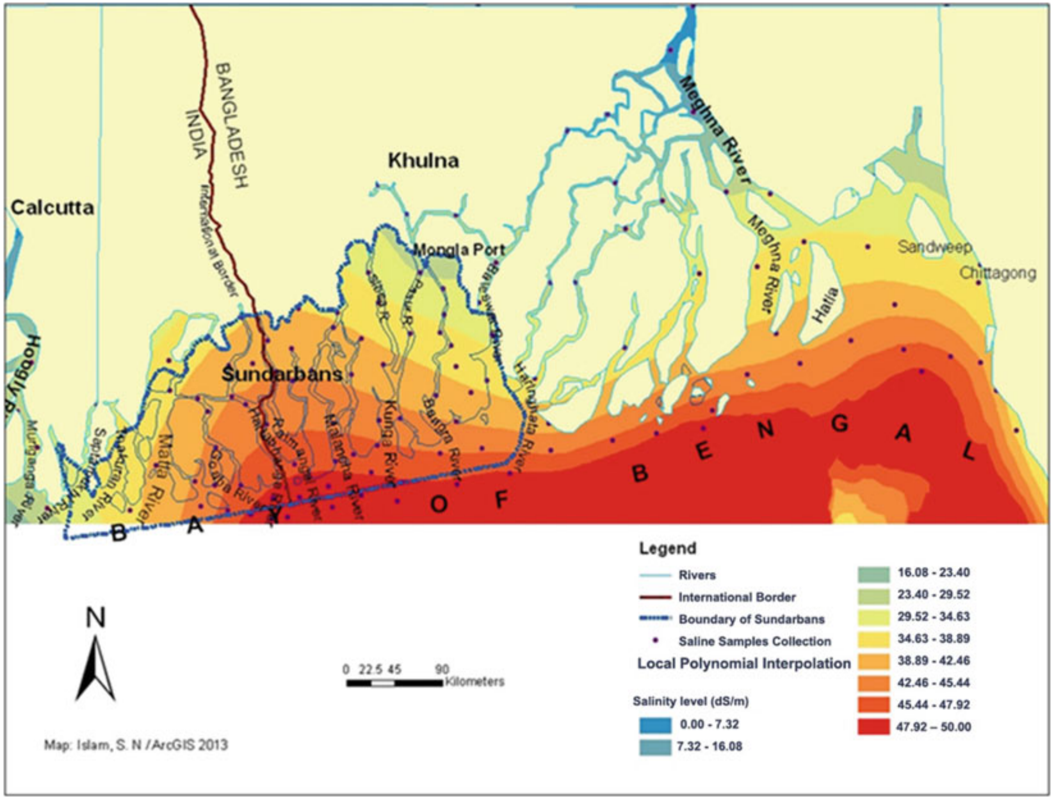

Fig. 2.6 Salinity intrusion pattern in the Sundarbans mangrove deltaic region of Bengal coast. (Source: Salinity model figure was prepared by author through ArcGIS 10.2 in 2013)

(Mohiuddin 2005). Based on a study of ESCAP (Economic and Social Council for Asia and the Pacific) GOB (Government of Bangladesh) has referred six sets of constraints for the development of a strategy for the coastal resource management in Bangladesh (ESCAP 1988).

Policy making includes planning for coastal resources, integrated resource management, coastal wetlands and marine resources sustainability, local environmental ecological perspective, and knowledge on coastal environment and its understanding (Jalal 1988; Akter et al. 2010). The National Water Policy, 1999 (GOB 1999, 2001) of Bangladesh also gives due importance on research and development of knowledge and capacity building for sustainable management. In article 3 of the NWPo, the objective was to develop a state of knowledge and capability that will enable the country to design water resources management plans by itself with economic efficiency, gender equity, social justice and environmental awareness (GOB 1999). In the article 4.15, (GOB 1999) the following specific objectives were not ensured, such as:

- Develop appropriate technologies
- Arrange awareness training and capacity building
- Develop and promote water management, and
- Educate skilled professionals for water resource management

The National Water Policy of Bangladesh provides a guideline framework for the nation. The quality of coastal water resources is dependent on the supply of upstream fresh water supply and its availability in the coastal region (Miah 1989). Sea level rise and tidal inundation factors are also potential issues, therefore some coastal issues such as coastal urban drinking water issue should be incorporated in the NWPo in Bangladesh (Akter et al. 2010).

2.7.2 Degradation of Mangrove Ecosystem and Biodiversity

The salinity investigation results show that the south-west Bengal coastal regions and, within this area, the Sundarbans Natural World Heritage site, is carrying the highest rate of water salinity rise, which is unbalancing the coastal ecosystem and general ecology (Jagtap 1985). According to salinity approximation, this high rate of rise is harmful to rural and urban biodiversity as well as to the urban drinking water (Brown 1997; Islam et al. 2017). The Fig. 2.3 demonstrates the water salinity intrusion trends in the south and south-west region of the Ganges deltaic region, which includes the entire Sundarbans mangroves.

Four major cities and 136 small towns are located in the coastal region, and a major portion of the inhabitants are dependent on mangrove resources in the coastal region. Most of the towns are affected through salinity intrusion and sea level rise impacts in the region as Sundarbans mangroves are also affected due to high salinity intrusion. Therefore, the investigation results of salinity modelling in the South and South-west coastal deltaic regions, including the coastal rural and urban ecosystem goods and services, are under threat and the biodiversity is getting reduced (Costanza 1997; Deb 1997).

Especially, the coastal mangrove and agro-biodiversity loss is a common scenario in the Ganges-Brahmaputra-Meghna Rivers deltaic region between Bangladesh and India (Anwar 1988). The Fig. 2.2 demonstrates the scenarios of the coastal mangrove forest and wetland region in the Sundarbans and its Sundarbans Natural World Heritage Site in Bangladesh. The quality of mangrove forest as well as wetland water and soil are rapidly degrading due to high saline water intrusion and anthropogenic influences (Anwar 1988; Miah 2001; MOWR 2005).

The study also found that the mangrove reduction rate is about 45% in both countries (Bangladesh – India). Deforestation is rising, and land cover is changing due to shrimp farming, salt farming, agricultural land extension, and urbanization extension and settlement development. These development processes adversely affect coastal fish production and lead to a loss of agro-biodiversity and coastal floodplain biodiversity, and of livelihood, which mean to negatively influence 3.5 million people, who are dependent on natural resources in the coastal region in Bangladesh (Anon 1995; Primavera 1997; Wolanski et al. 2009). Almost the entire mangrove forest needs freshwater supply from the upstream. In the Sundarbans Ganges deltaic coastal region, the two potential rivers, such as the Passur-Mongla and Chunar-Munchigannj cause high rate of salinity intrusion. The Fig. 2.3 shows the high salinity intrusion trends in the coastal mangrove forest and wetland region. The salinity model also demonstrates that the salinity trends are much higher in the south-western region of the Sundarbans mangrove wetlands regions (Anwar 1988). The salinity was 30.37 dS m^{-1} in 2003, whereas in 2010 the salinity was 38.32 dS m^{-1} in the Passur-Mongla river point (Joseph 2006).

The salinity penetration in the upstream areas of the coastal zone is one of the main obstacles to maintenance of water quality for drinking, irrigation and fisheries purposes (Grigg 1996; Islam and Gnauck 2009b) as well as for the mangrove ecosystem and biodiversity, in general. Already the coastal mangrove and wetland ecosystems have been recognized as a driving force for biodiversity conservation and coastal urban socio-economic improvement (Nishat 2003; Ahmed and Falk 2008; Islam et al. 2017).

Also, in the Ganges-Brahmaputra rivers deltaic floodplain alone approximately 2.1 million ha of wetlands have been lost due to flood control, drainage, and irrigation development (Khan et al. 1994; Goodbred and Nicholls 2004). Therefore, coastal urban wetlands biodiversity is facing serious challenges from salinity intrusion, environmental changes and anthropogenic impacts (Sarker 1993; Sarker et al. 2003; Nair 2004; Ahmed and Falk 2008; Goodbred and Nicholls 2004).

2.7.3 Degraded Mangrove Ecosystem and Threatened Community Livelihoods

The benefits of mangrove forests serve as diverse habitat for many species, including fish, birds, reptiles, amphibians, mollusks, crustaceans and many other invertebrates (McGarigal and McComb 1999). Mangroves produce little leaf and detritus matter; and the leaves of the mangrove trees are valuable sources of food for animals in coastal waters (Helmer and Hespanhol 1997).

Mangrove is a rich source responsible to create fish diversity and satisfy the local demand. Fishing is a very important issue and activity in the Sundarbans (DoF 2003). The fish production has been reduced since the land use and landscape have been changed, which is not suitable for fish cultivation (Freemark et al. 1996; Daily 1997). At present the area is providing only shrimp and some marine fish species in the offshore area. Up to 80% of global fish catches are directly or indirectly dependent on mangrove wetlands (Fujimoto 2000). The Sundarbans mangrove forest produced an average of 600 tons of nutrients per hectare to provide a great source of natural food in the coastal offshore area (FAP 1996). It is a good service and poles for fish traps. Fish, crustaceans and mollusks can be harvested from mangroves. Aquaculture and commercial fishing also depend on mangroves for juvenile and mature fish species.

Clearance of mangroves in the south-east causes a loss of coastal habitat, aquatic resources, increased erosion, and vulnerability to natural disasters (Nishat 1988). The coastal communities are coping with the threats under reduced resources. The livelihood assets, such as physical asset, financial asset, human asset, natural asset, economic asset, social asset, and cultural and heritage assets were interconnected for maintenance of local coastal community livelihoods (Hossain and Lin 2002; MEA 2003). In general, mangrove vegetation acts as a barrier against damage due to natural disaster. Coastal water resources have been supporting the livelihoods of the poorer sections of society. In one instance, the Gorai River which was used to play a potential role, by enormous opportunities for varies fisheries, aquatic resources, river navigation, and mangrove forest goods and services (Miah 1989; EGIS 1997, 2000), is now fully dead because of anthropogenic activities (Hidayati 2000; Miah et al. 2010). The salinity problem in soil, aggravated by the brackish water shrimp farming introduced, increases beyond tolerable limits for agricultural crops and other vegetation (Adeel and Pomeray 2002; FAO 2007; Miah et al. 2010), thus affecting the livelihood. The river water salinity shows that the upper limit (30–45 dS m^{-1} during the peak period) is beyond the tolerable limits for crops and vegetation (Hossain and Lin 2002; Miah and Bari 2002; Miah et al. 2010).

The most alarming threat to the Sundarbans is destruction of fauna and flora, because 50,000 fisherman and local coastal communities are directly dependent on the mangrove coastal natural resources. Encroachment into the mangrove forest created multifarious impacts on both resources and livelihoods of the local inhabitants. Diverse livelihood activities of the local inhabitants in its vicinity were nearly lost. Attempt is made on building of the remaining reserved forest resources (Miah et al. 2010).

There are not enough initiatives or policies to protect mangrove ecosystems in the south-east coast of Bangladesh. The unplanned policy has created crucial problems on coastal ecosystems and threat for community livelihoods (Peine 1998; Richards and Flint 1991). Especially the coastal indigenous people, who were totally dependent on mangrove resources, are facing critical problem for their livelihoods from natural hazards and cyclones. In Mexico, Nicaragua, Ecuador and Panama the indigenous people in the coastal regions are asking for the protection of mangroves. The demand of mangrove protection is getting popular in India, Sri Lanka, and other parts in Asia Pacific zone too (UNEP 1995). There is an example that the Government of India and Ecuador has banned the further cutting of mangroves for shrimp farms, but in Ecuador, 127.5 $km^2$of mangroves were still illegally cut even after the ban. This type of illegal activities is continuing in many countries, even in Bangladesh. Therefore, a common universal policy and guideline framework is necessary to protect the mangrove forests which will secure the livelihoods of the coastal community (Gopal and Chauhan 2006; Wolanski et al. 2009). Since 1996 afforestation programme is supported by the World Bank and Government of Bangladesh. Several projects: Forest Resources Management Project (FRMP), Sundarbans Biodiversity Conservation Project (SBCP), etc. are in progress. The floral richness is one of the highest in the world mangroves and consists of no less than 123 woody plant species (Dutta and Iftekhar 2004; Gopal and Chauhan 2006). However, in spite of many programmes currently in progress to protect the mangrove ecosystem and the rich biodiversity in Sundarbans across both countries it does not appear to be adequate either to conserve the ecosystem, at the same time, maintain the livelihood of the coastal community.

2.8 Conclusions

Factors damaging the ecology including the rich biodiversity of Sundarbans across both countries, as well as, limitations in the various approaches currently underway for arresting the damage and maintain the livelihood of the coastal community have been discussed. It is amply clear that the issues and problems being trans-boundary in nature are complimentary to each other. What's more, the climate change phenomenon, which is one of the hardest issues to be solved, making the sub-continent increasingly disaster-prone, and complicated over time, is looming large over the entire eco-region. Therefore, what probably is lacking is a holistic and integrated approach covering both countries, wherever possible and necessary, since no individual effort will result in a lasting solution. Following are the immediate suggestions of general nature.

- Mangrove wetland ecosystems have historically been considered as wastelands unworthy of consideration for conservation. As a result, wetlands have frequently been altered or lost because of their ecological functions and values to society not having been understood. Therefore, it should be introduced to the people as a common property in view of its importance and community rights (Rahman and Haque 2003; Rahman 1995; Islam 2007b).
- Based on the present degraded environmental condition, the coastal zoning approach should be included and that could improve land use planning, minimize conflicts over land tenure, and identify appropriate areas for shrimp cultivation, without destruction of mangrove wetlands and the ecology, and those areas need to be protected. There is also need to improve information system to manage and plan for future growth.
- Improvement of the existing mangrove wetland resource related policies, strategies and common conflicts in the areas, where rural communities are dependent on the mangrove ecosystems services, should be understood.
- Capacity building of environmental awareness and development of institutional organizations at international level with legislation rights to regulate all activities should be planned.
- Ensure with short- and long-term strategies planned at the trans-boundary scale for the Sundarbans wetlands eco-region to meet food security for improved livelihood of the coastal community for both countries, and without damage to the ecological balance, in the Ganges-Brahmaputra deltaic landscapes in Bangladesh and West Bengal of India.
- Both countries should show strong political commitments and wills for better management and conservation of the mangrove forest wetlands. An integrated wetland ecosystem management plan and policy guidelines should be developed, based on the findings of several studies, and plan for future studies, if necessary, to address more areas of genuine importance.

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Part II
Societal Transformation and Livelihood Options

Eco-tourism holds prospect with mangrove forest as destination (Courtesy Anil Mistry)

Chapter 3
Transformation of the Sundarbans Eco-region: Lessons from Past Approaches and Suggested Development Options

Anamitra Anurag Danda and Mowdudur Rahman

Abstract Transformation of forests to agriculture is common but the scale of transformation of the Sundarbans under British administration was such that it changed the physical configuration of the region. Post-independence, despite the knowledge that brackish river water is a serious constraint, rice cultivation has been persisted with. Rising population and tidal waters, declining land and productivity, as well as more intense storms are making the already non-conducive situation worse. Options for resilient and sustainable development in the eco-region, therefore, have to be explored beyond climate-sensitive primary production systems. In a biodiversity rich area with a large population, finding resilient and sustainable development options involve direct trade-off. Under such situations Portfolio Decision Analysis (PDA) framework is useful in allocating management actions to pursue options that maximise natural assets while minimising impact on human assets. Based on a hierarchy of objectives and criteria, Multi Criteria Decision Analysis (MCDA) is a valuable tool to decide on options ranging from elevation recovery of forested and inhabited islands, brackish water culture fishery, and tourism, to rapid urbanization in safer locations and planned retreat under 2 °C warming scenario, a very likely prospect at the turn of the century. Given that the currently implemented policies are not strong enough to achieve the pledges governments have made under the Paris Agreement, the article examines tourism in some detail, including jointly managed trans-boundary tourism. Finally, the article examines the challenges in realising the potential of jointly managed tourism in Sundarbans and proposes ways of overcoming the challenges.

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Keywords Sundarbans · Mangrove · Biodiversity · World Heritage Site · Sustainable development · Portfolio Decision Analysis (PDA) · Multi Criteria Decision Analysis (MCDA) · Eco-tourism

3.1 Introduction

The Sundarbans eco-region formed by the Rivers Ganges, Meghna and Brahmaputra is the tidally active lower part of the largest delta in the world consisting of a warren of rivers, creeks, marshes and alluvial floodplain. Morphological zones of this lower part of the delta are the Ganges tidal plain (West) between rivers Hugli and Baleswar, the Ganges tidal plain (East) between rivers Baleswar and Tetulia, and the Meghna deltaic plain stretching from river Tetulia until Chittagong coastal plain. At the confluence of the delta and the Bay of Bengal, is the single largest mangrove patch of the world spread across about 10,000 km^2 of which about 60% is in Bangladesh and the rest in India. This mangrove patch is acknowledged worldwide for its outstanding biodiversity, including the Bengal Tiger, and designated as World Heritage Site in both the countries. This littoral mangrove forest besides serving as the habitat for about 200 tigers, accounting for roughly 5% of the global population in the wild, also imparts protection from storm surges caused by tropical cyclones by attenuating the impact of cyclones that recur on sub-decadal time scales in the Bay of Bengal.

For the purpose of this chapter, the Sundarbans eco-region encompasses the Sundarbans Reserve Forest (SRF) of about 6000 km^2 (including 1397 km^2 of Protected Area) and the Sundarbans Impact Zone (SIZ) in Bangladesh, and parts of Barguna and Perojpur districts outside the SIZ with similar characteristics due to the presence of tidal channels. The SIZ, as defined by the Bangladesh Forest Department (BFD), is the inhabited area within 20 km of the SRF where most of the Sundarbans resource users live. This covers an area of 3641 km^2 (Hussain 2014). In India, the Sundarbans region, designated as Sundarbans Biosphere Reserve, comprises of an area of about 9630 km^2 of which around 4260km^2 is under Reserve Forests (including about 2300km^2 of Protected Area). In totality, the geographical area of this region is about 19,271km^2 with 19% as Protected Area (3697km^2) and 47% inhabited (9011km^2), spread over parts of seven adjoining districts (24-Parganas South and North, Satkhira, Khulna, Bagerhat, Perojpur and Barguna) covering 40 sub-districts encompassing 327 village clusters known as Union Parishad (UP) in Bangladesh and Gram Panchayat (GP) in India with a population of over 7.2 million, largely dependent on agriculture, fisheries and the collection of minor forest produce (WWF 2017) [insert See Fig. 3.1]. To put it in perspective, the eco-region holds about 0.1% of the global population, 137 countries/territories have population less than the Sundarbans, 67 countries/territories are smaller in size, and only 29 nations and territories have a higher population density. The region, therefore, is globally significant not only for the natural area and biodiversity, but also for the number of people who inhabit.

Officially, however, the eco-region is defined somewhat differently. The SIZ, for example, is a 20 km band from the forest in Bangladesh that does not take into account natural features of the inhabited area. On the Indian side, the inhabited part of the eco-region is defined by the extent of forest in the 1830s. There have been significant alterations since that time and 29% of the Gram Panchayats no longer bear the defining characteristics of the eco-region – tidal channels – and could be considered to be outside the eco-region. On the other hand, in Bangladesh, because of the fixed distance from forest, UPs in Upazilas that have tidal channels have been left out, for example, Amtali, Taltali, Baruguna, Patharghata and Bamna in Barguna District, Mathbaria, Bhandaria and Indurkani (formerly Zianagar) in Perojpur District. For a list of UPs and GPs in the eco-region defined on the basis of presence of tidal channels and embankments see Annex 1 of the WWF-India Discussion Paper (WWF 2017).

3.2 Transformation of the Sundarbans Eco-region

Transformation of forests to agriculture is a dominant theme in human history. Currently about half the land on the planet is under agriculture and habitation (Rockstrom and Klum 2015). This transformation was previously associated with revenue maximization and progress but increasingly associated with local and global concern. It is a story shared by many regions particularly the colonized world including the Sundarbans, initially characterised by indiscriminate exploitation of available resources, and human desire for transformation. Later, a new set of values emerged from Europe in the form of scientific forestry and conservation that challenged the notion of unrestricted conversion of forest to agricultural fields that found expression in the actions of the likes of Richard Temple, Lieutenant Governor of Bengal, who assumed office in 1874. Without Temple's active support, the world's single largest mangrove patch might not have been the Sundarbans. "Reclamation is not wanted there [existing forest tracts]. In some places the substitution of rice fields for jungle may be desirable. But in this particular case the ground already bears produce which is more valuable to Bengal than rice" (Sarkar, 2010). Temple's policy resulted in the creation of reserved and protected forest in the eco-region. Sundarbans eco-region today, is the result of two different forces, the reclamation of forests to cropland, and the preservation of the forests for wood products.

3.2.1 Expansion of the Frontier

Historically, the Sundarbans has been a frontier, more in the American sense than in the European sense. According to the American definition, a frontier is described as the border between the settled and unsettled, the "civilized" and the "wilderness" (Turner 1962). The region presented the conditions which allowed a process of

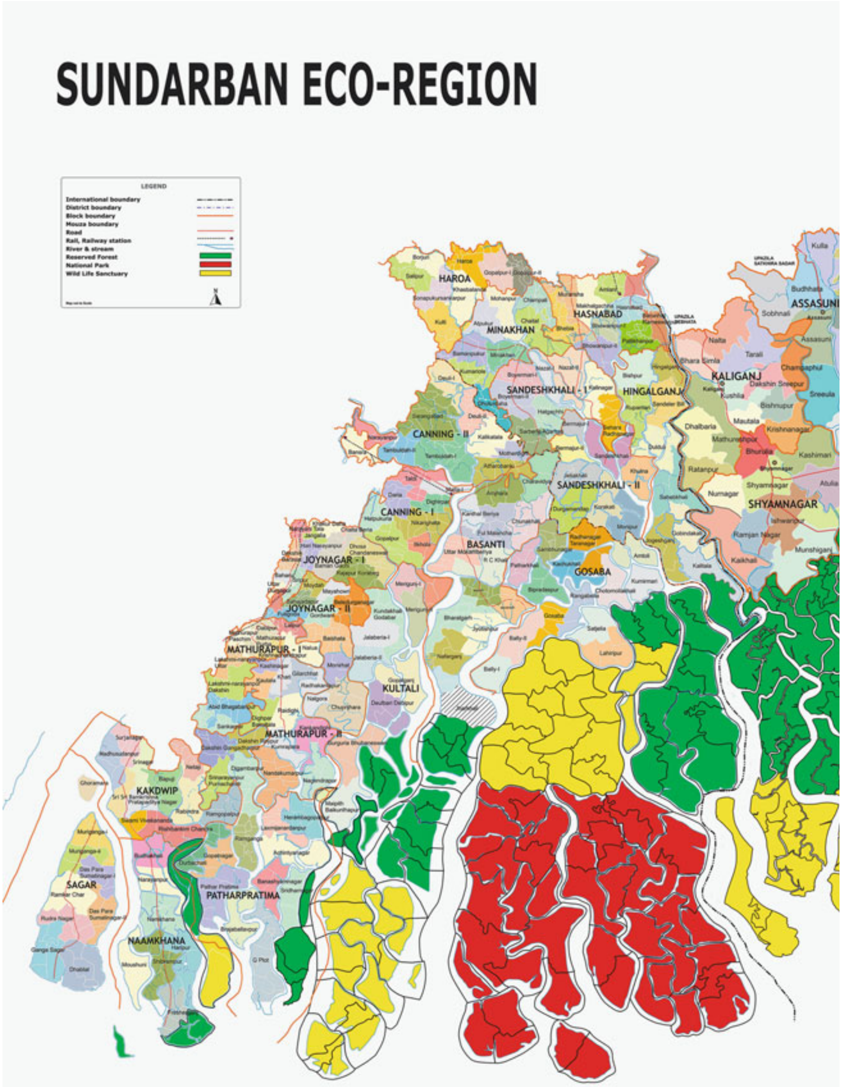

Fig. 3.1 Representational map of Sundarbans eco-region. (Source: WWF (2017) Discussion paper https://www.wwfindia.org/about_wwf/policy_and_research/adaptation__programme_in_the_sundarban.cfm)

continuous advance, both in physical and socio-political terms, and has been the arena for transformation of land, religion and values.

Extension of the frontier into forested Sundarbans began prior to the rule of the Muslim Indo-Turkish Sultans in Bengal from 1204 until 1575 (Townsend 1987). Eaton notes: "…between the thirteenth and eighteenth centuries Muslim pioneers, locally remembered as holymen, not only established the Islamic religion in much of

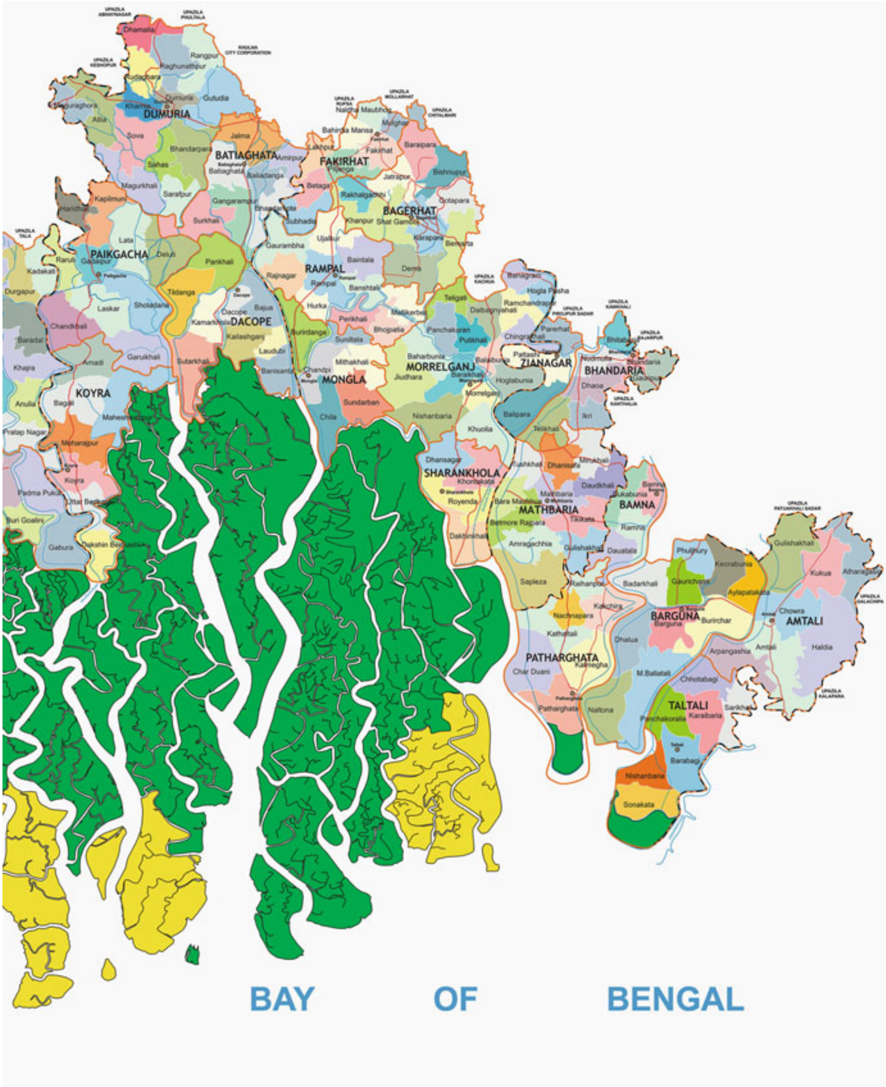

Fig. 3.1 (continued)

south and eastern Bengal, but also played important roles in the intensification of wet rice agriculture, established new modes of property rights, and contributed to a fundamental altering of a natural, forested ecosystem" (Eaton 1990). The Muslim pioneers are believed to have either obtained land assignments from authorities in control of forest tracts or were incorporated within the state when the clearing had progressed to the extent where it was capable of generating revenue (ibid).

The reverence of the holymen continued into the Mughal period as the locals continued converting the Sundarbans forest to wet rice. Even the Hindu Bengali castes living in the Sundarbans of that time prior to the Muslims, the *Pods* in the west, and the *Chandals* (a lower order caste among the Hindus) in the east were strongly influenced in their livelihoods by such figures, converting these fishing castes to agricultural ones. In 1883, James Wise noted that the Muslims consider fishing to be a lowly occupation because of its historical association with non-Muslims and outcasts, who never became integrated into the Muslim society around them. It was not only the Muslims that preferred the farmer to the fisher, Hindu sentiments toward fishing and agriculture paralleled those of their Muslim neighbours; farming was the chosen profession. The cultivator's product, grain, could be easily converted into cash, which the government could tax. As a result, many of those who had previously depended upon fishing for their livelihoods increasingly turned toward cultivation.

This preference for cultivation over fishing continued into the British period. With a keen eye for profits, the British East India Company realized that the Sundarbans, acquired in 1757 with the 24-Parganas, had to be cleared and settled. Transformation of the Sundarbans was initiated under the Collector General Claude Russell in 1770, and operationalized in 1783 by the Magistrate of Jessore, Tilman Henckell (Sarkar 2010).

Confident that increase in revenue could be achieved by bringing uncultivated land under cultivation and sending the produce to the markets of Kolkata (then Calcutta), Henckell applied to Governor General Warren Hastings for granting leases of forests lands directly to settler-cultivators (*ryots*) rent-free for the first 3 years, and at an increasing rate until the seventh year after which the full rate would apply. Between April and October of 1785, Henckell made 144 grants between the rivers Raimangal and Haringhata. Naturally available resources such as timber, firewood, wax, and shell lime were meant to provide the means of sustenance during the period of clearing (Pargiter 1934). To facilitate land reclamation and to prevent *zamindars,* with estates abutting the forest from clandestinely extending cultivation by clearing forests, three outposts were established. These were at Henckellganj, Chandkhali, and Kachua. Henckellganj subsequently came to be known as Hingalganj, now in North 24-Parganas District in India bordering Bangladesh. Chandkhali and Kachua are in Bangladesh; in Paikgacha Upazila of Khulna District, and in Kachua Upazila of Bagerhat District, respectively. Thus, the British government and the Bengalese worked to push the frontier farther south. However, by 1790, 119 grants had lapsed and the scheme was discontinued as profits remained elusive. Sporadic attempts at reclamation continued as did the disputes with adjoining landlords. This was the time when William Dampier and Alexander Hodges were charged with the responsibility of surveying and demarcating all lands brought under cultivation between Permanent Settlement of 1793 and 1828. The Dampier-Hodges line separated the forest and settled lands. This line delineates the Sundarbans Biosphere Reserve on the Indian side.

The first century of British colonial rule in lower Bengal had little impact on the delta. Only 14% of the total area was cleared and cultivated (Hunter 1875). By 1870, there was stagnation in land reclamation and Government's attention was diverted towards preservation of forests.

During the last two decades of the nineteenth century, Bakerganj district, rather than the 24-Parganas or Khulna district, was the area most favoured by settlers. After 1879, a stream of settlers poured into the fertile lands of Bakerganj. Here the conditions for rice cultivation were generally more favourable than in neighbouring districts. Land was higher and better drained. Embankments were required to prevent salt water from flowing into the new fields but they needed only to be of modest height. The waters in Bakerganj streams tended to be less saline, with direct access to the main river. As a result, the district was over 90% occupied and reclaimed in 1904. In parts of the eastern Sundarbans, clearings and cultivation extended almost to the sea face, whereas in the western Sundarbans, around this time, *ryots* (settler-cultivators) were directly being granted land leases after repeated failure of capitalists on Sagar Island.

3.2.2 Legacy of Frontier Expansion

Although clearing of land for cultivation was not new to this part of the world, the British appear to have carried it out at a scale that changed the face of the Sundarbans by altering the physical and geographical configuration of the region. "During the time of Pratapaditya [1561–1611 CE], forests were cleared from land where the delta-building processes had reached some order of maturity...But, during the British rule, even low-lying tracts were occupied ...and circuit embankments were constructed. ... This is the basic difference between the interventions made during these two regimes" (Chakraborty 2005).

As the frontier was being extended into the Sundarbans, deterioration of the forests continued as there was little understanding of the ramifications that would later develop as a result of such an active focus upon cultivation. Within the past three hundred years, the two-horned rhinoceros (last recorded in 1870), the Indian rhinoceros, the golden eagle, and the pink-headed duck, wild buffalo (last shot in 1890), all species indigenous to the Sundarbans, have disappeared (Mukherjee and Tiwari 1984). However, the Sundarbans has the distinction of being the first mangrove forest in the world where scientific management of resources was practised; a Forest Management Division was established in 1869, and the first management plan was implemented in 1892. The forest was administered as a single management unit until 1947, when India was partitioned. The Sundarbans today comprises approximately of 10,000 km^2 of mangrove forest and intricate water channels fringing the river deltas at the head of the Bay of Bengal. Although remaining wetlands left untransformed are probably less than half of the area intact in the late eighteenth century (Sengupta 1972), the Sundarbans is the only mangrove tiger habitat in the world.

3.3 Limitations of Past Approaches and Lessons not Learnt

Sundarbans with its physical features offered a tough proposition to human habitation throughout the ages. Shifting rivers, cyclonic hazards and occasional flooding, despite embankments, and exploits of animals, hindered efforts of clearing forests for cultivation. The situation was clearly non-conducive to long-term settlements leading to prosperity and the blossoming of civilization of a high order (Sarkar 2010). Despite the challenges, wet rice agriculture, essentially *Aman* paddy, sown in May–June and harvested in December–January (almost coterminous with the pre- and post-monsoon cyclone season) was promoted for socio-cultural and economic reasons. For the population, fishing was a lowly occupation irrespective of religious affiliation, and for the East India Company, both the cleared land and the grain was a source of revenue. Timber and wood from the cleared land was a one-time source of revenue as well, until the concept of sustainable harvest was put to practice in the closing years of the nineteenth century.

Conditions for rice cultivation in Bakerganj District of that time were more conducive than elsewhere as land was higher, better drained, and the surrounding water less saline. In other places, low-lying tracts were occupied, and circuit embankments were erected leading to siltation in tidal creeks and sediment starvation inside the embankments (Rogers and Goodbred 2014) creating a gradient difference that would not allow water to drain out of the islands until the lowest level during low tide.

Distress of the subjugated population was of no concern to the Company or the colonial administration barring a few exceptional officials, and distress was common either due to breach in embankments or overtopping of embankments during frequent cyclonic storms. The following example illustrates the distress in times of calamity, the concern for revenue, and the thinking and conduct of exceptional officials.

Sagar Island was leased out to Sagar Island Society, a joint stock company in 1819. The lease was revenue-free for the period 1820 through 1850. Within 10 years, about 13,380 ha of land was cleared and brought under cultivation. A severe storm in 1833 forced discontinuation of agriculture. Concern for revenue prompted salt manufacturing from 1835 until another storm in June 1842 forced commercial salt production out of the island. Repeated storms either in June or in October at sub-decadal frequency inflicted serious damage. The storm of October 1864 destroyed all of the 19,200 ha of agricultural land. This was followed by another storm in November 1867. Severity of the calamity forced the investors out and drew attention to the need for providing means of safety since it was clear that the embankments already erected did not provide sufficient protection (Pargiter 1934).

Soon after assuming office of the Lieutenant Governor in 1874, Richard Temple visited Sagar Island and directed for six revenue-free grants over half of the land that was destroyed. Revenue-free grants incentivised creation and maintenance of protective works geared towards disaster management. Temple directed that in each of the estates a place of refuge consisting of a tank and an embankment terraced inside surrounding it was to be constructed on a specified spot, shown on a plan attached to the deed. The tank was to be of 200 by 150 feet with 16.5 feet high embankment with crest 5 feet broad, and a slope of 3.5:1 outside and 2:1 inside. Embankment was to be properly rammed and turfed. No habitation was to be allowed more than a mile from the place of refuge unless its basement was raised 16.5 feet above ground, and good *bund* road was to be constructed connecting the place of refuge with the habitations on the estate. As cultivation extended beyond the prescribed distance, fresh protective works would have to be constructed (ibid.).

Despite the knowledge that "presence of salt in river water is and will remain a serious constraint to efforts for a fuller and more intensive utilization of the land and human resources of this region" (Sarkar 2010 p. 102), rice cultivation was persisted with and the distress continued. With impacts of climate change becoming more apparent in the eco-region, conditions would become even worse in the business-as-usual scenario. Moreover, nowhere is Temple's prescription of a place of refuge with embanked tank evident.

In 1947, the rulers in the Indian subcontinent changed but the rules did not, much of which still persist. The mind shift that could and should have occurred with independence did not happen. Although in theory, the two nations were no longer driven either by profit or by the need to repatriate revenue, the countries continued to administer the eco-region with similar indifference of the disaffected administration of the colonial past.

Agriculture in the tidally active lower part of the Bengal delta was and continued to be conducted not primarily for the market but for subsistence, mostly through unpaid family labour. This was borne by the fact that the Matla Port that became operational in 1861–62 had to be abandoned in 1870–71 due to lack of traffic and unfavourable weather. During its years of operation, the port received only 84 ships. The railway line to Canning that became operational in 1863 had to be nationalised after 5 years due to extensive losses, the first case in India of a railway being taken over by the state. Although the accounting system of the Indian Railways at present is organized to cater to government budget and control functions and not to shed light on the cost of various activities and services making computation of the losses on various activities difficult, it is common knowledge that all suburban railway lines in India including the Sealdah to Canning line do not make money, yet the Indian Railways at one time partly invested to extend the line across River Matla. Agriculture and naturally available resources (minor forest produce) that was originally meant to provide the means of sustenance during the period of clearing continued to be a means of livelihood for a large section of the population.

Rising population and tidal waters, declining land productivity, as well as more intense storms, is making the situation that was clearly non-conducive to long-term settlements and prosperity even worse. Fuller and more intensive utilization of land and human resources of this eco-region has over the past two and a quarter century been constrained and will be further constrained by rapid relative sea level rise and more intense cyclonic storms on a warmer planet. Options for resilient and sustainable development in the eco-region will have to be explored beyond climate-sensitive primary production systems.

3.4 Way Forward: Towards Sustainable and Resilient Development in the Eco-region

Sustainable development requires managing many threats and risks, including climate change. Because climate change is a growing threat to development, sustainability will be more difficult to achieve for many locations, systems, and populations unless development pathways are pursued that are resilient to effects of climate change.

The links between sustainable development and climate adaptation and mitigation are cross-cutting and complex. First, the impacts of climate change, and ill-designed responses to these impacts, may derail current sustainable development policy and potentially offset already achieved gains. These impacts are expected to affect sectors such as agriculture and fishery; threaten coastal zones; and pose critical challenges to governance and political systems (World Bank 2010; Adger et al. 2011; IPCC 2012). Effects of climate change on key ecological resources and systems can jeopardize sustainable development in systems closely dependent on natural capital as in the Sundarbans owing to lower adaptive capacity (World Bank 2010; Lemos et al. 2013). Second, mitigation has the potential to keep these threats at a moderate rather than extreme level, and adaptation will enhance the ability of different systems to cope with the remaining impacts, therefore modulating negative effects on sustainable development (IPCC 2007).

Third, many of the conditions that define vulnerability to climate impacts and the ability to moderate and adapt to them are firmly rooted in development processes (e.g., structural deficits and available assets and entitlements) (Brooks et al. 2005; Lemos et al. 2013). Indeed, climate change will act as a threat multiplier and will enhance poverty. Fourth, because several of the desirable characteristics of climate responses and sustainable development may overlap (e.g., implementation of no-regrets options, equitable distribution of resources, increased adaptive capacity and livelihood capitals, functioning ecosystems and maintained biodiversity), systems that prioritize sustainable development may be better at designing and implementing successful mitigation and adaptation (Forsyth 2007).

Finally, climate mitigation and adaptation, if planned and integrated well, have the potential to create opportunities to foster sustainable development. Under the threat of climate change, sustainable development depends on changes in social awareness and values that lead to innovative actions and practices, including increased attention to both disaster risk management and climate change adaptation in anticipation of (and in response to) changes in climate extremes (IPCC 2012). Enhancing resilience to response to climate change effects includes adopting good development practices that are consonant with building sustainable livelihoods and, in some cases, challenging current models of development (Boyd et al. 2008). Challenging current thinking and models of development in the Sundarbans is necessary to not only usher in sustainable development but also be future ready in terms of dealing with impacts of climate change on natural and social systems.

In the Sundarbans, the relationship between vulnerability to climate impacts and development is very close and mutually dependent as low per capita income and inequitable distribution of resources; inadequate or inappropriate education, health care, and safety; and weak institutions and unequal power relations fundamentally shape sensitivity, exposure, and adaptive capacity to climate impact. Here, reducing risks that affect resource-dependent communities is necessary but insufficient way to tackle the myriad problems associated with climate change impacts. Building the capacity of individuals, communities, and governance systems to adapt to climate impacts is both a function of dealing with developmental deficits (e.g., poverty alleviation, reducing risks related to food insecurity, enabling/implementing public health and mass education and literacy programmes) and of improving risk management (e.g., alert systems, disaster relief, crop insurance, seasonal climate forecasts, risk insurance) (Mirza 2003; Schipper and Pelling 2006; Warner et al. 2012).

3.4.1 Options for Resilient and Sustainable Development

The options for resilient and sustainable development will depend on either the time horizon or on the future emission scenario. Given that there is no temporal certainty about when temperature thresholds will be crossed it might be prudent to think of the options in terms of scenarios defined by warming levels given that the average temperature in the region is about a degree higher than pre-industrial times, and that the world is locked in for an average decadal temperature rise of about 0.2 °C per decade for the next two decades due to historical emissions irrespective of current climate action and future pathway. Emitted carbon is expected to persist in the atmosphere long enough to prolong temperature increases for thousands of years, long after human beings stop burning fossil fuels or clearing forests.

A Climate Central research (Strauss et al. 2015) has translated global temperature increases from carbon emissions into projections of locked-in long-term sea level rise and puts these projections into context by assessing the current global population living on land that could be submerged. The temperature scenarios that appear logical at this point in time for the Sundarbans eco-region are 1.5 °C and 2 °C. The anticipated inundation due to sea level rise beyond 2 °C appears so severe and widespread that it might not be worthwhile trying to identify options for higher global temperature rise. The image series on projected sea level rise in the eco-region is derived from the sea level tools and analysis by Climate Central for different Global Temperature Rise scenarios (Surging Seas Seeing Choices 2015) (Figs. 3.2, 3.3, 3.4 and 3.5).

These figures are not meant to be used for planning but to inform public discourse and policy dialogues about the future of the Sundarbans post 2100.

Resilient and sustainable development under climate change may be thought of as preparing for, coping with, or adjusting to climate changes and their associated impacts. To be able to do so, in a biodiversity rich area such as the Sundarbans, a methodology needs to be identified that will allow selection of options keeping in

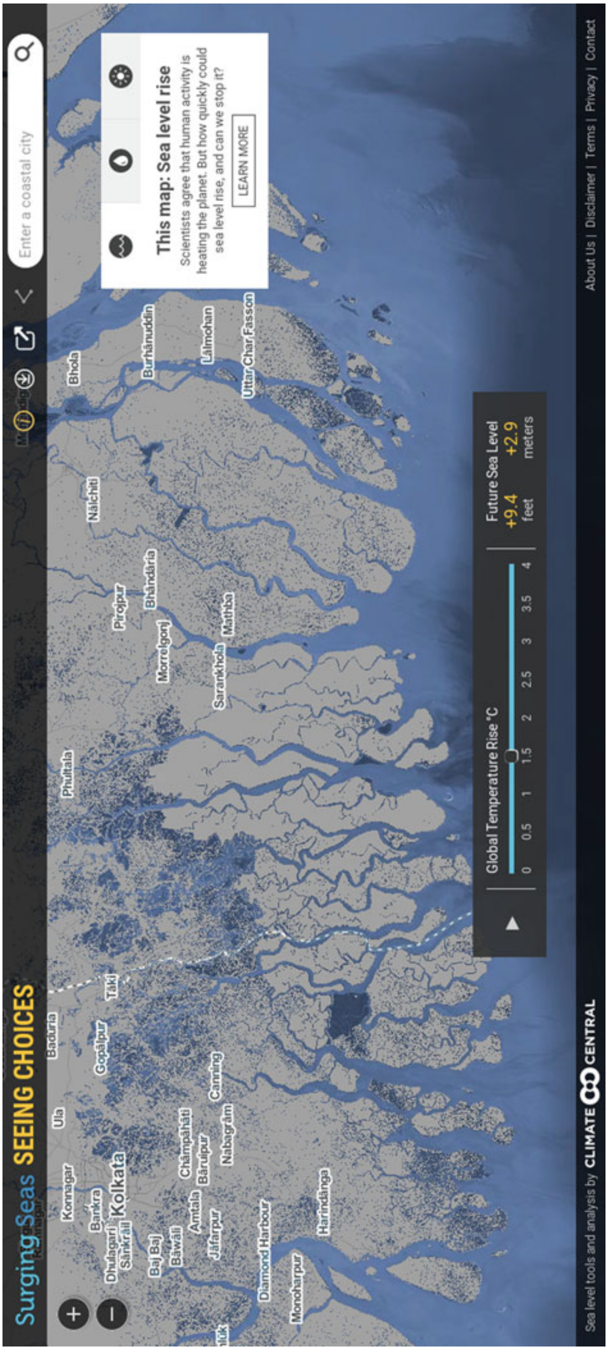

Fig. 3.2 Estimated sea level rise for 1.5 °C temperature rise. (Open access)

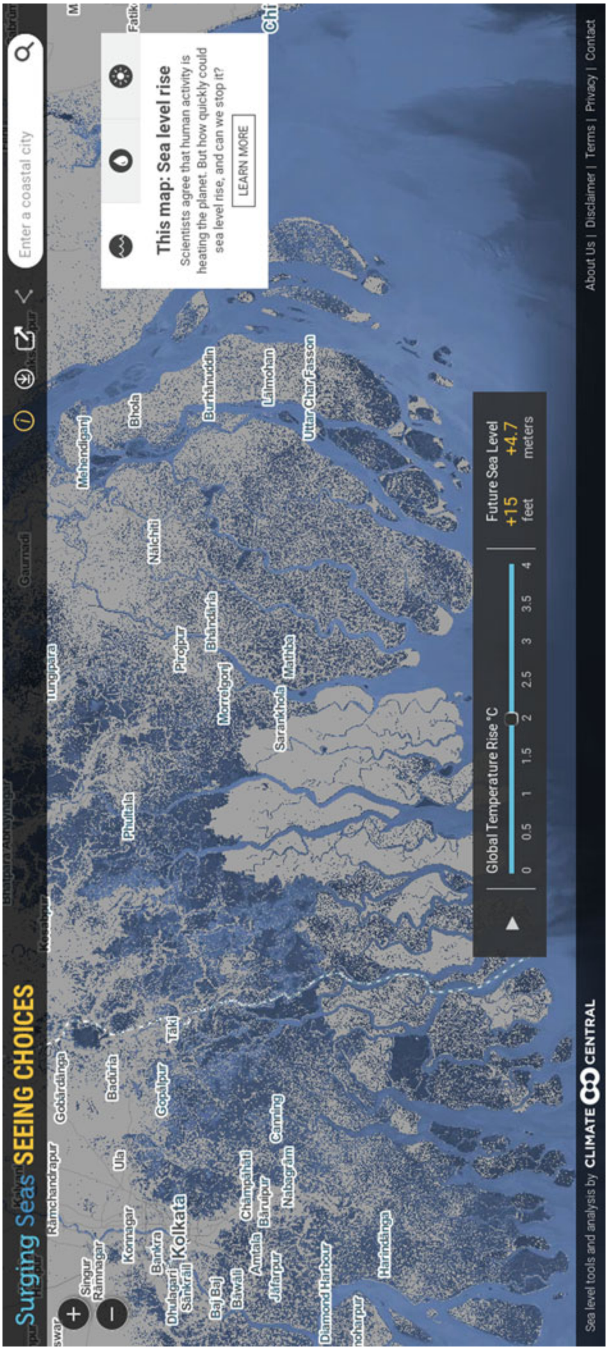

Fig. 3.3 Estimated sea level rise for 2.0 °C temperature rise. (Open access)

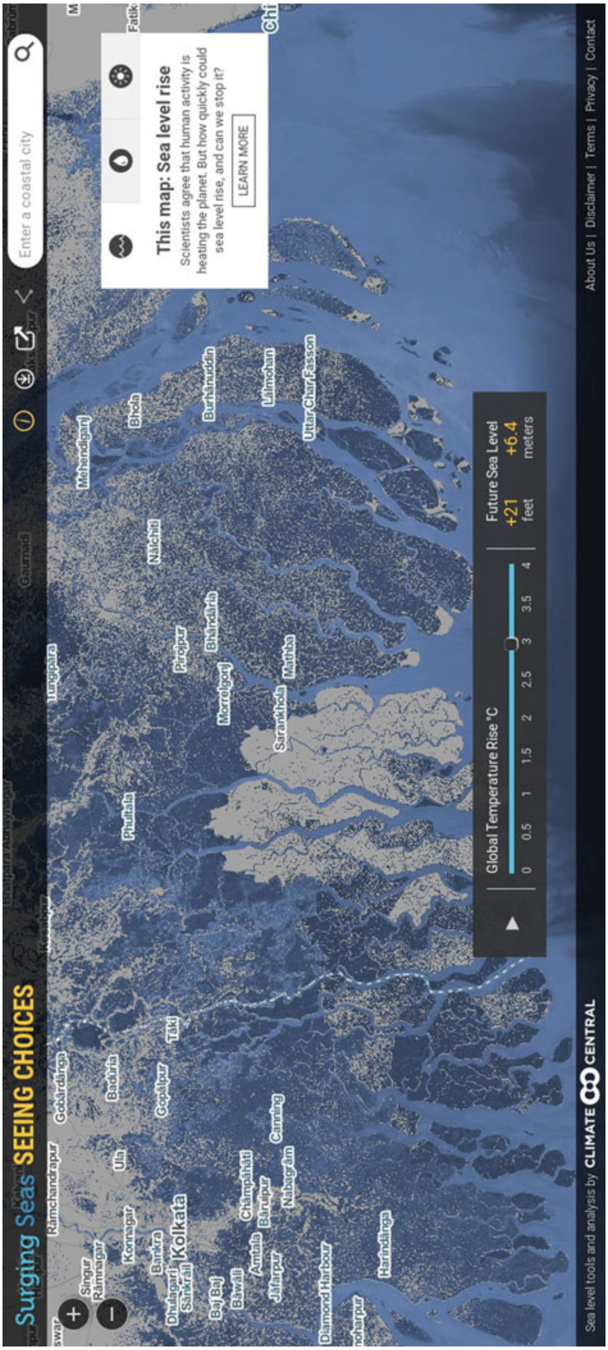

Fig. 3.4 Estimated sea level rise for 3.0 °C temperature rise. (Open access)

Fig. 3.5 Estimated sea level rise for 4.0 °C temperature rise. (Open access)

mind direct trade-off between human activities and biodiversity conservation. The Portfolio Decision Analysis (PDA) framework offers that opportunity (Convertino and Valverde 2013). The approach is similar to optimising financial portfolios, where natural resources and the built environment are considered natural and human assets respectively, and allocation of management actions are either optimised to maximise natural assets while minimising impact on human assets or vice versa. Because the region in question is the Sundarbans, despite the large human population, allocation of management actions is optimised to maximise natural assets. It is accepted that this is a value judgement and that others might wish to maximise human assets while minimising impact on natural assets.

The value of each asset varies over time as a function of climate conditions (sea level rise in this case) and management actions. Venturing into the details of the PDA framework is not intended here but the general steps are mentioned to serve as reference while evaluating the options for resilient and sustainable development. In general, the steps are: (1) identify natural and human assets of interest, (2) determine vulnerabilities of and risks to assets, (3) identify potential management action, (4) quantify the effectiveness value of management actions, (5) determine costs of management actions, and (6) determine an optimal set of management actions given costs and budget constraints. Steps 4 through 6 have been kept out of the ambit of this chapter.

In the case of the Sundarbans, at the broadest level, the assets of interest are the tiger habitat that makes this mangrove patch unique in the world, and the adjoining human inhabited areas. For both the asset categories, vulnerability emanates mainly from sea level rise and the risk is permanent inundation accentuated by the possibility of more severe storms. Regarding protection from storm surges, Odd (1980) mentioned that it would be impractical to build embankments high enough to contain the waters from a peak surge occurring with spring tides. Instead, he proposed that each polder should contain special low lengths of embankments, which could be allowed to spill waters into the polders so that damage caused is reduced. In the villages prone to storm surges on the Arakan coast of Burma, artificial earthen mounds have already been constructed. Cyclones and storm surges, although not preventable, can at least be made less harmful and the suffering they inflict can be considerably diminished by timely action (Khalil 1992).

At 1.5 °C of warming Namkhana, Patharpratima, Hingulganj sub-districts (blocks) in India and Shyamnagar, Koyra and Dacope sub-districts (upazilas) appear to bear the brunt (WWF 2017). A detailed study would allow identification of affected GPs and UPs, and thus identification and quantification of the population at risk. Tiger habitat does not appear to be greatly affected at this stage so as to necessitate management action.

Given that the afore-mentioned description of scenario is decades away and the recorded rates of sea level rise is 18 mm per year at its highest, and elevation recovery if permitted is higher by a factor of 10, elevation recovery in the sub-districts may be possible through controlled embankment breaches. Controlled breaching of embankments has been reported to restore elevation and relieve environmental problems in some sites in Bangladesh but there has not been a detailed scientific study of this process. Post Aila, Polder 32 (Dacope) experienced tidal flooding for 2 years resulting in a mean annual accretion rate of about 18 cm per year. Of course, the sustained human suffering during the process of elevation recovery will have to be addressed. Also, it has to be borne in mind that unless drastic mitigation action is implemented globally, greater inundation is in store at 2 °C of warming towards the close of the century or after.

Multi Criteria Decision Analysis (MCDA) would be a valuable tool to decide whether elevation recovery as opposed to brackish water culture fishery and tourism is a better option, while building homes and public infrastructure on artificially raised land or on stilts, based on a hierarchy of objectives and criteria, each weighted or assigned a measure of relative importance, on the basis of value judgments and/or technical relevance to stated goals (Andersen et al. 2004; Malczewski 2006). Should culture fishery be the more optimal option, retraining the population and concerted support all along the value chain would have to be provided. Also, mangrove regeneration will have to be supported at strategic locations to serve as storm surge barriers.

At 2 °C of warming not only the extent of inundation of inhabited areas is much greater (apparently more in Bangladesh than in India), about half of the tiger habitat on the Indian side and about a quarter on the Bangladesh side would no longer be available for tigers. It may be possible to create large mounds from dredge material in forested and no longer human inhabited areas for tigers to take refuge. The human dimension acquires a much bigger scale in this temperature scenario and planned retreat may be the most viable option. This of course raises questions regarding host locations for the displaced population and their livelihoods. Rapid urbanization and orienting to an urban way of life is possibly the way forward but it has to be carried out in a manner that the well-being of the displaced is improved and that of the host population is not compromised, at the least.

While anticipating the future and preparing for it is necessary, current development deficit needs to be addressed as well. Service delivery is inadequate for the population to be productive up to its potential and the economy small to support the population. Productive potential can be enhanced through better hygiene and health care delivery, and education. Water, sanitation and waste management are crucial for improving public and personal hygiene. These as of now are non-existent and are more of infrastructure requirements. Healthcare and education infrastructures exit but need improvement. In both these sectors the human dimension is of greater significance. The current socio-cultural ecosystem is unattractive for health and education professionals to locate themselves in the Sundarbans and the required ecosystem change is an intractable challenge as of now. The solution then lies in application of technology for bridging the distance.

The main economic activity being rainfed paddy agriculture on degrading and shrinking land, remittances play an important role although it is not enough to transform well-being of the population. Agriculture output has to be and can be doubled provided land can be put to use during dry winter months which is currently constrained due to unavailability of irrigation. Rainwater harvesting has been promoted by the government, but this route cannot meet the demand for all the agricultural land that remains fallow during winter months. Desalinisation of either shallow subsurface water, provided it does not result in greater subsidence, or of creek water, and efficient irrigation could be a set of option, but input costs would be higher and therefore high value crops rather than paddy would have to be promoted. Support for the entire value chain would have to be in place. This will expand the economy but bearing in mind that the region has time between a few to several decades before sea level overwhelms the place, it would then be worth investing in human capital that will provide not only immediate benefits but also in the long run. This has the added advantage of not only pulling people out of poverty but also physically out of a very vulnerable region. The urban places suggested earlier for hosting the displaced population could be the human capital building sites not only for the people of the region but from afar to be financially viable. One of the typical features of comprehensive development in Smart Cities identified by the Ministry of Housing and Urban Affairs, Government of India is giving an identity to the city. For the Sundarbans eco-region, identity of these new habitations could be based on building human capital. In these habitations, homes and public infrastructure should be built on artificially raised land to deal with periodic flooding with rising sea level and more intense storms. Nearer to the coast, conserving and planting trees could create a buffer against storm surges (Schiermeier 2014).

3.4.2 An Alternate Option: Tourism

Tourism in the Sundarbans eco-region is of three types: wildlife tourism, beach tourism and religious tourism. Religious tourism is restricted to Sagar Island in the west where during a particular lunar position in the month of January almost half a million Hindu pilgrims, mostly from North India, visit for a holy dip at the confluence of the Hugli River (revered as the holy Ganges) and the Bay of Bengal. For the rest of the year, Sagar Island hosts insignificant number of religious tourists (visiting the confluence and a shrine connected with the great epic behind the holy dip). Further east, it is Dublar Char (Alor Kol) that receives a large number of Hindu pilgrims around early November. For the period between October and February, fishermen use the island for fish landing, processing and drying. Other religious events in the Sundarbans do not attract visitors in any significant number.

Beach tourism as a standalone segment is not well developed except for Bakkhali in the west. In the east, the various beaches such as Katka are associated with wildlife viewing rather than conventional beach activities or water sports.

Wildlife tourism is the most developed in the Sundarbans and the segment receives most visitors (overwhelmingly domestic) although it is unlike conventional wildlife safari experience. The tiger is the main attraction despite being mostly elusive, and despite the extraordinary richness of the natural area. The way wildlife tourism is conducted in the Sundarbans allows participation of local communities by way of providing boats and on-board services. Most private sector establishments ranging from basic sleeping arrangement for the night to modest resort with modern amenities are on forest-fringe inhabited islands on the Indian side. Establishments with basic arrangements are usually locally owned and managed, thus accruing benefits locally but the establishments with better facilities are not locally owned and seldom locally managed although it generates employment for the people in its immediate vicinity. The basic establishments procure most of their supplies locally, but the better ones are able to procure at most 70% of their supplies locally after conscious efforts. In general, this figure would be lower and not all procurement would be local produce.

Given the spate of seasonal migration from the Sundarbans region it is evident that agriculture and fishery as means of livelihood under current circumstances do not promise much in terms of attaining sustainable development goals in the region, nor are the enabling physical conditions in a state to usher in large-scale economic uplift of the people. Although tourism conducted responsibly has the potential to offer market linked economic incentives for conserving bio-cultural diversity and generating a source of revenue for local communities, as of now neither are the benefits accruing to local communities large enough nor are the number of beneficiaries significant in proportion to the population of forest fringe villages. This is primarily because of low revenue from day trippers who constitute the bulk of visitors to the Sundarbans. Overnight visitors, unless naturalists or novelists, spend 2–3 nights at the most, on board or on land-based facilities. For tourism to be transformative, it has to be conducted responsibly on low volume-high value model and take advantage of trans-boundary opportunities. Tourism circuits could be developed in a way that the itinerary begins in Kolkata or Dhaka, covers areas of tourist interest in these metropolitan areas and includes not only natural areas in the Sundarbans but also religious and cultural sites. These will need far reaching institutional changes discussed in a subsequent section.

3.4.2.1 Responsible/Sustainable/Eco-tourism

Tourism as an economic activity cuts across many sectors, levels and interests. These range from the hotel industry to National Parks authorities, from tourism boards to government departments, and from tour operators to conservation organisations, as well as the host community. The various interests involved can be grouped into four categories: the host population, tourist guests, tourism entrepreneurs/organisations, and the natural environment. Tourism is a powerful economic force in the development of both community-based and global markets. Despite its economic significance, debate continues whether or not tourism truly benefits all entities. Tourism can maximise positive returns to a community's overall growth while minimising the costs to the environment and culture, provided all parties or stakeholders interested in or affected by this business within a particular market or community collectively manage the sector and adhere to a commonly agreed Code of Conduct. However, the relationship between tourism development, socioeconomic development and the environment is circular and cumulative. While safeguarded environment and improved infrastructure results in continued tourist arrivals resulting in relatively improved standards of living due to tourism earnings and better infrastructure, it also places additional pressure on the environmental resources upon which the entire system rests. Globally, the experience has been that initially there is snowballing in economic terms and later of degradation of the environment jeopardising future interests of tourist and host populations as well as those of tourism organisations, unless sustainably managed.

Responsible tourism would amount to developing tourism in a way that it benefits the local communities, strengthens the local economy, employs local workforce and, wherever ecologically sustainable, uses local materials, local agricultural products and traditional skills. Tourism activities should respect the ecological characteristics and capacity of the local environment in which they take place. All efforts should be made to respect traditional lifestyles and cultures. Also, mechanisms including policies and legislation should be introduced to ensure the flow of benefits to local communities. Government mandated limited benefit sharing is already in operation in the eco-region. On the Bangladesh side, 76 forest-fringe villages are allocated 50% of gate receipts while on the Indian side, 46 forest-fringe villages receive 25% of gate receipts.

Unfortunately, in majority of the works published under the banner of sustainable tourism, much of the detail of sustainability remains hidden behind the rhetoric of balance, or obscured by a variety of labels, such as ecotourism or alternative tourism, which may amount to little more than an attempt to give the impression of environmental stewardship. Therefore, to ensure true sustainability, it is vital that the local population is involved in the management of their tourism resources and that the local population benefits directly from the utilisation of these resources.

Central to sustainable tourism development then, is the issue of how to manage the natural, built, and socio-cultural resources of host communities in order to meet the fundamental criteria of promoting their economic well-being, preserving their natural and socio-cultural capital, achieving intra- and inter-generational equity in the distribution of costs and benefits, securing their self-sufficiency, and satisfying the expectations of tourists.

3.4.2.2 Natural and Socio-cultural Capital

Sundarbans is known for its natural capital and multiple sites under the jurisdiction of the respective Forest Directorate are open to tourists. There are at least 21 sites that can be offered for beach tourism, mangrove tourism, nature and wildlife trails, historical and archaeological tours, besides watch towers for viewing tigers (Table 3.1).

There are at least two small interesting museums in the Sundarbans region maintained privately. An archaeological museum is in Canning Town and a natural history museum is in Mongla Town. Relics of earlier settlements going back several centuries can be found in several places in the forests and inhabited places that are not on tourist radar but are potential sites. Some of the more prominent ones are

Table 3.1 Potential sites for jointly managed tourism in the Sundarbans

Sl. No.	Site	Location	Attributes/what to expect
1	Jambudwip	Namkhana Block	Ecological succession. Formerly a fish landing and drying site. Boat ride in open waters
2	Fraserganj and Bakkhali	Namkhana Block	Beach, fishing harbour, wind turbines
3	Lothian WLS	Namkhana Block	Widest mangrove diversity in Indian Sundarbans trails
4	Bhagabatpur	Patarpratima Block	Crocodile project and mangrove interpretation centre
5	Kalas Forest Camp	Patarpratima Block	Watch tower
6	Bonnie Forest Camp	Kultali Block	Watch tower
7	Dabu Tourist Spot	Canning I Block	Riverside tourist spot with possibility of historical tour of port canning
8	Jharkhali	Basanti Block	Tiger Rescue Centre
9	Sajnekhali	Gosaba Block	Mangrove interpretation Centre and River terrapin breeding centre
10	Sudhanyakhali	Gosaba Block	Watch tower
11	Dobanki	Gosaba Block	Canopy walk
12	Netidhopani	Gosaba Block	Watch tower and ancient temple
13	Burirdabri	Hingalgunj Block	Cage trail
14	Mandarbaria sea beach	Shyamnagar Upazila	Wildlife trail
15	Dobeki Eco Park	Shyamnagar Upazila	Watch tower
16	Kolagachia Eco-tourism Centre	Shyamnagar Upazila	Forest trails
17	Nilkomol or Hiron Point	Koyra Upazila	Watch tower
18	Harbaria Ecotourism Centre	Mongla Upazila	Wooden watch tower
19	Katka Observation Tower	Sarankhola Upazila	Watch tower
20	Koromjol Eco-tourism Centre	Dacope Upazila	Crocodile breeding centre
21	Jamtala Sea Beach	Sarankhola Upazila	Watch tower

Source: Authors

Shat-Gambuj Mosque near Mongla, Shekher Bari Kali Temple south of Khulna on River Sibasa, and Jatar Deul near Raidighi in Mathurapur Block II.

Socio-cultural events associated with religious figures and agrarian production cycles are widespread in the region. As yet these are untapped tourism opportunities barring a couple such as Ganges Sagar Mela in mid-January on Sagar Island and Raas Mela on Dublar Char in early November.

3.4.2.3 Challenges in Realising the Potential of Jointly Managed Tourism in the Sundarbans

Although ecotourism seeks to increase opportunities there are no automatic benefits associated with ecotourism; success depends on good planning and management. In the absence of good planning and management, opportunities remain unrealized and benefits do not accrue, and unavoidable threats turn into cost. Multiple challenges need to be overcome to not only realise the potential of jointly managed tourism in the Sundarbans but also to make the operations sustainable in terms of the fundamental criteria of (a) economic well-being of the local population, (b) preserving natural and socio-cultural capital, and (c) satisfying tourist expectations. These are discussed below.

1. Visitor experience: Because of tigers in the Sundarbans the region got promoted as a destination for tiger tourism which completely misses the point that this is a unique tiger habitat with the most diverse mangrove vegetation anywhere in the world where tiger sighting is a matter of chance more than anywhere else. Unending boat ride is the predominant visitor experience in the Sundarbans with short walks from the jetty to watch tower except at Kolagachia Ecotourism Centre where tourists are permitted to walk inside the forest. From the boat, one only sees the forest edge unlike terrestrial forest safaris where one is inside the forest. Wild animals can be seen during low tide while during high tide, partially submerged forest edges are visible with the rare exception of tiger swimming across creeks. Narrow creeks are out of bound for tourist boats. For most visitors this is an uninteresting visual after the first few hours, and inability to sight a tiger results in disappointment. The challenge is to break the monotony by involving tourists in diverse range of activities and introducing them to the rich floral and faunal diversity.
2. Tourist accommodation: On the Indian side, land-based and on-board options are available mostly ranging from basic to modest. On-board options are constrained by space and supply of freshwater if visitors are in groups. The lay of the land is such that while on land-based accommodation view of the natural area is cut off due to very low elevation of the inhabited islands and circuit embankments, as well as location of the facilities except at Sajnekhali but here too the view is away from the forest.

3. Institutional challenges:
   (a) Competitive use of freshwater/groundwater is an area of concern that needs to be resolved if tourism is to become a major driver of the economy. The population of the Sundarbans region depends on groundwater for cooking and drinking. As of now the same resource is used by tourist facilities mostly for bathing and flushing toilets. This is ethically problematic and solutions for cleansing have to be found to cater to tourists. Also, withdrawal of groundwater irrespective of purpose in a sinking delta hastens sinking and alternative freshwater sources need to be identified and promoted.
   (b) Forest administration is not geared to facilitate tourism at scale either in terms of capacity or in terms of infrastructure. Facilities need to be upgraded, trails need to be identified, designed and managed in a way that it enhances tourist experience, optimizes visitor circulation, as well as ensuring that the habitat is not compromised.
   (c) Border crossing: For trans-boundary tourism, border crossing needs to be facilitated without losing sight of security issues and it necessitates novel solutions for trans-border movement of tourists and tour operators. As of now Hemnagar on the Indian side and Angtihara on Bangladesh side have immigration and customs facilities but these are meant for freight vessel movement under Protocol of Inland Water Transit & Trade (PIWTT).
   (d) PIWTT: While the Protocol provides an opportunity, in its current form, it is unlikely to be helpful for tourism for various reasons. The Protocol does not allow trans-border movement of vessels that are popular with tourists (launch and engine boat), vessels are allowed to travel along specified route with specific port of call (Chalna for example), and specific sites for replenishment. An evaluation of the utility of the modified PIWTT for tourism as opposed to a subsidiary agreement or even a fresh protocol for trans-border tourism would be useful.

3.4.2.4 Way Forward to Overcome the Challenges

1. Foremost is a marketing campaign to promote Sundarbans as a mangrove tourist destination. This will not only inform potential tourists of the rich biodiversity but also shape their expectations. Moreover, visitors' experience can be enhanced significantly by developing micro-circuits along the Protocol route and by incorporating sites of tourist interest in the metropolitan areas of Kolkata and Dhaka. The micro-circuits should be designed in a manner that it provides a mix of experiences and is not solely dependent on wildlife sighting. Historical sites, pilgrimage sites, natural sites, and adventure sites would add to enriching the visitor's experience. At the forest fringe, there are 17 Gram Panchayats and 25 Union Parishads, parts of which could be developed for catering to tourists, particularly those parts that are increasingly becoming unsuitable for conventional livelihood activities such as paddy agriculture. These could be turned into woods or wilderness zones, leisure zones, culture zones and adventure zones.

Live mangrove interpretation centres could be developed and maintained through direct tourist participation. Water adventure sports could also be promoted in areas that are not only safe for tourists but also outside critical ecological areas including tethered paragliding and ballooning. Jointly managed tourism in the Sundarbans should not necessarily be long trips spread over several nights and days but provide opportunity for trans-border short trips, even day trips.

2. Overnight trips should be so managed that tourists do not spend two nights at the same location. This will not only spread economic benefits more widely but also eliminate the possibility of making the location uninteresting to tourists. For example, a combination of land-based, on-board, and in cottages built on barges either stationary or slow moving could be thought of. The land-based accommodation should be meant for experiencing agrarian life and socio-cultural heritage, and trips to mangrove and water adventure sites, on-board accommodation should be meant for trips to distant watch towers to experience wildlife with the possibility of experiencing the tranquillity of narrow creeks and otter fishing on small country boats, whereas cottages on barges tethered close to forest should be bereft of electric lighting and humming of equipment and meant for experiencing the sight and sound of forest at night. All accommodations should meet high hygiene standards and promote local cuisine made of local produce.
3. Regulations need to be in place so that groundwater is not tapped for tourist operations. Instead, technological solutions, such as atmospheric water generator and brackish water desalinization must be mandated and incentivised. This has the additional advantage of freshwater availability in times of calamity due to high intensity weather events. Commercial scale solutions are already available from Watergen and GAL Technologies among others.
4. As of now the Forest Departments make their facilities for monitoring and enforcement available to tourists. This need not be the case. Instead, the Forest Departments should make sites available and stipulate norms such as daily footfall and permitted infrastructure and activities that tourism entrepreneurs can develop on a concessionaire model with defined obligations towards local communities. These obligations could be in the form of building community preparedness for disasters and providing emergency services to predefined adjacent communities.
5. The passport is a globally accepted travel document, but governments routinely accept various other documents as valid travel documents such as crew manifest prepared by the freight vessel owner in case of PIWTT. To realise the transformative tourism potential of the Sundarbans the two countries need to think of novel ways of facilitating trans-border movement of tourists. For example, a group of Indian tourists from Kolkata wishing to make the trip only up to Hiron Point now have to undertake a journey northward for land border crossing at Petrapole/Benapole, and then travel south until Hiron Point and retrace the route. Similarly, for Bangladeshi tourists from Khulna wishing to make the trip only up to Sajnekhali have to avail the same land border crossing point. Subject to political willingness this can be avoided by allowing tourists to travel with accredited tour operators who prepare the tourist manifest based on normally accepted identity and address proofs. The tour operator then files the requisite

information regarding number and identity of tourists, destination, route and electronically tagged vessel with the designated authority within a stipulated time prior to departure for clearance. There is no harm done if the vessel crosses international boundary so long credentials are verified at the pint of origin (at departure and return) and destination (on arrival and before departure) by designated state officials manning the points of origin and destination. For longer trips culminating in Kolkata or Dhaka, it might be prudent to continue with the normally accepted passport control and visa procedures.

6. The PIWTT was agreed upon with a view on transit and trade and using the same protocol and route for tourism is unlikely to yield desired results. A separate agreement might be better suited or modification of the Protocol to cater to the needs of the tourism industry might serve the purpose. Either way, first and foremost passenger vessels will have to be permitted and not restricted to barges. Smaller, certified, electronically tagged and surveillance compliant passenger vessels should be permitted. An electronic vessel monitoring system (VMS) needs to be agreed upon and put in place so that passenger vessel movement is unrestricted except for electronically fenced off zones.
7. Finally, a jointly managed Sundarbans tourism regulatory framework needs to be agreed upon and implemented so that economic well-being of the local population is served. Economic well-being needs to be defined so that benefits that accrue are transformative and not incremental. Design and implementation of the regulatory framework has to be such that natural and socio-cultural capital are undiminished, and that tourist experience is uncompromised. The regulatory framework has to be jointly developed not only by state parties but also tour operators and investors, community representatives at appropriate level (Block/Upazila or even Gram Panchayat/Union Parishad), and conservation organizations of the two countries.

Globally several examples of sustainable and trans-border tourism exist that can be studied in detail so as to incorporate elements in design and implementation of regulatory framework and practice of tourism. Some of the examples that showcase one or more of the fundamental criteria of sustainable tourism are Galapagos Islands (Ecuador), Kakadu National Park (Australia), Masai Mara (Kenya, Tanzania), Wadden Sea World Heritage Site (Netherlands, Germany), Waterton Glacier International Peace Park (USA, Canada), and the Great Limpopo Trans-frontier Park (Mozambique, South Africa, Zimbabwe).

3.5 Conclusions

Review of societal transformation in the Sundarbans eco-region with intervention from administration time-to-time in respect of use of various professional practices over ages and lessons learnt therefrom showed interesting insights into their prospects and sustainability in as far as livelihood security was concerned. Climate change has been and is likely to complicate the prospects in future threatening the livelihood security. For instance, transformation of forests to agriculture was common, but in view of the knowledge that brackish river water was a serious constraint, rice cultivation was persisted with since independence. Rising population and tidal waters, declining land and productivity, as well as more intense storms made the already non-conducive situation worse. It is strongly suggested, based on the lessons learnt to explore newer development options for livelihood security, this time in non-farm sector. Thus, although ecotourism with mangrove destinations, preferably on transboundary mode, seeks to increase opportunities to a significant note, there are no automatic benefits associated with ecotourism; and the success depends on joint exercise desired on good planning and management.

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Part III
Forestry, Mangroves and Biodiversity

Mangrove forest under high-tide (Courtesy R. N. Mandal)

Chapter 4
Current Status of Mangrove Forests in the Trans-boundary Sundarbans

R. N. Mandal, Peter Saenger, Chandan Surabhi Das, and Abdul Aziz

Abstract Sundarbans is the largest single block of mangroves forest in the globe, stretching over both India and Bangladesh. The entire land mass is situated in the estuary of Ganges-Brahmaputra-Meghna (GBM) river systems that carry the world's largest sediment load to the Bay of Bengal. The present article reviews the environmental characteristics and biological diversities of the Sundarbans in general and the present status of mangroves in particular. Environmental factors such as hydrology, topography, texture of substrata, salinity and their interactions cause to develop a wide heterogeneity in the mangrove ecosystems that support to nurture a great biodiversity. Mangrove diversity comprises a total of 45 species and 21 species more considered as under-canopy vegetation. All these intertidal flora have made the Sundarbans a unique habitat in which a diverse range of biota, including flora, fauna and microorganisms have been part of this ecosystem that renders staggering services to coastal inhabitants, which have been enumerated. Thus, the values of mangroves are classified in view of a wide range of benefits harnessed out of ecosystem services. The spatio-temporal changes highlight the rate of degradation or loss of forests in last two decades. The tropic pathways of mangrove ecosystem exhibit how leaf litter enriches the productivity of the Sundarbans forests. In this perspective, the present article suggests that the joint efforts are required from both India and Bangladesh to protect and preserve such incredible natural resources.

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Keywords Sundarbans · Mangroves · Diversity · Environment · Ecosystem · Spatio-temporal changes

4.1 Introduction

> *There are no borders here to divide fresh water from salt, river from sea. The tides reach as far as three hundred kilometres inland and every day thousands of acres of forest disappear underwater only to re-emerge hours later.* ('The Hungry Tide' – by Amitav Ghosh (2004))

Sundarbans–the euphony has its genesis. The name is derived from the Bengali vernacular 'Sundari'/'Sundri' of a tree species, *Heritiera fomes* Buch Ham., a dominant constituent of the Sundarbans mangrove forest (Prain 2003). Literally, 'Sundari' means beautiful. Folklore holds that the Sundarbans was initially coined as 'Samudraban'. The Bengali words, 'Samudra' and 'Ban' mean sea and forest, respectively, which indicate forest within the sea. Later, Samudraban is believed to have been modified as 'Sundarbans' in the course of time. In the *East India Gazetteer,* Walter Hamilton called it 'Sunderbunds' meaning the 'Forest of the 'Soondry', now spelled 'Sundri' meaning beautiful (Aziz and Paul 2015). Folk literatures also suggest that 'Sundarbans' was derived from two words such as beautiful forest which means 'Sundar' and 'Ban' respectively (Naskar 2004); because this inter-tidal forest along with a long stretch of water bodies is of a spellbound beauty. People nurture the idea that the Sundarbans means mangroves forest. UNESCO declared the Indian Sundarbans a 'World Heritage' site in 1987 and the adjacent Bangladesh Sundarbans in 1997.

4.2 Etymology of Mangroves

The etymology of the English word 'mangrove' has been variously defined. The Oxford dictionary mentions the word 'mangrove' as tropical trees growing in mud or at the edge of rivers, which have roots rising above ground. The term 'mangrove', considered to be the individual plant or tidal forest, refers to both 'Mangrove plants' and 'Mangrove ecosystem' (MacNae 1968). Chapman (1976) used the term 'mangrove' for intertidal plants, and he termed the plant communities as intertidal forests, mangrove ecosystems or 'mangal'. The term 'mangal' was also commonly used in French and in Portuguese to refer to both forest communities and to individual plants. The Americans, the Spanish, and the Portuguese used the term 'Mangle' and 'Mangue' indicating trees and shrubs of the genus *Rhizophora* (Mepham and Mepham 1984). Mangroves constitute intertidal plant communities growing in the sheltered tropical and subtropical coastlines (Davis 1940; Aubreville 1964; MacNae 1968; Blasco 1975; Clough 1982; Saenger et al. 1983; Tomlinson 1986; Naskar and Guha Bakshi 1987; Naskar and Mandal 1999; Mandal and Naskar 2008). They have been variously described as 'coastal woodlands', 'mangals', 'tidal forests' or 'mangrove forests' (Saenger 2002). However, tidal limits vary in the different mangroves habitats.

4.3 Genesis and Origin of the 'Sundarbans' Delta

Formation of the Bengal basin wherein the present-day Sundarbans mangrove forest exists was initiated as early as 126 million years before present (BP) with the start of Alpine Himalayan Orogeny (McDowell 1995). Considered as a primitive 'Proto-delta', initial landmass building continued up to 49.5 million years BP. The proto-delta experienced a strong regression of the sea and the coastline shifted southwards attaining almost the present-day configuration. Consequently, an incomplete 'Transitional-delta' was formed during 49.5–10.5 million years BP. Later, the transition delta reached the present shape of 'Modern-delta' some 10.5–4.5 million years BP through rapid deposition (Sanyal 1999).

Active sedimentation began on the fan, and rates continued to increase over the next several thousand years to ca. 15,000 year BP (Weber et al. 1997). A growing stratigraphic and geochronologic data base from the Bengal basin through 50 boreholes and 71 radiocarbon dates helped explain the depth and timing of late Quaternary Ganges-Brahmaputra fluviodeltaic deposits (Japan International Cooperation Agency 1976; Banerjee and Sen 1987; Master Plan Organization 1987; Umitsu 1993; Hait et al. 1996; Goodbred and Kuehl 2000). Development of the Ganges-Brahmaputra delta began ca. 11,000 year BP. During early delta formation from ca. 11,000–7000 year BP, river sediment flux was sufficient to counter the rapid sea-level rise, thereby trapping most of the river's discharge on the inner margin (Goodbred and Kuehl 2000). The sediment flux led to 50 m vertical aggradations and thus flooded the Bengal basin (Goodbred and Kuehl 2000). By the middle Holocene, decelerating sea level rise facilitated subaerial delta progradation and development of a subaqueous delta on the shelf (Kuehl et al. 1997). From ca. 7000 year BP sea level rose very slowly and was virtually stable by 2000 ~ 3000 year BP (Pirazzoli 1996). The present age of Sundarbans mangroves can be dated as 3000 year BP. During sixteenth to eighteenth Century the Bengal basin tilted eastward along a 'Hinge zone' starting from Sagar to Malda and curving towards north of Dhaka, resulting in a raise of the western part of the delta and dissociating ancient branches of the Ganges from the present Indian Sundarbans (Sanyal 1983, 1999). This alteration caused reduced freshwater flow which resulted in increasing salinity (Chaudhuri and Choudhury 1994).

Importantly, the Ganges-Brahmaputra-Meghna (GBM) river systems carry the world's largest sediment load to the oceans (Coleman 1969; Milliman and Meade 1983; Milliman et al. 1995). Morgan and McIntire (1959) mentioned that the Bengal Basin tilted towards the eastern side due to Neotectonics movements between the twelfth and fifteenth century AD. During the sixteenth century, the Ganges shifted its course eastwards and joined the Brahmaputra (Deb 1956; Blasco 1975; Snedaker

1991) and the combined river system (Ganges and Brahmaputra) tilted further eastwards to merge into the river Meghna during the mid-eighteenth century (Williams 1919; Snedaker 1991). The tectonic activity that continued shifting eastwards had great impact on the hydrology of the Sundarbans delta due to deposition of a huge amount of sediment loads and changes of freshwater flows. In this natural process, the western side (Indian part of the Sundarbans) was deprived of receiving a substantial amount of freshwater as compared to freshwater amounts flowing in the rivers of the Bangladesh part of the Sundarbans (Gopal and Chauhan 2006). Most of the distributaries, which were earlier connected to the river Hooghly (lower stretch of river Bhagirathi), are now severed due to large scale urbanization around the Kolkata city (Mandal et al. 2009). In effect, their lower stretches are fed with strong tidal saline water which is only diluted when rain falls during the monsoon (Cole and Vaidyaraman 1966). Chakrabarti (1995) suggested that mangroves play the dominant role as geomorphic agents in the evolution of such a tidal inundated landmass. Nevertheless, the cumulative effect of all these factors has great influence on the diverse form of vegetative structure of mangroves forest spread over the numerous rivers mouth of the transboundary Sundarbans.

4.4 Geographical Identity

The trans-boundary Sundarbans lies between latitudes as 21°27′30″N and 22°30′30″N between longitudes 88°02′00″E and 89°53′13.93″E, stretching from the Baleswar River of Bangladesh in the east to the Hooghly River of West Bengal in the west (Fig. 4.1).The total area covers approximately 10,000 km^2, of which about two-third area falls in Bangladesh and one-third in West Bengal, India. Within Bangladesh,the Sundarbans covers a geographical range between latitudes 21°38′10.18″ and 22°29′51.65″N and longitudes 89°02′22.87″E–89°53′13.93″E from Harinbhanga and Raimangal River in the west to Baleswar River in the east. Within India, the Sundarbans covers a geographical range between latitudes 21°27′30″N and 22°30′30″N and longitudes 88°02′00″E and 89°51′ E from Hooghly river in the west to Harinbhanga and Raimangal Rivers in the east.

4.5 Physical Environment

4.5.1 Terrain Characteristics

The alluvium carried down from the Himalayas and the Chhotanagpur uplands built the lower Ganges delta, where the Sundarbans mangrove forests are located. Previously it represented a sag or depression, which was ultimately filled in by thick layers of sediments of late Pleistocene origin (Wadia 1973). Deposition and distribution of the sediments were further aided by the tidal currents from the sea. So, the terrain

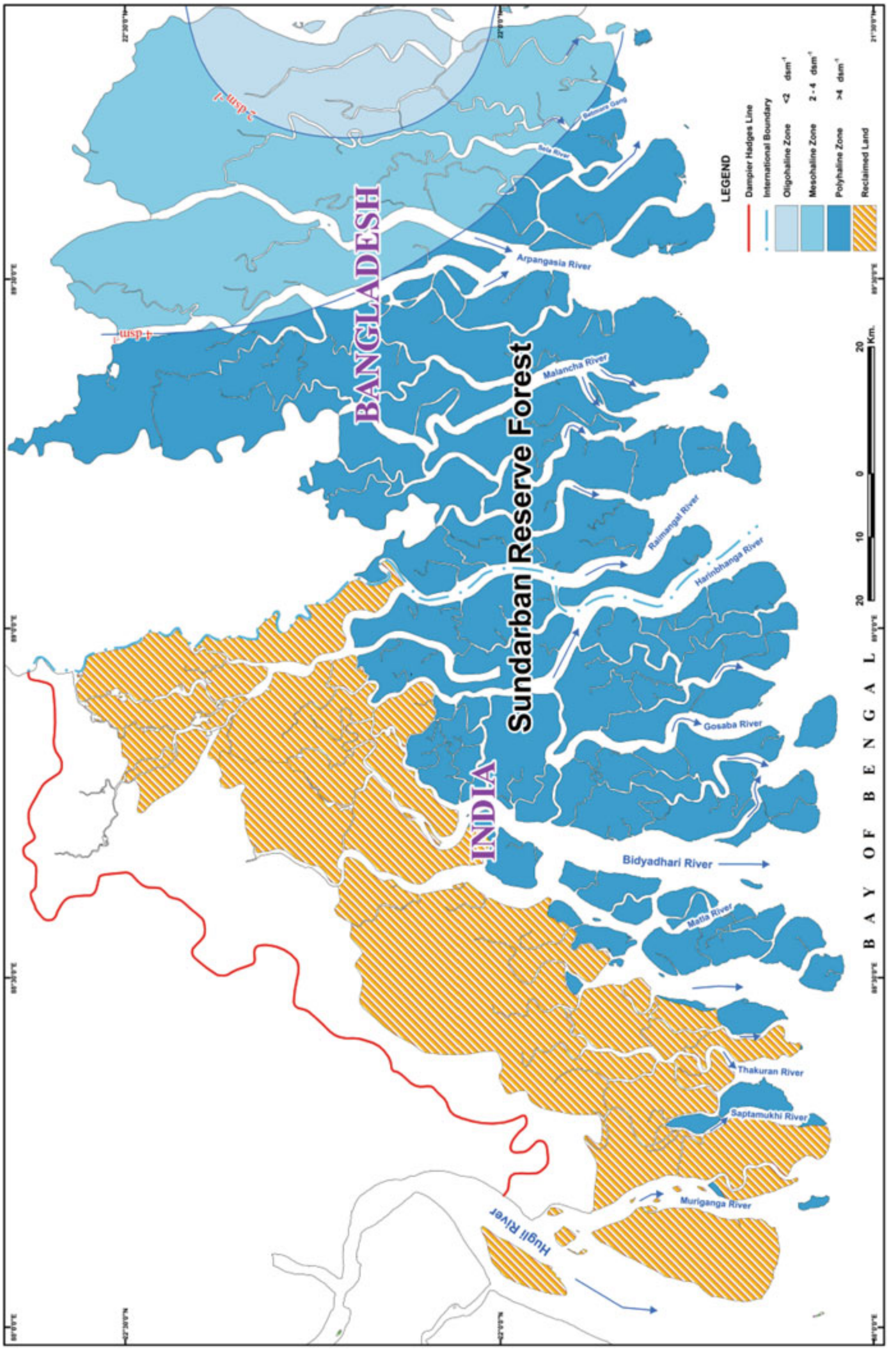

Fig. 4.1 Map of the trans-boundary Sundarbans

condition of the Sundarbans has been influenced by strong tidal regimes that cause transformation of entire land masses into a series of low elevated isolated deltas. Based on Thom's (1982) classification of coastal habitats, the Sundarbans can be considered as 'Deltaic mangroves habitat' (Mandal and Naskar 2008) characterized by a high tidal amplitude ranging between 5 and 8 m. The morphological nature of the entire Sundarbans is more or less uniform with an average elevation of 5–8 m from the mean sea level (Deb 1956). Based on tidal amplitude, velocity of water, productivity of the soil and position of the estuaries, the lower Ganges delta can be divided into three zones. These are: the seaward outer estuarine zone, the landward inner estuarine zone, and the middle estuarine zone–the last-mentioned falls between the first two regions. Based on surface configuration, the Sundarbans may be divided into three major physiographic regions. These include the tidal flood plain of Hooghly-Matla-Hariabhanga complex (3–5 m above msl); the Sundarbans mangrove swamps (1–3 m above msl), and the estuarine and tidal river mouths (<1 m above msl) (Das and Bandyopadhyay 2012).

The hydrological regime, including tidal fluctuation, range, salinity variation, tidal ingression, inundation frequency, depth and duration has substantial influences on the process of sedimentation (both accretion and elevation of land). The process of accretion and erosion within the Sundarbans is highly complex due to the large number of interconnecting waterways. Sediments of both river and tidal waters are distributed on the forest floors, although net erosion occurs along the sea face that facilitates new islands (locally called chars) emerging in places. Eventually, the cumulative effect of all the factors governs the vegetation development and its temporal changes in the Sundarbans mangroves forest. Thus, topography of the Sundarbans has a complex drainage pattern made up of inter-connected rivers, cross channels and estuaries, and is affected by heavy seasonal rainfall, inflow of fresh water and sediments (IUCN 2014).

4.5.2 Climatic Characteristics

4.5.2.1 Seasons

The Sundarbans is subject to four distinct seasons (summer, monsoon, winter, and spring) that changes sequentially, although six seasons (additionally, autumn and late autumn) are climatic features of both Bangladesh and West Bengal. The monsoon months from June to August cause heavy rains due to the influences of South-West trade winds, with 75% of the annual precipitation occurring during this period (JOEC 2002). During monsoon months, the temperature varies from 23 to 35 °C. The monsoon winds bring high rainfall and humidity characterized by sultriness due to cloud cover. Transportation of sediment load increases in all the rivers due to high water levels from heavy rainfall and the release of huge amounts of water from the upper catchment areas. The dry season starts from November and continues to February during which temperature varies between 18 and 25 °C.

Winter months are followed by a short span of spring that covers 2 months such as March and April. Summer months cover usually May and June during which temperature reaches up to 42 °C, which are also known as pre-monsoon months. The season is characterized by southerly winds, high temperatures, occasional thunderstorms, cyclones and strong tidal surges and maximum evaporation from water surface. Salinity of river water reaches maximum during this season.

4.5.2.2 Rainfall

Monsoon rains commence in early June and last for about 4 months at a stretch and ultimately declining by the end of September, sometimes accompanied with the post-monsoon storms known as *Áshwiner Jhar*. The average annual rainfall in slightly higher in the Sundarbans region of Bangladesh compared to the Indian part of Sundarbans. The annual rainfall ranges between 1500 and 2000 mm, with the monthly average rainfall varies from 16 mm in December to 344 mm in July. It is mono-modal with 83% falling between May and September. Erratic and scattered showers occur between November and March. A considerable year-to-year variation from this pattern is observed and in some abnormal years, it could be as low as 1240 mm (at Gosaba in 1972) or as high as 2720 mm (at Sagar in 1973). Throughout the year, the relative humidity remains over 70%. The mean annual relative humidity varies from 70% at Satkhira to 80% in Patuakhali (Banglapedia 2006).

4.5.2.3 Temperature

As the Sundarbans lies close to coasts, extreme climatic conditions are not seen in the area. For about 6 months of the year, the typical monsoon conditions prevail with high humidity and moderately warm day and night. Winter is cool but not very cold. In a year, the range of average monthly maximum temperature varies from 34.6 °C (April) to 27.6 °C (November) and the range of average monthly minimum temperature varies from 24.1 °C (May–June) to 11.3°C (December).

4.5.2.4 Cyclonic Storms

In a typical year, showers in the Sundarbans are heralded by Nor'westers, commencing from April. The Nor'westers, locally known as *Kalbaishaki*, is a short-lived phenomenon with strong winds, rain and thunder accompanied by a sudden fall in temperature. This is almost a regular phenomenon in the pre- monsoon season. On the other hand, the Sundarbans, being situated in a tropical coastal area, is also vulnerable to severe tropical cyclones and depressions. Tropical cyclones accompanied by storm surges are very common in the Sundarbans areas. The Sundarbans witnessed several monsoon and post-monsoon cyclones which crossed through the areas. During the last 10 years, the cyclone *Sidr* and *Aila* were the most devastating among others. *Sidr*, which hit on the night of 15th November 2007 mainly in the Bangladesh part of Sundarbans, claimed the lives of 3406 people, apart from damaging huge amounts of resources. The velocity of the wind ranged from 220 to 240 km per hour. The similar intensity of cyclone, known as *Aila*, which hit on 25th May 2009 mainly in the West Bengal part of Sundarbans, also caused almost similar damage and brought sufferings to a substantial number of coastal people. The effect of these cyclones caused massive damage to the Sundarbans in terms of mangrove biodiversity loss and physical infrastructure required for mangroves management.

4.5.3 Soil Characteristics

The soils of the Sundarbans were derived allochthones from deltaic floodplain alluviums and autochthonously from tidal marsh materials consisting mainly of organic matter (i.e., peat deposits). To a lesser extent, deposition of carbonates from shell fragments of marine-estuarine organisms is also found (Naskar and Guha Baksi 1987). In general, the soils of Sundarbans are deep and poorly drained. The top horizon tends to be clayey, overlain by thin layers of fresh silt, delivered annually by monsoon floods. Below it, alternating horizons of clay and sand are generally present (Chaudhuri 1965). Most of the land derived from alluvial deposits has little or no profile development (Chaudhuri and Choudhury 1994; Sarkar et al. 1999). Clay loam is the predominant soil type in the Sundarbans, though silty and sandy loams also occur in many areas. Soil is grey in colour, finely textured and the subsoil is stratified, compacted at greater depth. The tidal influence is very much predominant on the development of soil texture. Regular tides deposit sand and clay to make the land elevated to form a large-scale ‘chars’ (new silted area) that initially remain denuded and later become flat areas covered with grass. Finer silts are washed out into the Bay of Bengal, but mudflats are formed on the leeward side of the dunes where they are protected from wave action (Gopal and Chauhan 2006).The process of delta building continues with newly silted land after its consolidation; again another ‘char’ emerges as if it raises its head after its dip from the estuary, when other lands here and there may disappear quickly due to erosion (Seidensticker and Hai 1983).

The soil pH averages 8.0 (Christensen 1984). The coastal soils are usually classified as saline, non-saline and alkali soils. Pure sands, which form sand dunes, occur mainly along the coast and are prevalent in the western part of Sundarbans. There is a distinct variation in soil profile. In the Indian part, the parent deposits are either rich in calcium or magnesium, or these consist of half decomposed organic matter. Alluvial soils along the coast show a white efflorescence of sodium chloride, as they are covered with salts crusts carried over by tidal estuaries. In Bangladesh Sundarbans, the western part has been with hard soil mass because of deposition of scanty amount of fresh sediments, whereas the eastern part of the soil has been soft and fertile down to 15 cm layer due to an ample supply of fresh sediments (Siddiqi 2001). Sodium content of soils ranges from 5.0 to 30 meq per 100 g, with gradually lower value recorded in the eastern part. Magnesium varies from 4.0 to 10.0 meq per 100 g. Chloride is a dominant anion varying from 5.0 to 23.0 meq/100 g. Potassium varies from 0.3 to 1.0 meq per 100 g. Organic carbon and nitrogen are 0.62 and 0.05%, respectively. Organic matter ranges between 4% and 10% (Siddiqi 2001).

4.5.4 Salinity

Salinity in the Sundarbans varies greatly with seasonal influence. It is highly dependent on the salinities at the coast and the volumes of freshwater flowing from upstream. Salinity gradually decreases from south to north, higher nearer the coast and lower towards the inland side. On the other hand, salinity gradually decreases from west to east, higher recorded from the Indian part of Sundarbans and lower towards the Bangladesh part, a general scenario from polyhaline (>4 dSm^{-1}) to oligohaline (<2 dSm^{-1} salinity) (Fig. 4.2). The main river Hooghly and its distributaries and tributaries which run over the India part of Sundarbans are severed completely due to urbanization in and around Kolkata city, caused by tremendous anthropogenic pressure. The reduced freshwater flow in the western parts of the Sundarbans have caused increased salinity of the river waters and has made the rivers shallower over the years. Water salinity in the western part of Sundarbans is diluted only when heavy rainwater is mixed with tidal water during monsoon months (Mandal et al. 2009). Consequently, over the last few decades, all rivers in the western part of Sundarbans have been silted up. In the process, during ebb tides the receding water level causes scouring of top soil and creates an innumerable number of small creeks, which normally originate from the centre of the islands. The ebb tide eroding action is stronger in some islands than others within the Sundarbans (Gopal and Chauhan 2006), resulting in formation of degraded land. With time, deposition of sediments due to strong tidal current from sea and river flow in the opposite direction forms muddy substrata which are characterized with denuded flat land covered with salt crust, unfavourable for vegetation.

On the other hand, freshwater flows are much higher from the Brahmaputra and Meghna rivers on the Bangladesh side, particularly in the Baleshwar river in the eastern side of the Sundarbans (Seidensticker and Hai 1983; Ahmed et al. 2011). The substantial flow of freshwater from upstream restricts the ingression of saline water to the forested land. Therefore, the forests near the coast remain moderately saline. In addition, Bangladesh part receives extra benefit by flooding for nearly 4 months every year that reduces the salinity level to a great extent. The freshwater that flows from the rivers and the tidal ingress in the forest result in a varied gradient of salinity with both spatial and temporal pattern. The reduced freshwater flows in the western parts of the Sundarbans have resulted in an increased salinity of the river waters and have made the rivers shallow over the years. Usually, the salinity is higher nearer to the coast, while it is lower in the inland side of the forest. Similarly, the salinity

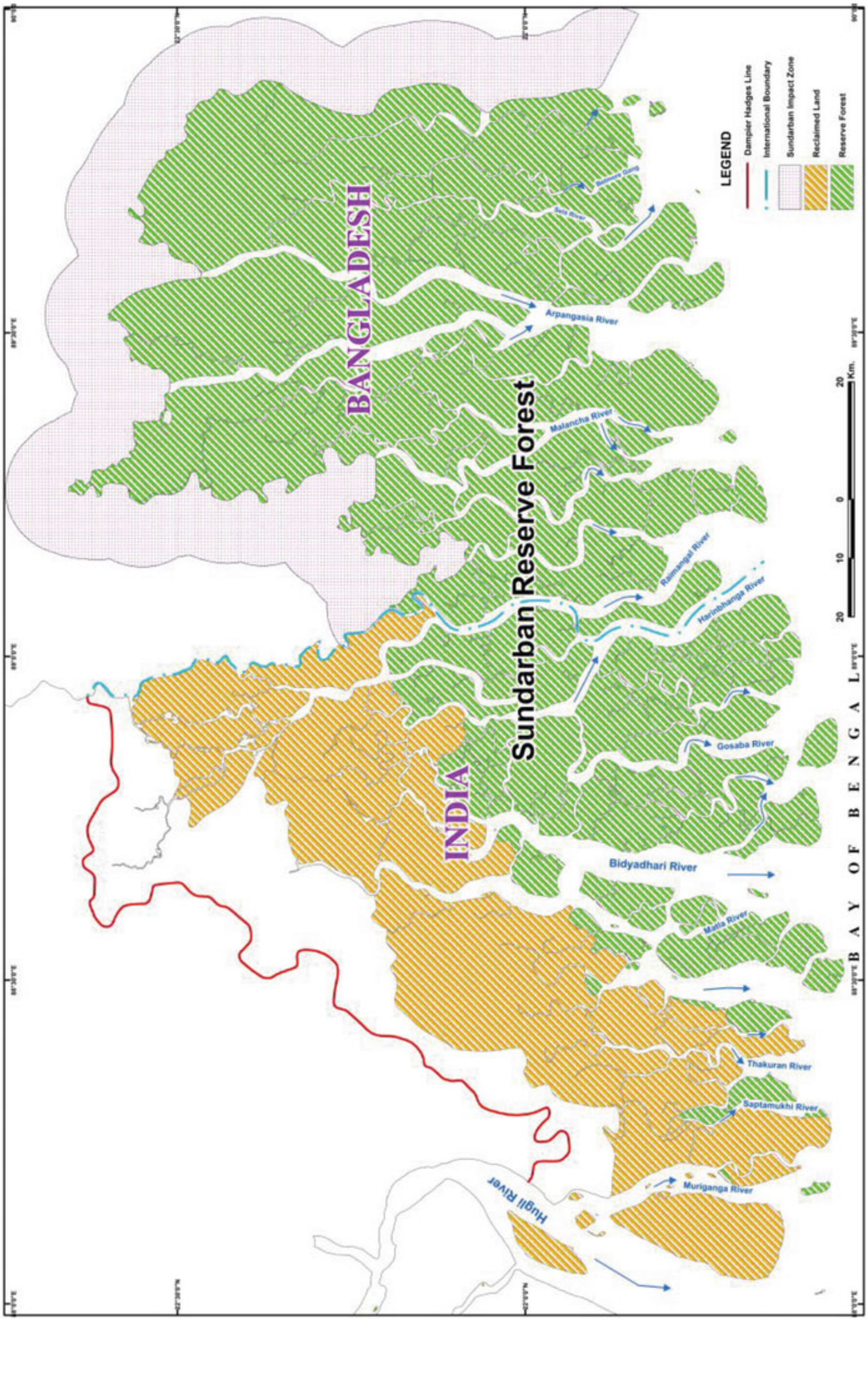

Fig. 4.2 Scenario of salinity changes in the trans-boundary Sundarbans

decreases from west to east, and part of the Sundarbans is oligohaline (<2 dSm^{-1}) distinct in eastern side. There are also greatly seasonal variations of salinity, lower salinity recorded during rainy months due to rain water that dilute salinity down to much lower levels. Comparatively, higher salinity has been recorded in the winter months due to ingression of tidal water due to strong tidal water caused by sea waves. Effects of Farakka Barrage on salinity changes of Bangladesh part are conspicuous. Salinity has increased in the Bangladesh part of Sundarbans after construction of Farakka Barrage due to diversion of freshwater flow (Khan 1983).

4.6 Mangrove Vegetation

Mangroves are restricted in their distribution generally to the areas where mean air temperatures of the coldest month are higher than 20 °C and where the seasonal range does not exceed 10 °C (Walsh 1974, Chapman 1977). Considering their distribution in relation to specific condition of climatic factors, air temperature in particular, mangroves habitats are classified into four groups: (i) Warm humid areas, (ii) Sub-humid areas, (iii) Semi-arid areas, and (iv) Arid areas (Blasco 1984). However, mangrove vegetation is found luxuriant in the areas when the following environmental features become predominant controlling factors, which include annual rainfall ranging between 1500 and 2500 mm, riverine input of freshwater discharge is substantial and moderate temperature ranging between 20 and 35 °C. On the contrary, aridity in the mangrove habitats restrict mangrove growth, resulting in stunted growth and sparse vegetation of the mangrove trees. Aridity refers to the values of ratio P/Etp, where P is the mean annual rainfall and Etp is the mean annual potential evapotranspiration (Blasco1984).

4.6.1 Structure of Mangrove Vegetation

The features of geomorphology, hydrology, and climatic factors that together constitute the 'macro environment' are distinct in the Sundarbans as compared to other mangrove habitats in the Indian subcontinent. Key ecological factors that strongly influence the biology of mangroves in the Sundarbans include freshwater carrying major rivers, strong tidal amplitude exceeding >6 m height, strong cyclonic storm with frequency within 1–4 years, moderate precipitation ranging from 1500 to 2000 mm, and high demographic pressure (>800 population km^{-2}), with the value of P/Etp being>0.75. The entire Sundarbans is intersected into a network of deltas covered with dense mangroves (Blasco and Aizpuru 2002). Based on the height and density of vegetation, they classified mangroves into 12 types in the world perspective. The world's most extensive mangroves forest in a single block exists in the Sundarbans, spread over about 2000 km^2 in the Indian territory and about 3700 km^2 in Bangladesh (Blasco and Aizpuru 2002). Practically, all mangrove types are found in the

Table 4.1 Mangroves vegetation type and dominant species in the trans-boundary Sundarbans

Sl. No.	Type of distinct mangroves vegetation	Dominant species in Sundarbans	
		Bangladesh	India
1	Tall dense forests	*Heritiera fomes*	*Avicennia officinalis*
2	Low dense forest	*Ceriops* spp.	*Ceriops* spp.
3	Low dense forest at edge of mangroves	*Nypa fruticans*	–
4	Open mangroves thickets	–	*Phoenix paludosa*
5	Scattered mangroves under shrubs	–	*Suaeda* sp.
6	Abundant throughout area coverage	*Excoecaria agallocha*	*Excoecaria agallocha*
7	Vegetation at newly formed land	*Sonneratia apetala*	*Avicennia alba* and *A. marina*

Sundarbans (Table 4.1), though their types are distinct in different parts due to salinity differences. *Heritiera fomes,* which prefers growing in freshwater dominated areas and of which seed germination is quite optimal in less saline condition (<2 dSm^{-1}) (Mandal et al. 2009), is common in the eastern part of the Bangladesh (Blasco and Aizpuru 2002). On the other hand, the western part of Sundarbans characterized by high salinity is covered with *Avicennia* spp. which are able to grow in highly saline conditions. However, the assemblage of species varies from place to place, with *Excoecaria agallocha* (gewa) abundant everywhere. Another species *Ceriops decandra* (Griff.) Ding Hou which is also common in the Sundarbans forms 'low dense forests'. *Nypa fruticans,* a freshwater loving mangrove palm which forms narrow fringes at the edge of the mangroves close to the principal water course, is dominant in Bangladesh. *Sonneratia apetala,* which prefers growing in low saline condition, is dominant as pioneer species in newly silted up coastal deposits in the Indian part, adjacent to Bangladesh, whereas a different scenario exists in the western part of Indian Sundarbans in which *Avicennia* spp. is dominant as a pioneer species growing in newly silted up beds characterized by high salinity.

4.6.2 *Vegetation Dynamics*

The general process of habitat progression from instability through various sequential intermediate states to one of stability has long been recognised (Clements 1928). This maturation process, often termed succession, is accompanied by the successive occupation of a site by different plant associations reflecting pioneer, intermediate and mature stages in relation to the prevailing conditions. In mangroves, the succession of plant associations is brought about by sediment changes with time, predominantly sediment elevation and interstitial soil salinity, as a consequence of which zonation has often been interpreted as the expression of plant succession.

The generalised successional sequences noted from the Sundarbans are as follows (for more detail see Sect. 4.6.5): Grasses, such as *Leersia* and *Porteresia*, or succulents, such as *Sesuvium*, may initially colonise newly-deposited silty or sandy sediments, respectively, and stabilise these surfaces, which is usually followed by the pioneering mangroves such as *Aegiceras corniculatum, Avicennia alba, A. officinalis* and *Sonneratia apetala* in monospecific stands or as multi-specific associations. On riverbanks, the mangrove palm *Nypa fruticans* commonly forms a narrow monospecific mangrove belt. With further elevation of the partially stabilised sediment surface, the hydroperiod will change and interstitial salinities are generally reduced, allowing additional mangrove species associations to develop. This may include monospecific stands or, more usually, multi-specific associations of *Bruguiera* spp., *Ceriops decandra* and *Excoecaria agallocha*. With further elevational change and further reductions in soil salinities, additional species may be found, often considered to be characteristic species of stable habitats, such as *Heritiera fomes, Rhizophora mucronata* and, *Xylocarpus granatum*.

While some sequences of this scheme can be recognised in the Sundarbans mangroves, the patterning of species is more complex and more obscure (Ellison et al. 2000). Monospecific stands of some mangrove species do occur in the Sundarbans, but mixed species stands are much more widespread. As Karim (1994b) has warned: ‘there are many local variations in the succession and it must not be assumed that all mangrove swamps pass through a typical sequence of succession or that all types are necessarily present, even in extensive forests’.

Any of these common patterns or sequences, however, can be disrupted by natural or man-made events such as floods and droughts, storms and tsunamis, pollution or exploitative activities. The effects of these disruptive events depend to a large extent on when they occur (which season), as natural regeneration will depend on what propagules and of which species are available at any particular time. In this sense, the disruptive events will add a large random component in terms of what any natural dynamic sequence might be. More significantly, disruptive events characteristically affect ecological turnover rates, which might involve (a) altered rates of leaf shedding or new leaf formation, possibly leading to reduced leaf longevity or increased deciduousness; (b) altered rates of litter turnover; (c) increased rates of tree mortality, leading to die-back; and (d) changed recruitment rates, generally resulting in reduced natural recruitment.

Through a review of four forest inventories of the Sundarbans mangroves of Bangladesh between 1926 and 1997 (Iftekhar and Saenger 2008), the following trends have been identified over that period:

* The diversity of forest types has been gradually reduced over time, but *Heritiera fomes* and *Excoecaria agallocha* associations have maintained their dominance over large portions of the Sundarbans, particularly in the north-eastern area.
* The coverage of forests dominated by *Heritiera fomes,* the most important species of the Sundarbans, has declined at a rate of −0.27% per year over 1926 to 1997, but has declined at −0.43% per year¯in the recent period 1981 to 1997.
* The coverage of forests dominated by *Excoecaria agallocha*, the second most important species of the Sundarbans, has declined at a rate of −0.23% per year but has increased at 0.6% per year during 1981 to 1997.

* The coverage of forests dominated by *Avicennia* spp., *Xylocarpus moluccensis, Bruguiera gymnorhiza, Ceriops decandra* and *Sonneratia apetala*, has increased at a rate of 0.06% per year during 1926 to 1997, and has increased at 0.10% per year more recently.
* Overall, the mangrove forests have maintained a relatively constant tree density over time, but the number of large trees with >15 cm dbh has declined at a rate of −0.27% per year over 1926 to 1997, largely due to ongoing exploitation. The number of trees with >30 cm dbh is low.
* Natural regeneration rates have been maintained over time, but the density of trees with large diameters is decreasing, which is probably attributable to changes in hydroedaphic conditions, particularly in relation to soil salinities, and timber exploitation over approximately 120 years.
* Disease-related mortality, particularly of *Heritiera fomes* was observed as early as the 1930s. At present, the volume of Top Dying disease-affected trees is around 215,000 m^3.

Many of the trends identified above have been further enhanced by the recent estimation of ecosystem carbon stock in the Sundarbans of Bangladesh (Rahman et al. 2015a). The amount of carbon stored varied significantly among the diversity of forest types and also within the different salinity zones. Forests dominated by *Heritiera fomes* stored more ecosystem carbon than other vegetation types and the freshwater (oligohaline) zone showed the highest ecosystem carbon stock followed by moderate to strong salinity zones. As soil salinity was found to enhance below-ground carbon stock, the strong saline zone was found to contain the highest sediment carbon stock. The data also showed that the sediment carbon stock was significant in both tall or short mangroves and that the plant attributes (mean tree height and basal area) of the dominant mangrove species in each forest type could be used as key indicators of ecosystem carbon stock.

While the ecosystem carbon stock from the Sundarbans of Bangladesh ranged from 160–360 Mg Cha^{-1} (Rahman et al. 2015a), a similar study based on the Indian Sundarbans (Donato et al. 2011) found a virtually identical range of 170–336 Mg Cha^{-1}, suggesting that increasing soil salinities, that might have reduced above-ground carbon stock in recent decades, has enhanced the below-ground carbon stock by an equivalent amount. The ecosystem carbon stock of the Sundarbans mangroves is low compared with estimates from other parts of the world, and the long-term ongoing exploitation of above-ground carbon stock (timber) seems the most probable explanation.

4.6.3 Mangrove Diversity

Considering the amount of floral diversity recorded in and around the Sundarbans by different workers, it is difficult to reach a consensus on what should be the total number of mangroves in the trans-boundary Sundarbans. We prefer the terminology 'Intertidal vegetation' for accommodation of more numbers of flora growing in the Sundarbans than mere mangroves, considered strictly a group of flora. Thus here, we follow classification of mangroves of the Indian habitats (Mandal and Naskar 2008) that categorized the intertidal flora into three groups such as (i) Major mangroves, (ii) Mangroves associates and (iii) Back 'mangals', based on exclusively morpho-anatomical features. The study considered both morphological and anatomical features of intertidal flora of such classification purposes. The flora exhibiting greater degree of modifications of organs essential to any survival strategy in intertidal habitats are considered to be major mangroves and those with less modified organs considered to be mangroves associates. Back 'mangals' do not exhibit any modification of organs, but are mere communities growing in the peripheral boundary of intertidal zones. Though the study of morpho-anatomical features was restricted only in the Indian mangroves, particularly in the Indian Sundarbans, such evaluation seems to be effective to be applied across vegetation in the trans-boundary Sundarbans.

We initially put the entire intertidal vegetation growing in the trans-boundary Sundarbans into two groups based on life form, which are 'Canopy vegetation' comprising mainly shrubs and trees and 'Under-canopy' vegetation comprising herbs, grass, creepers and hedges. A total of 45 species falls into canopy vegetation category distributed in 32 genera and 21 families; of which 26 species belong to major mangroves, 6 species to mangrove associates and 13 species to back 'mangals' (Table 4.2a). In under-canopy vegetation, a total of 21 species are considered, which are distributed in 20 genera and 14 families (Table 4.2b).

In mangroves diversity, a few species which are mentioned by different workers based on earlier records are not listed here because their existence is ambiguous. For instance, *Sonneratia alba*, which is commonly found in Goa, along with other few habitats of west coast of India, is not recorded in the trans-boundary Sundarbans since the beginning of floral enumeration of mangroves, dating back to 1903 (Prain 2003). An important true mangrove such as *Scyphiphora hydrophyllacea* which has been first reported from the Indian part of Sundarbans (Mandal et al. 1995) is not reported from the Bangladesh Sundarbans (Rahman et al. 2015b). *Flagelleria indica* is recorded from Bangladesh Sundarbans but is not found from the Indian part of Sundarbans during many times of survey (Naskar and Mandal 1999; Mandal and Naskar 2008). Only *Heritiera fomes* grows in the Sundarbans for which the name 'Sundarbans' is believed to have originated, but another species of genus *Heritieria fomes, H. littorea* has recently been recorded (Encyclopaedia of Flora and Fauna of Bangladesh 2007). Possibly, this is misidentification as Rahman et al. (2015b) did not mention *H. littorea* in their recent taxonomic enumeration of plant diversity recorded from the Bangladesh Sundarbans. In the trans-boundary Sundarbans, diversity of mangroves is the same in India and Bangladesh, but their distribution is conspicuously variable across the boundary primarily because of differing salinity regimes.

Table 4.2a Intertidal vegetation, comprising true mangroves, mangroves associates and back mangals recorded from the trans-boundary Sundarbans

Sl. No.	Scientific name	Family	Sundarbans		CAT	Structural features			Estuary location			Intertidal position			DU	RLC	GL (%)
			BS	IS		FM	CY	AR	DS	MS	US	LT	MT	HT			
1	*Acanthus ilicifolius* L.	Acanthaceae	●	●	MM	S	UC	S	–	+	+	–	*	*	SD	LC	22
2	*Acanthus volubilis* wall.	,	●	●	MA	S	UC	–	–	–	+	–	–	*	SD	LC	24
3	*Acrostichum aureum* L.	Pteridaceae	●	●	MA	F	UC	–	–	+	+	–	–	*	SP	LC	19
4	*Aegialitis rotundifolia* Roxb.	Plumbaginaceae	●	●	MM	S	C	–	+	–	–		*	–	HC	NT	24
5	*Aegiceras corniculatum* (L.) Blanco	Primulaceae	●	●	MM	S	C	–	+	–	–	–	*	–	HC	LC	21
6	*Aglaia cucullata* (Roxb.) Pellegr.	Meliaceae	●	●	MA	T	C	–	–	–	+	–	–	*	SD	DD	23
7	*Avicennia alba* Blume	Acanthaceae	●	●	MM	T	C	PE	+	+	+	*	*	–	CS	LC	24
8	*Avicennia marina* (Forssk.) Vierh.	,	●	●	MM	T	C	PE	+	+	+	*	*	–	CS	LC	21
9	*Avicennia officinalis* L.	,	●	●	MM	T	C	PE	+	+	+	–	*	–	CS	LC	24
10	*Barringtonia racemosa* (L.) Spreng.	Lecythidaceae	●	●	BM	T	C	–	–	–	+	–	–	*	SD		
11	*Brownlowia tersa* (L.) Kosterm.	Tiliaceae	●	●	BM	S	UC	–	–	+	–	–	–	*	SD	NT	26
12	*Bruguiera cylindrica* (L.) Blume	Rhizophoraceae	●	●	MM	T	C	K, B	+	–	–	–	*	–	H	LC	24
13	*Bruguiera gymnorhiza* (L.) Savigny	,	●	●	MM	T	C	K, B	+	–	–	–	*	–	H	LC	20
14	*Bruguiera parviflora* (Roxb.) Wight &Arn. Ex Griff.	,	●	●	MM	T	C	K, B	+	–	–	–	*	–	H	LC	21
15	*Bruguiera sexangula* (Lour.) Poir.	,	●	●	MM	T	C	K, B	+	–	–	–	*	–	H	LC	21
16	*Caesalpinia bonduc* (L.) Roxb.	Caesalpiniaceae	●	●	BM	S	UC	–	–	–	+	–	–	*	SD		

17	*Caesalpinia crista* L.	,	●	●	BM	S	UC	–	–	–	+	–	–	*	SD		
18	*Cerbera odollam* Gaertn.	Apocynaceae	●	●	MA	T	C	–	–	–	+	–	–	*	SD		
19	*Ceriops decandra* (Griff.) Ding Hou	Rhizophoraceae	●	●	MM	S	C	BS	+	+	–	–	*	–	H	NT	12
20	*Ceriops tagal* (Perr.) C.B. Rob.	,	●	●	MM	S	C	BS	+	–	–	–	*	–	H	LC	18
21	*Clerodendrum inerme* (L.) Gaertn.	Apocynaceae	●	●	MA	S	UC	–	–	–	+	–	–	*	SD		
22	***Cynometra iripa*** Kostel.	Fabaceae	●	●	MA	T	C	–	–	–	+	–	–	*	SD		
23	*Dalbergia spinosa* Roxb.	,	●	●	BM	S	UC	–	–	–	+	–	–	*	SD		
24	*Derris scandens* (Roxb.) Benth.	,	●	●	BM	S	UC	–	–	–	+	–	–	*	SD		
25	*Derris trifoliata* Lour	”	●	●	BM	S	UC	–	–	–	+	–	–	*	SD		
26	*Dolichandrone spathacea* (L.f.) Seem.	Bignoniaceae	●	●	BM	T	C	–	–	–	+	–	–	*	SD	LC	23
27	*Excoecaria agallocha* L.	Euphorbiaceae	●	●	MM	T	C	SP	+	+	+	–	*	*	SD	LC	21
28	*Heritiera fomes* Buch.-Ham.	Malvaceae	●	●	MM	T	C	PE, B	–	+	–	–	*	–	SD	EN	50–80
29	*Hibiscus tiliaceus* L.	Malvaceae	●	●	BM	T	C	–	–	–	+	–	–	*	SD		
30	*Kandelia candel* (L.) Druce	Rhizophoraceae	●	●	MM	S/T	C	BS	+	–	–	–	*	–	H	LC	23
31	*Lumnitzera racemosa* Willd.	Combretaceae	●	●	MM	S	C		+	+	–	–	*	–	SD	LC	19
32	*Nypa fruticans* Wurmb	Arecaceae	●	●	MM	P	C		–	+	–	*	–	–	HC	LC	20
33	*Pandanus furcatus* Roxb.	Pandanaceae	●	●	BM	T	C	S	–	–	+	–	–	+	SD		
34	*Phoenix paludosa* Roxb.	Arecaceae	●	●	MM	P	C	PT	+	+	+	–	*	*	SD	NT	14
35	*Pongamia pinnata* (L.) Pierre	Fabaceae	●	●	BM	T	C		–	–	+	–	–	*	SD		
36	*Rhizophora apiculata* Blume	Rhizophoraceae	●	●	MM	T	C	S	+	–	–	*	*	–	H	LC	20
37	*Rhizophora mucronata* Lam.	,	●	●	MM	T	C	S	+	–	–	*	*	–	H	LC	20
38	*Scyphiphora hydrophylacea* C.F.Gaertn.	Rubiaceae	●	●	MM	S	C		+	–	–	–		*	SD	LC	20

(continued)

Table 4.2a (continued)

Sl. No.	Scientific name	Family	Sundarbans BS	IS	CAT	Structural features FM	CY	AR	Estuary location DS	MS	US	Intertidal position LT	MT	HT	DU	RLC	GL (%)
39	*Sonneratia apetala* Buch.-Ham.	Lythraceae	●	●	MM	T	C	PE	+	+	+	*	*	*	SD	LC	7
40	*Sonneratia caseolaris* (L.) Engl.	,	●	●	MM	T	C	PE	–	+	+	*	*	–	SD	LC	20
41	*Sonneratia griffithii* Kurz	,	●	●	MM	T	C	PE	+	+	–	*	*	–	SD	CR	80
42	*Tamarix gallica* L.	Tamaricaceae	●	●	BM	S/T	C		–	–	+	–	–	*	SD		
43	*Thespesia populnea* (L.) Sol. ex Corrêa	Malvaceae	●	●	BM	T	C		–	–	+	–	–	*	SD		
44	*Xylocarpus granatum* J. Koenig	Meliaceae	●	●	MM	T	C	PE	+	–	–	–	*	–	SD	LC	21
45	*Xylocarpus moluccensis* (Lam.) M.Roem.	Meliaceae	●	●	MM	T	C	PE	+	–	–	–	*	–	SD	LC	21

BS Bangladesh Sundarbans, *IS* Indian Sundarbans, *CT* category, *LF* life form, *CY* Canopy, *AR* aerial root, *DS* downstream, *MS* midstream, *US* upstream, *LT* low tide, *MT* medium tide, *HT* high tide, *DU* dispersal unit, *RLC* Red list category, *GL* global loss, *MM* major mangrove, *MA* mangrove associate, *BM* back mangal, *T* tree, *S* shrub, *P* palm, *C* canopy, *UC* under canopy, *S* stilt root, *PE* pneupatophore, *K* knee root, *B* buttress root, *BS* broom stilt, *PT* pneumatothod, *SD* seed, *SP* spore, *HC* hidden cotyledon, *CS* cotyledon- seed, *H* hypocotyl, *LC* least concern, *NT* near threatened, *DD* data deficient, *EN* endangered, *CR* critically endangered

Table 4.2b Intertidal vegetation, comprising under-canopy groups, recorded from the trans-boundary Sundarbans

Sl. No.	Sc. name	Family	Sundarbans		CT	Estuary location			Intertidal position		
			BS	IS		DS	MS	US	LT	MT	HT
1	*Aeluropus lagopoides* (L.) Thwaites	Poaceae	●	●	G	+	+	–	*	*	–
2	*Crinum defixum* Ker Gawl.	Amaryllidaceae	●	●	H	–	–	+	*	–	–
3	*Cryptocoryne ciliata* (Roxb.) Fisch. ex Wydler	Araceae	●	●	H	–	–	+	*	–	–
4	*Dendrophthoe falcata* (L.f.) Ettingsh.	Loranthaceae	●	●	E	–	+	+	–	–	–
5	*Flagellaria indica* L.	Flagellariaceae	●		TW	–	–	+	–	–	*
6	*Halosarcia indica* (Willd.) Paul G.Wilson	Amaranthaceae	●	●	H	–	–	+	*	–	–
7	*Heliotropium curassavicum* L.	Boraginaceae	●	●	H	–	+	+	–	–	*
8	*Hoya parasitica* Wall. ex Traill	Asclepiadaceae	●	●	TW	–	–	+	–	–	*
9	*Hydrophylax maritima* L.f.	Rubiaceae	●	●	H	+	+	–	–	*	–
10	*Ipomoea pes-caprae* (L.) R. Br.	Convolvulaceae	●	●	CR	–	+	+	–	–	*
11	*Myriostachya wightiana* (Nees ex Steud.) Hook.f.	Poaceae	●	●	G	+	+	–	*	–	–
12	*Pentatropis capensis* (L. f.) Bullock	Asclepiadaceae	●	●	TW	–	–	+	–	–	*
13	*Phragmites karka* (Retz.) Trin. Ex Steud.	Poaceae	●	–	G	+	–	–	*	–	–
14	*Porteresia coarctata* (Roxb.) Tateoka	Poaceae	●	●	G	+	+	–	*	*	–
15	*Sarcolobus carinatus* Griff.	Asclepiadaceae	●	●	TW	–	–	+	–	–	*
16	*Sarcolobus globosus* Wall.	Asclepiadaceae	●	●	TW	–	–	+	–	–	*
17	*Sesuvium portulacastrum* (L.) L.	Aizoaceae	●	●	H	+	+	–	*	*	–
18	*Solanum trilobatum* L.	Solanaceae	●	●	TW	–	–	+	–	–	*
19	*Suaeda maritima* (L.) Dumort.	Amaranthaceae	●	●	H	–	–	+	*	*	–
20	*Typha elephantina* Roxb.	Typhaceae	●	–	H	+	–	–	*	–	–
21	*Viscum orientale* Willd.	Loranthaceae	●	●	E	–	–	+	–	–	–

BS Bangladesh Sundarbans, *IS* Indian Sundarbans, *CT* category, *G* grass, *H* herb, *E* epiphyte, *TW* twinner, *CR* creeper, *DS* downstream, *MS* midstream, *US* upstream, *LT* low tide, *MT* medium tide, *HT* high tide

Table 4.3 Mangroves species association in the trans-boundary Sundarbans

	Sundarbans	
Species association	Bangladesh	West Bengal, India
1. *Heritiera fomes*	Dominant	Rare population
2. *Excoecaria agallocha*	Dominant	Mixed vegetation
3. *Ceriops decandra*	Dominant	Mixed vegetation
4. *Sonneratia apetala*	Dominant	Dominant
5. *H. Fomes* + *E. Agallocha*	Dominant	Not conspicuous
6. *E. Agallocha* + *H. Fomes*	Dominant	Not conspicuous
7. *E. agallocha* + *C. decandra*	Dominant	Conspicuous
8. *C. Decandra* + *E. Agallocha*	Dominant	Conspicuous
9. *Avicennia* spp.	Not conspicuous	Dominant
10. *Phoenix paludosa*	Not conspicuous	Dominant
11. *Porteresia coarctata*	Not conspicuous	Dominant
12. Mixed species	Common	Dominant

4.6.4 Species Association

'Species association' usually refers to how many species grow together in a given area that is determined by respective species dominance among the referred vegetation. Single species association usually indicates as having 80–100% density of population of particular species in a given area; presence of other species, if any, seems to be irrelevant. When the concept of mixed species association arises, it refers to the association of more than two species with almost equal share of the population in the particular vegetation. We consider 12 types of mangroves association are prevalent in the trans-boundary Sundarbans (Table 4.3) based on different studies with times (Karim 1994b; Naskar and Mandal 1999; Blasco and Aizpuru 2002; Mandal and Naskar 2008; Aziz and Paul 2015). However, a total of eight mangroves association are distinct in the Bangladesh part, including four single species' dominance. *S. apetala* is common in the trans-boundary Sundarbans, but more dominant in eastern side because of much flow of freshwater. Other species which are prevalent on the eastern side are also present on the western side of trans-boundary as a part of mixed vegetation. On the other hand, *Avicennia* spp., *Phoenix paludosa* and *Porteresia coarctata* exhibit respective dominance in the Indian part of Sundarbans. When salinity is considered to be the most influential factor to control such distribution of species in distinct zonation a visible pattern of species association is demarcated from west to east in the trans-boundary with the following trend: *Avicennia* spp. – *Avicennia marina* + *Sonneratia apetala* – *Ceriops decandra* + *Excoecaria agallocha* – *E. agallocha* + *Heritiera fomes* (Karim 1994b; Siddiqi 1994; Naskar and Mandal 1999; Aziz and Paul 2015).

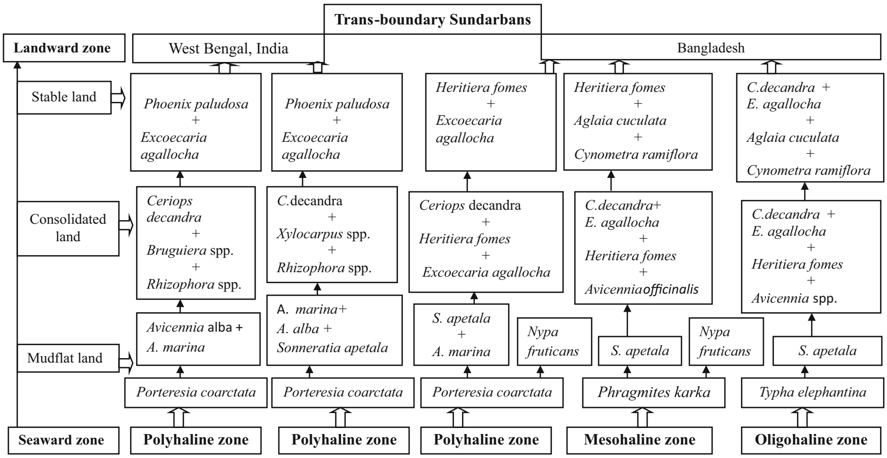

Fig. 4.3 Succession of mangroves from seaward to landward direction in the trans-boundary Sundarbans

4.6.5 Species Succession with Salinity and Consolidation

The term 'succession' refers to the change in a pool of individual plants growing as single stand or as communities forming complex structure on a land surface in a given time. There are succession sequences in mangroves vegetation which may be classified, based on geomorphic, structural and functional features of mangrove environment (Karim 1994a). Species occur in various proportions and combinations. All the mangroves successions are of some value in respect of particular zonation in a finer scale, because most the vegetation shows features of heterogeneity (Karim 1994b). However, all these succession sequences are not considered at a broader scale in a landscape scenario of Sundarbans. Here only the very distinctive succession primarily on the basis of salinity and consolidation in the trans-boundary Sundarbans is discussed (Fig. 4.3). In mangroves habitats, different types of microalgae start assembling and initiate proliferation in newly silted and loose soil strata, followed by grass vegetation; both contribute to make the habitat rather more consolidated mud.

In the polyhaline zone, there are three succession patterns prevalent across political boundary from west to east direction. *Porteresia coarctata*, as a grass species, first colonizes new silted up substrata, which indicates that this grass species can tolerate high salinity, even long periods of submergence during tidal ingression. In the western part of Sundarbans in West Bengal, with the rise of land elevation *Porteresia coarctata* is replaced by pioneer tree mangroves such as *Avicennia marina* and *A. alba,* recognized as high salt tolerant mangroves. When land becomes consolidated, members of family Rhizophoraceae such as *Rhizophora* spp., *Bruguiera* spp. and *Ceriops decandra* are prominent. However, in consolidated beds with slightly elevated land, *Aegiceras corniculatum* and *Aegialitis rotundifolia* become more common in place of members of the Rhizophoraceae. In stable land with high rise of land elevation, *Excoecaria agallocha* and *Phoenix paludosa* are common among plant communities. *Ceriops decandra* forms scrubby thicket covering a large area, but in salt encrusted areas are covered with *Suaeda maritima,* a high salt tolerating shrub forming scattered patches among the mangroves scrub (Blasco and Aizpuru 2002).

In the far eastern of West Bengal Sundarbans, although it falls in the polyhaline zone, salinity becomes slight lower than western part. *Porteresia coarctata,* as a grass species is distinct as in western part, but is replaced by *Sonneratia apetala* as a pioneer mangroves species with rise of land elevation. However, *S. apetala* is not as much as distinct, rather it is seen growing with *A. marina* and *A. alba* as an associated species in most of the area. When land is consolidated as well as elevated, *Xylocarpus* spp. occur along with members of the Rhizophoraceae. *Aegiceras corniculatum* and *Aegialitis rotundifolia* are also visible in plant communities. In stable land with considerable land elevation, *Excoecaria agallocha* and *Phoenix paludosa* are common among plant communities of the western part.

In the polyhaline zone of Bangladesh Sundarbans, *Porteresia coarctata,* as a grass species is distinct and replaced by *Sonneratia apetala* with rise of land elevation. However, *S. apetala* grows in association with *A. marina.* When land is consolidated and elevated, *Ceriops decandra*, *Excoecaria agallocha* and *Heritiera fomes* are common and visible after pioneer mangroves from seaward to landward zonation. Members of the Rhizophoraceae, along with *A. corniculatum, A. rotundifolia* and *Xylocarpus* are also common mangroves communities among others. In stable land with more rise of land elevation, *H. fomes* is very common as tall mangroves along with *Excoecaria agallocha*, which is available, but form scattered vegetation.

In the mesohaline zone, *Phragmites karka* as a grass species appears in mudflat land, which is associated with *P. coarctata* in some areas. This association of grass species may be indicative of salinity transition in which lower salinity facilitates *P. karka* while higher salinity enhances *P. coarctata*. Variation of salinity may be one of the reasons to favour the growth of particular species, although the ecology is not clearly understood. In consolidated land with elevation, *Ceriops decandra*, *Excoecaria agallocha* and *Heritiera fomes* are common and visible, which are seen in association with *Aegiceras corniculatum, Aegialitis rotundifolia, Lumnitzera racemosa* and members of the Rhizophoraceae. In stable land with more rise of land elevation, *H. fomes* is very common along with *Excoecaria agallocha*.

In the oligohaline zone, *Phragmites karka* and *Typha* spp. grow as pioneer species in mudflat land, which indicates that salinity is much lower than that of other zones. When land becomes consolidated, *S. apetala* grows as pioneer mangrove, which is replaced by *A. officinalis,* and usually prefers growing at a lower salinity as compared to other two members of genus *Avicennia*. In consolidated land with elevation, like mesohaline zone *Ceriops decandra*, *Excoecaria agallocha and Heritiera fomes* are common and visible, which are commonly in association with

Aegiceras corniculatum, Aegialitis rotundifolia and *Lumnitzera racemosa*. In stable land with greater land elevation, *H. fomes* is very common along with *Excoecaria agallocha* and *Aglaia cucullata,* considered to be a mangroves associate.

In both mesohaline and oligohaline zones, mudflat areas are occupied by mangrove palm, *Nypa fruticans.* The river banks or freshwater flowing channels are ideal habitat for *Nypa* vegetation which is considered to be freshwater loving mangrove palm. When freshwater flow is progressively reduced, *Nypa* vegetation gradually disappears and mangroves grasses occupy such place as salinity increases.

4.6.6 Adaptation

The term 'Adaptation' refers to the modification of organs or of whole organism to cope with existing environmental conditions. Both the morphological and anatomical modifications are found in the leaf, stem, root (vegetative organs) and reproductive organs of mangrove species. Mangroves have a wide range of modifications essential to sustain them in estuarine habitats characterized with a wide range of salinity, considered to be single determining factor of the mangroves environment. Therefore, intake of salt and maintenance of water balance is the most important physiological phenomenon mangroves adapt to survive in a coastal environment (Saenger 2002). Excess salt needs to be removed from mangroves otherwise it appears to be toxic in plant tissues. Therefore, mangroves require essentially to cope with high salinity through removal of such excess salt for survival (Scholander 1968; Tomlinson 1986). All mangroves show some features of salt resistance that may broadly include 'salt exclusion', 'salt extrusion' and 'succulence', mechanisms.

4.6.6.1 Mangroves' Resistance to Excess Salt

Root systems of some mangroves (*Rhizophora, Ceriops, Bruguiera, Sonneratia, Excoecaria* and *Aegiceras*) act as potential filter to exclude about 80–95% excess salt during water uptake through effective filtration mechanism, known as 'salt exclusion' (Popp et al. 1993). The remaining 5–20% salt entering into the roots may be considered essential for survival of mangroves (Saenger 2002). Leaves of some mangroves (*Avicennia, Aegiceras, Aegialitis, Acanthus*, *Rhizophora and Clerodendrum*) exhibit a variety of salt glands as adaptive features to extrude about 2.1–33% excess salt through a mechanism known as 'salt extrusion', with variable rates as recorded from 12–24 hr (Popp 1995; Weiper 1995; Field et al. 1998). In other mechanism, some mangroves (*Avicennia, Aegiceras, Acanthus*, *Sonneratia, Lumnitzera, Scyphiphora, Conocarpus and Rhizophora*) are able to store excess salt in their leaves. This mechanism, known as 'succulence', is attributed to an increase of cell length in central mesophyll layers to adjust accumulated salt through its dilution by increasing water content per leaf area volume (Saenger 2002; Saenger and West 2016).

4.6.6.2 Mangroves' Response to Water Conservation Due to Xeromorphy

Water conservation is an adaptive response of mangroves and an essential strategy to cope with the saline environment. There are some attributes of leaves which are related to xeromorphy of mangroves (Saenger 1982; Tomlinson 1986; Naskar and Mandal 1999; Saenger 2002; Mandal and Naskar 2008).

- Thick walled, often multi-layered epidermis on the upper leaf surface covered with a thick, waxy, lamellar cuticle to reduce evaporative loss.
- A well-developed hypodermis acts as water storage, salt accumulation or osmo-regulation, mesophyll protection through heat dissipation, and nutrients conservation.
- Dense layer of various shaped hairs on the lower leaf surface perform to cover salt glands and stomata to check the loss of water through these apertures.
- Distribution of cutinized and sclerenchyma cells throughout the leaf responds to physiological dryness of saline environment, with provision of mechanical support against wilting and against the frequent occurrence of natural calamities including strong wind and cyclone.
- Dominance of palisade mesophyll provides toughness and rigidity to the leaves and reduces damage from wilting, with provision of water conservation.
- Sunken stomata beneath the level of epidermis in several mangroves facilitate water storage in one hand, and check the evaporative loss of water on the other.
- More vessels per unit area with distinctly smaller pores in wood, with a larger cross-sectional area, perform transport of sap from the root to other parts of the plants (Panshin 1932; Janssonius 1950; Vliet and Van 1979; Naskar and Mandal 1999).

4.6.6.3 Root Systems and Adaptations

Muddy substrata of estuarine habitats exhibit anaerobic conditions due to scanty soil porosity; this condition is aggravated when water logging persists. Mangroves habitats are devoid of sufficient oxygen essential for physiological function of underground and related organs. Soils of mangrove habitats are known as being 'physiologically dry'. In addition, the location of estuarine ecosystems results in natural stressors such as sea surges, high tidal flow, strong winds flow, soil erosion, coastal storms, etc. To overcome such disturbances, mangroves develop a survival strategy in their root system, referred to 'halophytic adaptation', with a variety of modification in roots for the provision of both physiological and mechanical support. In the field, there are two kinds of rooting patter distinct in mangroves: (i) underground root system and (ii) aboveground root system.

Underground root systems exhibit a horizontally spreading cable root system just beneath the soil surface (sometimes exposed above the ground), with descending roots known as anchor roots at certain intervals. In addition to tap roots, comparatively smaller fibrous like roots known as nutritive roots develop from anchor roots.

Aboveground root systems exhibit a wide range of diversity prevalent in most mangroves species: Pneumatophores found in some mangroves (*Avicennia alba, A. marina, A. officinalis, Sonneratia alba, S. apetala, S. caseolaris, S. griffithii, S. ovata, Xylocarpus granatum, X. moluccensis, Heritiera fomes*) arise from cable roots and ascend upward into the air against gravitation. However, upward roots arising against gravitation in fibrous roots, are known as Pneumatothods in *Phoenix paludosa.* Knee roots (*Bruguiera* spp.) develop from cable roots, rising upward above the surface and again bending downward. Stilt roots (*Rhizophora* and *Acanthus ilicifolius*) develop around from trunk base at a certain height above the ground, descending with numerous branches and penetrating into ground. Buttress roots (*Xylocarpus granatum* and *Heritiera* spp.) develop from the trunk base like stilt roots, but are a flattened, blade like structure. Aerial roots (*Avicennia, Sonneratia* and *Rhizophora*) develop from branches or trunks, descending towards ground, but not penetrating the substrata.

4.6.6.4 Reproductive Organs and Adaptation

Mangroves exhibit sexual reproduction. Fruits are the exclusively reproductive organs bearing seeds which germinate into new propagules. Initially, development of seed germination in mangroves is highly sensitive to high salinity and the propagule may become withered, until the substrata become suitable. To avoid such high salinity, seeds germinate without any dormant period to develop a hypocotyl while fruits remain attached to the parent tree. This phenomenon is referred as viviparous germination as seen in species of *Rhizophora, Bruguiera, Ceriops* and *Kandelia*. Other form of germination is referred to cryptovivipary when the seed germinates to develop a radicle which has restricted elongation and remains hidden within fruit coat as seen in the species of *Acanthus*, *Avicennia, Aegialitis, Aegiceras* and *Nypa*.

4.7 Spatio-temporal Changes of the Mangrove Forest in the Trans-boundary Sundarbans

Sundarbans reserve forest (both in India and Bangladesh) is showing an insignificant sign of degradation since last 20 years (Fig. 4.4a and b). Reliable estimates of aerial extent of the Sundarbans forest are not available prior to 1870 (Iftekhar and Islam 2004). So, from the available record it may be stated that degradation started since last 200 years or more. It has also been estimated that during 1873–1933 the forest was reduced from 7500 km^2 to 6000 km^2 (Curtis 1933; Blasco 1977). Until then the boundary of Bangladesh's forest remained almost unchanged and its vegetation

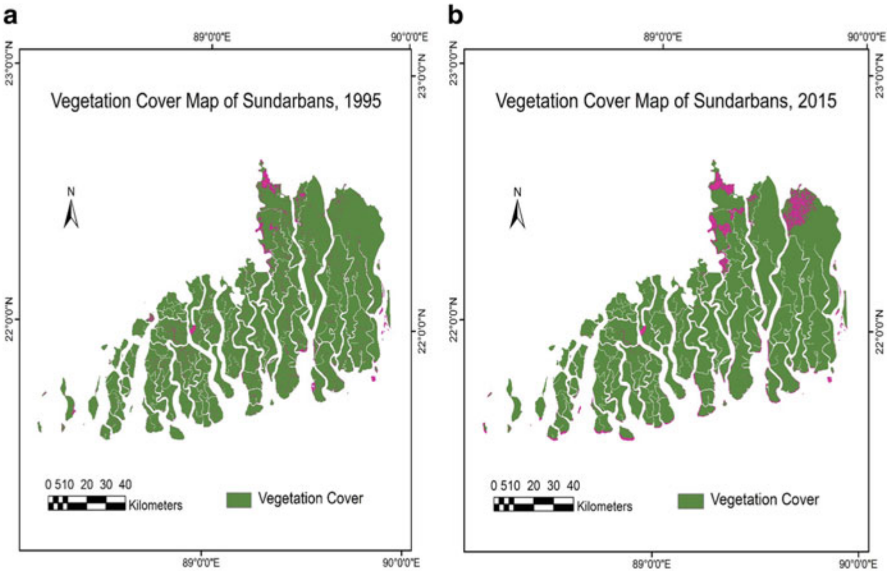

Fig. 4.4 (**a** and **b**) Changes of vegetation cover in the trans-boundary Sundarbans since last 20 years (1995–2015). (Pink colour shows degradation of the forest cover)

inventories show that the aerial extent of the tree coverage has been reduced by 0.04% per year during the period 1926/28–1995 (Iftekhar and Islam 2004). Comparatively in the Indian Sundarbans, reclamation started and forest cover has gradually declined.

Over the past two decades, remote sensing techniques has played crucial role in mapping and understanding changes in the aerial extent and spatio-temporal pattern of mangrove forests related to natural disaster and anthropogenic forces (Heumann 2011). But, site-specific or micro-level studies are very rare for the Indian Sundarbans, especially in the south-western parts, and among these few studies, the majority deals with coastal geomorphic, sea level rise and shoreline changes (Jayappa et al. 2006) only. Changes in vegetation dynamics are somehow neglected in these micro/meso-level studies.

So, an attempt has been taken to calculate gross changes of areas of vegetation of whole undivided Sundarbans by traditional NDVI methods to determine areas of temporal forests loss as well as degradation. Two multi-temporal cloud-free satellite images (Landsat 5 and 8) covering whole or parts of the Sundarbans were downloaded from the freely available United States Geological Service (USGS) (http://glovis.usgs.gov). The whole image processing procedure was conducted using Arc GIS 10.1software. Individual band data stacking to produce false colour composites (FCCs) was done for all three bands of MSS (bands 3, 4, 5 for TM and bands 3, 4, 5 ETM+ image).

We analyzed multi-temporal satellite data of 1995 and 2015 using NDVI approach. The number of pixel for vegetation in 1995 is shown: 7947403 pixels i.e., 715.26627 km^2 area and for 2015, 7859377 pixels i.e., 707.34393 km^2 area. The net loss in last 20 years (1995–2015) is 88026 pixels i.e., 7.92234 km^2 area only (30 × 30 m pixels). The rate (per year) of depletion of forest is, however, 0.396117 km^2 area (7.92234 km^2 per 20). So, it is quite clear that the areal extent of the mangrove forest of the Sundarbans has not changed significantly in the last 20 years. Almost similar type of study was done by Giri et al. (2007) where they found approximately 1.2% of forest lost during last 25 years taking multi-temporal satellite data from 1970s, 1990s, and 2000s using supervised classification approach. This success story was generally due to the management and protection status of the Sundarbans in both the countries particularly after 1990s, including the ban on clear cutting and forest encroachment.

4.8 Sundarbans Floral Biodiversity

Diverse ecological conditions, including hydrology, topography, texture of substrata, salinity and their interactions cause to develop a wide heterogeneity in the mangrove ecosystems that support to nurture a great biodiversity. Though Sundarbans is the house of the diverse biological organisms, it is famous for its mangroves vegetation. Gopal and Junk (2000, 2001) suggested that all the organisms, both flora and fauna, living in mangroves area might be considered as mangrove organisms in such an important wetland. The present chapter has no scope, however, to discuss the faunal diversity, so we restrict the discussion to floral diversity only, although the economic services of the ecosystem have been enumerated taking all components into consideration (see Sect. 4.10 in this chapter).

4.8.1 Algae

The algal diversity of the Sundarbans is poorly explored, but the habitats heterogeneity suggests that the Sundarbans may have a highly diverse algal flora comprising of both benthic and planktonic communities ranging from the freshwater to marine environments (Gopal and Chauhan 2006). Despite limitation due to non-accessibility of the Sundarbans forest, some studies have been carried out by Islam (1973) and Aziz et al. (2012) in the Bangladesh Sundarbans. Phytoplankton communities consist of a total of 35 taxa (Aziz et al. 2012) including nano- and picoplankton, and the number exceeds 50. *Oocystis pussilla*, a freshwater phytoplankton, was recorded as dominant under all salinity conditions. The presence of a good number of Pennales members and some other freshwater species indicates a strong influence of freshwater in the BSMF (Bangladesh Sundarbans mangroves forest) or that they have adapted to varying salinity. A total of 35 benthic algae have been recorded (Islam 1973). Most spectacular are species of *Catenella*, *Caloglossa*, *Bostrychia* and *Cladophorella* growing on pneumatophores and on stems submerged during high tide; *Enteromorpha intestinalis* is found as a drifted form, while others grow on muddy forest floor. *Colpomenia sinuosa*, though small in size, was found growing on the margin of inundated forestland.

In the Indian part of Sundarbans, Chaudhuri and Choudhury (1994) recorded several species of Centric diatoms, such as *Coscinodiscus excentricus, C. radiates, Ditylim brightwellii,* and *Rhizosolenia alata.* Sen and Naskar (2003) recorded 80 species of algae (32 Cyanophyceae and 27 Chlorophyceae). These included only 7 species of diatoms, whereas Banerjee and Santra (1999) listed 48 species of diatoms from the Hooghly-Matla estuary alone. Diatoms and their characteristics with particular reference to climate change phenomenon will be discussed in more details in the next chapter. Naskar (2004) further listed 150 species including 15 species of Rhodophyceae and 2 species of Phaeophyceae. Mandal and Naskar (1994), in a short period study, mentioned some species of *Lyngbya*, *Oscillatoria* and *Microcoleus* as common organisms attached on the surface of pneumatophores of mangroves, though their biological association is not explored. However, some published reports provide few algal enumerations, which seem scattered and are based on short-term surveys over small isolated areas (Pal et al. 1988; Santra et al. 1988, 1991). There are studies left which may look into association among mangroves roots and an algal community whether it is specific and any mutualism occurs through exchange of nutritional benefit.

4.8.2 Microorganisms

The diversity of microorganism is poorly understood in view of ecological perspective in the Sundarbans. Microorganisms play an important role in decomposition of litter and thus release of nutrients which make the habitats productive. Even though, no particular study on food comprising various levels of trophic system has been undertaken. Nevertheless, some studies mention various microorganisms in the soils and on decomposing litter, besides pathogens infesting mangrove leaves (Pal and Purkayastha 1992).

4.8.3 Lichens

Santra (1998) reported 32 species of lichens from the Indian Sundarbans as a short-term study, which is mainly a taxonomic enumeration, but the concern related to ecological perspective in view of climate change and global warming is yet to be explored. Lichens is considered to be an indicator organism in relation to the degree of changing aerial pollution.

4.8.4 *Higher Plants Community*

Higher plants communities of the Sundarbans forest have been explored since early twentieth century (Prain 2003). Since then some attempts were made to enumerate the list of species growing in mangroves areas of the Sundarbans, though much emphasis has been given to the mangrove flora and its management. Recently, few studies are worth mentioning: enumeration of floral account from Bangladesh Sundarbans (Encyclopaedia of flora and fauna of Bangladesh 2007; Rahman et al. 2015b), enumeration of floral account from lower Gangetic plain (Naskar 1994) and intertidal floral account from the Indian part of Sundarbans (Naskar and Mandal 1999). Chaffey et al. (1985) argued that there have been frequent explorations with greater detailed study in the Indian Sundarbans as compared to the Bangladesh part. However, a recent study conducted on taxonomic enumeration of higher plants of Bangladesh Sundarbans by Rahman et al. (2015b) deserves credibility in view of taxonomic study. There are some efforts in studying ecology of mangrove flora and its succession, association and adaptation from the Bangladesh Sundarbans (Ismail 1990; Seidensticker et al. 1991; Hussain and Acharya 1994; Karim 1994b; Siddiqi 1994; IUCN-BD 2002a, b, c; Islam and Wahab 2005). Nevertheless, a collaborative effort is essentially required to explore the Sundarbans in greater details.

4.9 Tropic Pathways in Mangroves Ecosystems

Mangrove ecosystems provide a trophic link right from microbial activities in litter decomposition to nutrient release and thus provision of nutrition to autotrophs from which successive energy flow occurs to higher organisms (Fig. 4.5) as classically worked out by Odum and Heald (1972). Further, Twilley (1988) estimated the

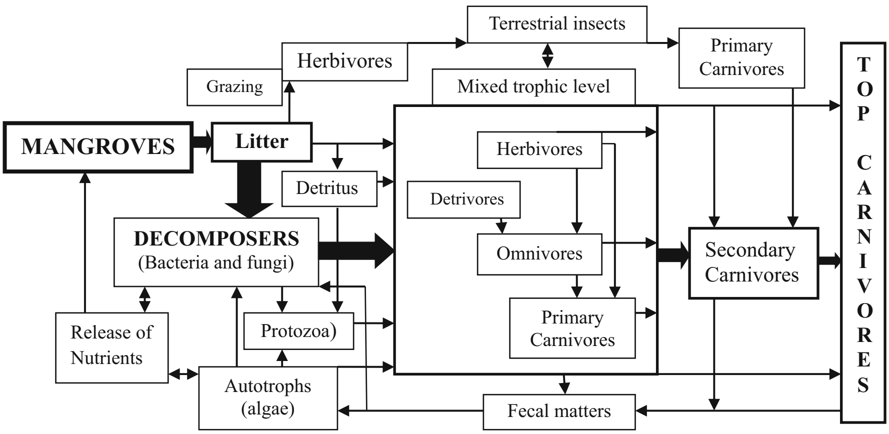

Fig. 4.5 Tropic pathways in mangroves ecosystems

dynamics of mangrove litter, including productivity, decomposition, and export influencing the coupling of mangroves to coastal ecosystems. The primary productivity of mangroves is mostly measured by means of the rate of litter fall (Brown and Lugo 1982; Odum et al. 1982; Twilley et al. 1986; Saenger and Snedaker 1993; Twilley and Day 1999). Litter productivity values for mangrove forests worldwide range from about 2–16 $tonha^{-1}$ $year^{-1}$ and also decrease with increase in latitude (Saenger and Snedaker 1993, Twilley and Day 1999). The estimates of carbon export from mangrove ecosystems range from 1.86 to 401 g Cm^{-2} $year^{-1}$ and the average rate of carbon export is about 210 g Cm^{-2} $year^{-1}$ (Twilley 1989). A high amount of carbon export from mangroves may be associated with the more buoyant mangrove leaf litter along with related climatic factors (Twilley 1988). The organic matter released from mangroves to adjacent systems seems to vary according to the environmental setting and geomorphology of the system (Nagelkerken et al. 2008) and has been more important in riverine/estuarine systems than in lagoon or island settings (Pineda 2003). The impact of mangrove invertebrates on litter dynamics, based on different feeding experiments has been well documented and highlights the role of faunal communities on nutrients release in such ecosystems (Lee 1998).

In the perspective of litter dynamics as per worldwide view, no substantial work has been done from either part of the Sundarbans forest. There are some reports on nutrients release from mangroves litter (Mitra et al. 2011), but they seem very low and limited to a particular zone and thus do not have sufficient reliability to be applicable across the trans-boundary Sundarbans, a vast area characterized with variable and dynamic environmental settings.

4.10 Value of Mangroves

Mangroves vegetation has been considered to have immense values which usually refer to a variety of benefits harnessed out of ecosystem services (Mandal et al. 2010). Nevertheless, there must be some accounts or a gross estimation by which common people can understand the importance of mangroves vegetation. All these benefits mangroves accrue to people, primarily the coastal inhabitants, as has been reported by those working on mangroves ecosystems. Saenger (2002) highlighted many facets of benefits that mangroves provide, categorized broadly into four groups: (i) economic, products value; (ii) usefulness, ecosystem value; (iii) intrinsic, natural value; and (iv) symbolic, cultural and mythical value (Fig. 4.6). These benefits occur through ecosystem services by means of interaction between biotic and abiotic components. The consequence of interaction generates goods and services, including nutrients cycling, flow of energy and other materials, considered as production of ecosystem functions. Use of goods and services manifests a variety of purposes, seems to be almost region-specific and thereby are classified into three groups (Fig. 4.6): (i) direct use: it refers to consumptive and non-consumptive uses that involve into direct physical interaction with the mangroves and their services,

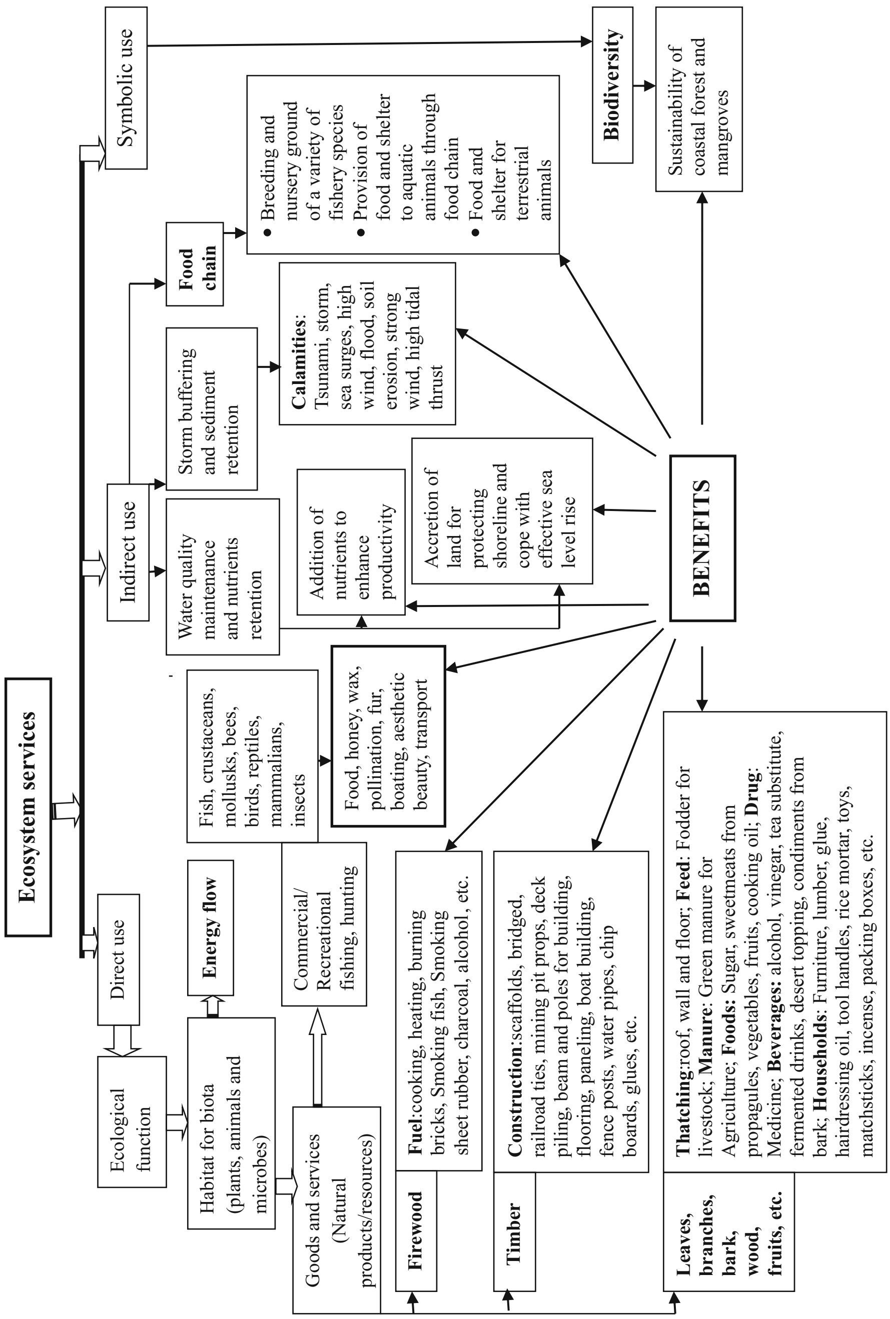

Fig. 4.6 Benefits through ecosystem services by mangroves

(ii) indirect use: it refers to regulatory ecological function, leading to indirect benefits, and (iii) symbolic use: it refers to existence and bequest values of mangroves (Salem and Mercer 2012).

4.11 Conclusions

It is no wonder that the trans-boundary Sundarbans is of a global importance because of its mangroves forest and rich biological diversity as well, which altogether has made this coastal forest a unique eco-region. Its staggering ecosystem services, including protection of coastal inhabitants from natural calamities, are still unaccounted. A great many people, who are residing in this region across transboundary, earn their substantial livelihood supports from the forest resources. Though tropical mangroves forests are now among the most threatened habitats in the world; evidently, there is no major degradation in the mangrove forest across the transboundary Sundarbans since the last 20 years as shown through satellite imagery. It indicates that mangroves forest degradation due to anthropogenic activities has been checked to a great extent. Nevertheless, there is a growing concern of latent degradation of mangroves vegetation across the transboundary Sundarbans due to certain environmental causes such as (i) increased salinity, (ii) erosion of forest-lands, and (iii) increased frequency of natural hazards. These issues are unlikely to develop any sudden impact on mangroves vegetation covering large scale areas, but their persistent effect may alter vegetation dynamics in long term. In this context, Indian part needs to recreate environment using and managing sediment laden freshwater of the feeder canal. Re-creation of the Bangladesh Sundarbans environment involves two steps- (i) dredging sand bars from the Ganges and distributaries leading to the Sundarbans and allowing uniform sediment-laden freshwater flow inside the Sundarbans for maintaining oligohaline environment, and (ii) uniform deposition of sedimentation around forest-lands. Unfortunately, no joint effort engaging experts from both the countries has been effective to protect mangroves and its ecosystem until now. Either part of the transboundary Sundarbans has been subject to individual effort to protect and promote the Sundarbans, but this means is insufficient, since they are mutually dependent on each other, and therefore a united effort is required. The difficulty to compile a biological resource inventory as a unified unit in each taxonomic hierarchy across the transboundary Sundarbans has been compounded. There are different enumerations of biological organisms in the respective Sundarbans and so there are chances of more errors surfacing. In such case ambiguity may occur when the Sundarbans – a united block of mangroves forest covering both countries is considered. Until recently, global warming and sea level rise has been predicted to cause adversity to the transboundary Sundarbans and in such case joint effort is urgently needed to protect the Sundarbans by way of plantation of climate resilient mangroves and the management practices. Sincerely, a joint collaboration involving both countries is required, else the fate of the unique eco-region across the trans-boundary Sundarbans may be at stake.

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Mangrove forest with river in the background (Courtesy R. N. Mandal)

Chapter 5
Dynamics of Algae in Sundarbans and their Implications as Climate Change Proxies

Neera Sen Sarkar and Sanoyaz Sekh

Abstract The algae as a group does not include single taxa but is an agglomeration of absolutely unrelated or distantly related groups of organisms. This confers them a variety of morphology, structure, process, and characteristics unknown in any other single group of organisms. Sundarbans spread across India and Bangladesh is reportedly quite rich in terms of its algal flora, the presence of 762 species of algae has been documented, and the present treatise has been prepared combining all available literature that have documented algal species' richness in Sundarbans. This includes information regarding their presence in different zones of Sundarbans with notes on the habitats they occupy. A spatial distribution model based on autocorrelation has been generated for the algal species reported. The dynamics of the system and the algae inhabiting this ecosystem are dependent on many different environmental variables; and a combined representation of a few such selected variables on a spatial range across India and Bangladesh has been generated for the purpose, based on works by different groups in the Sundarbans. This is accompanied by a discussion on the efficacy of diatoms as palaeo-ecological proxies and indicators of climate change.

Keywords Sundarbans · Estuarine algae diatoms · Spatio-temporal distribution · Palaeo-ecological proxies · Climate change

5.1 Introduction

The biodiversity of Sundarbans is widely acclaimed. The exclusive and exquisite floral components stand as tough contenders against the elusive and unique faunal components, albeit complementing each other to create the world's largest single expanse of mangrove forests. Among the floral components, mangrove trees and

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shrubs, mangrove associates and the back mangroves with their interesting architecture and adaptations are undoubtedly the prime attractants in this beautiful forest stretching across India and Bangladesh, but equally important are the not so visible but nevertheless ecologically important representatives of the major artificial group 'algae'. The group is designated so, since the realization that the organisms grouped as 'algae' occupy varied positions in the classification of life. The group's tremendous diversity is reflected in the existence of nine distinct lineages including the Chlorophyta, Rhodophyta, Glaucophyta, Euglenophyta, Chlorarachniophyta, Dinophyta, Cryptophyta, Heterokontophyta and Haptophyta, all of which together constitute the algae. The retention of Cyanobacteria within the 'algae' by phycologists further adds another dimension to the teeming algal diversity.

Sundarbans, both in India and Bangladesh, have been extensively explored for its algal flora. An assessment of the algal diversity reported from Sundarbans by various workers in entirety of existing publications reveal 762 different species of algae; this includes 232genera, 146 families and 81 orders belonging to 6 algal lineages (Tables 5.1, 5.2, 5.3, 5.4, 5.5, and 5.6). This is based on available published information in journals, books and reports and grey literature in institutional libraries. In terms of number of taxa belonging to each lineage, Heterokontophyta (majorly Bacillariophyceae) is represented by the highest number of taxa, followed by taxa belonging to the lineage Chlorophyta (Fig. 5.1).

Recent times have seen significant additions to the species richness in terms of green algae, euglenophytes and diatoms (Satpati et al. 2012, 2013; Satpati and Pal 2015, 2016, 2017; Aziz 2011; Aziz et al. 2012; Mukherjee et al. 2014; Manna et al. 2010; Samanta and Bhadury 2014; Bhattacharjee et al. 2013; Naha Biswas et al. 2013; Mandal et al. 2015a; Sekh et al. 2016). Recent studies in the Sundarbans have also witnessed newer habitats being explored (Mandal et al. 2015a; Naskar et al. 2013; Satpati et al. 2011), innovative approaches to biodiversity studies (Samanta and Bhadury 2014, 2016; Choudhury et al. 2015; Mitra et al. 2014; Dutta et al. 2016) and interpretations and implications of such studies on algae in diverse ways (Akhand et al. 2012, 2017; Dutta et al. 2016; Mitra et al. 2012, 2014; Sekh et al. 2016).

5.2 Dynamics of the Ecosystem

Dynamics of an ecosystem encompasses all the major driving forces that determine the structure and function of the system and its biotic components. Sundarbans represents a highly dynamic ecosystem in terms of parameters linked to its geo-morphological, climatic, hydrological, and biological characters. An understanding of the dynamics of the ecosystem of Sundarbans thus emphasizes upon the spatio-temporal variations of these parameters over the entire region. For the purpose of this treatise, the entire stretch of Sundarbans in India and Bangladesh is being considered. This includes the continuous stretch of mangroves in India and Bangladesh along with the spillover areas lying in the western side of India and in

Table 5.1 Richness of Chlorophyta taxa in Sundarbans of India and Bangladesh

Order	Family	Genus	No. of species
Chaetophorales	Chaetophoraceae	*Stigeoclonium*	1
	Uronemataceae	*Uronema*	1
Chlamydomonadales	Chlorococcaceae	*Chlorococcum*	1
	Chlorochytriaceae	*Phyllobium*	1
	Volvocaceae	*Volvox*	1
		Pandorina	1
		Eudorina	1
Oedogoniales	Oedogoniaceae	*Oedogonium*	7
		Oedocladium	1
Sphaeropleales	Hydrodictyaceae	*Pediastrum*	4
	Microsporaceae	*Microspora*	3
	Radiococcaceae	*Radiococcus*	1
	Scenedesmaceae	*Scenedesmus*	3
	Selenastraceae	*Ankistrodesmus*	1
	Sphaeropleaceae	*Sphaeroplea*	1
Chlorellales	Chlorellaceae	*Chlorella*	2
		Dictyosphaerium	1
		Franceia	1
		Geminella	1
	Oocystaceae	*Oocystis*	1
Trebouxiophyceae	Trebouxiophyceae	*Crucigenia*	1
Desmidiales	Closteriaceae	*Closterium*	2
	Desmidiaceae	*Cosmarium*	4
		Staurastrum	1
		Triplastrum	2
		Triploceras	1
Zygnematales	Zygnemataceae	*Spirogyra*	15
		Temnogyra	1
		Zygnema	2
Bryopsidales	Bryopsidaceae	*Bryopsis*	1
	Caulerpaceae	*Caulerpa*	12
	Codiaceae	*Codium*	4
	Halimedaceae	*Halimeda*	2
	Udoteaceae	*Boodleopsis*	1
Cladophorales	Boodleaceae	*Boodlea*	1
		Phyllodictyon	1
	Cladophoraceae	*Chaetomorpha*	6
		Cladophora	13
		Cladophorella	2
		Lola	3
		Rhizoclonium	11
	Pithophoraceae	*Pithophora*	3
	Siphonocladaceae	*Dictyosphaeria*	1

(continued)

Table 5.1 (continued)

Order	Family	Genus	No. of species
Ulvales	Ulvaceae	*Enteromorpha*	6
		Ulva	4
Dasycladales	Polyphysaceae	*Acetabularia*	1
Trentepohliales	Trentepohliaceae	*Trentepohlia*	4
Ulotrichales	Ulotrichaceae	*Ulothrix*	2
Charales	Characeae	*Chara*	2
		Nitella	1
Orders – 15	**Families – 32**	**Genera – 50**	**Species – 134**

Source: In-house study based on literature review

the eastern side of Bangladesh with the entire area having been divided into 4 zones (Fig. 5.2).

5.2.1 Ecosystem Dynamics Influencing Algae

The deltaic region of Sundarbans has proved to be one of the most dynamic estuarine deltas in the world that is constantly being reshaped. The genesis of the ecosystem can be expressed as a cumulative outcome of the combined effects of the deltaic deposits of the Ganges-Brahmaputra-Meghna rivers, tidal deposits from the Bay of Bengal, an overall southerly tectonic tilt, sediment compaction, change impacted owing to coastal management, all and more of these augmented by innumerable anthropogenic reasons (Bhattacharya 1999; Ericson et al. 2006; Syvitski 2008; Brown and Nicholls 2015). The dynamic nature of the ecosystem provides excellent examples of perceivable ecological processes. Significant importance of such processes is highlighted in the formation of the delta followed by distinct succession patterns of the mangrove flora, which is initiated by means of colonization of the first formed ill consolidated soil by different algae and bacteria.

The geomorphic units that classify the entire Sundarbans include coastal alluvial plains and alluvial plains, mangrove swamps, estuaries, river channels, creeks, salt flats, beaches, mud flats and dune complex. The geo-morphological dynamics of the area can be explained on the basis of impacts of sea-level rise, littoral current patterns, and sediment influx in different rivers. The major rivers of the system viz., Hugli, Muriganga, Saptamukhi, Thakuran, Matla, Bidya, Goasaba, Harinbari or Herobhanga, Raimangal, Malancha, Arpangachia, Passur and Baleswar along with several other smaller rivers, creeks, canals create a criss-cross network across the entire deltaic region. The signature mangroves in the region flourish well owing to their positional advantage in the meso-macrotidal area of the Bengal delta. The area is also built in such a way as to receive abundant freshwater supply through river discharges. Unfortunately, most of these freshwater connections have ceased to exist

Table 5.2 Richness of Rhodophyta taxa in Sundarbans of India and Bangladesh

Order	Family	Genus	Species #
Acrochaetiales	Acrochaetiaceae	*Acrochaetium*	6
Bonnemaisoniales	Bonnemaisoniaceae	*Asparagopsis*	1
		Falkenbergia	1
Bangiales	Bangiaceae	*Bangia*	1
		Porphyra	1
Ceramiales	Ceramiaceae	*Antithamnion*	1
		Callithamnion	1
		Centroceras	1
		Ceramium	5
		Crouania	1
	Dasyaceae	*Heterosiphonia*	1
	Delesseriaceae	*Vanvoorstia*	1
		Caloglossa	2
	Rhodomelaceae	*Acanthophora*	1
		Bostrychia	3
		Herposiphonia	3
		Laurencia	2
		Lophocladia	1
		Polysiphonia	3
		Pterosiphonia	1
	Sarcomeniaceae	*Cottoniella*	1
Corallinales	Corallinaceae	*Amphiroa*	2
		Jania	2
	Lithothamniaceae	*Lithothamnion*	1
Erythropeltales	Erythrotrichiaceae	*Erythrotrichia*	1
Erythropeltales	Erythrotrichiaceae	*Erythrocladia*	1
Gelidiales	Gelidiaceae	*Gelidiella*	3
		Gelidium	2
Gigartinales	Caulacanthaceae	*Catenella*	3
	Dumontiaceae	*Dudresnaya*	1
	Gigartinaceae	*Gigartina*	1
	Kallymeniaceae	*Callophyllis*	2
		Kallymenia	4
	Solieriaceae	*Eucheuma*	1
		Sarconema	1
	Cystocloniaceae	*Hypnea*	5
		Calliblepharis	1
Gracilariales	Gracilariaceae	*Gracilaria*	2
Halymeniales	Halymeniaceae	*Halymenia*	3
Hapalidiales	Hapalidiaceae	*Melobesia*	1
		Messophyllum	1

(continued)

Table 5.2 (continued)

Order	Family	Genus	Species #
Nemaliales	Galaxauraceae	*Actinotrichia*	1
	Liagoraceae	*Liagora*	3
	Scinaiaceae	*Scinaia*	2
Rhodymeniales	Champiaceae	*Champia*	1
	Rhodymeniaceae	*Chrysymenia*	3
Peyssonelliales	Peyssonelliaceae	*Cthonoplastis*	1
		Peyssonellia	1
Goniotrichales	Goniotrichaceae	*Goniotrichum*	1
Orders – 15	**Families – 28**	**Genera – 49**	**Species – 89**

Source: In-house study based on literature review

Table 5.3 Richness of Euglenophyta taxa in Sundarbans of India and Bangladesh

Order	Family	Genus	Species #
Euglenales	Euglenaceae	*Euglena*	11
		Euglenaformis	1
		Monomorphina	2
		Trachelomonas	3
	Phacaceae	*Lepocinclis*	9
		Phacus	19
Eutreptiales	Astasiaceae	*Astasia*	3
Orders – 2	**Families – 3**	**Genera – 7**	**Species – 48**

Source: In-house study based on literature review

Table 5.4 Richness of Dinophyta taxa in Sundarbans of India and Bangladesh

Order	Family	Genus	Species #
Dinophysiales	Dinophysiaceae	*Dinophysis*	1
Noctilucales	Noctilucaceae	*Noctiluca*	1
Gonyaulacales	Ceratiaceae	*Ceratium*	12
	Cladopyxidaceae	*Cladopyxis*	1
	Pyrophacaceae	*Pyrophacus*	1
Peridiniales	Protoperidiniaceae	*Protoperidinium*	13
	Peridiniaceae	*Diplopsalis*	1
		Peridinium	4
Prorocentrales	Prorocentraceae	*Prorocentrum*	1
Orders – 5	**Families – 8**	**Genera – 9**	**Species – 35**

Source: In-house study based on literature review

in recent times, especially in the mangrove forest stretches, where choking of the upstream freshwater discharge of the distributaries of the Ganges is intensely observed (Sen and Naskar 2003). According to Mandal and Naskar (2008) tidal waters bring in nutrients into the ecosystem, thus increasing their availability, not only to the mangroves that thrive in the region but also to the algae that inhabit such

Table 5.5 Richness of Heterokontophyta taxa in Sundarbans of India and Bangladesh

Order	Family	Genus	Species #
Xanthophyceae (Yellow-green algae)			
Vaucheriales	Vaucheriaceae	*Vaucheria*	5
Mischococcales	Centritractaceae	*Centritractus*	1
Orders – 2	**Families – 2**	**Genera – 2**	**Species – 6**
Phaeophyceae (Brown algae)			
Dictyotales	Dictyotaceae	*Dictyopteris*	2
		Dictyota	7
		Lobophora	1
		Padina	9
Ectocarpales	Actinetosporacea	*Feldmannia*	4
		Giffordia	5
	Chordariaceae	*Myriactula*	1
	Ectocarpaceae	*Ectocarpus*	2
	Scytosiphonaceae	*Chnoospora*	1
		Colpomenia	2
		Hydroclatharus	2
		Petalonia	1
		Rosenvingea	3
Sphaceleriales	Sphacelariaceae	*Sphacelaria*	2
Laminarales	Lessoniaceae	*Eisenia*	1
Ishigeales	Ishigeaceae	*Ishigae*	1
Fucales	Sargassaceae	*Sargassum*	9
Orders – 6	**Families – 9**	**Genera – 17**	**Species – 53**
Bacillariophyceae (Diatoms)			
Aulacoseirales	Aulacoseriaceae	*Aulacoseira*	1
Coscinodiscales	Coscinodiscaceae	*Coscinodiscus*	20
	Hemidiscaceae	*Actinocyclus*	4
		Hemidiscus	3
		Roperia	1
Corethrales	Corethraceae	*Corethron*	3
Melosirales	Melosiraceae	*Melosira*	7
	Paraliaceae	*Paralia*	1
Rhizosoleniales	Probosciaceae	*Proboscia*	2
	Rhizosoleniaceae	*Guinardia*	3
		Rhizosolenia	10
Stephanopyxales	Stephanopyxidaceae	*Stephanopyxis*	2
Triceratiales	Triceratiaceae	*Triceratium*	3
Biddulphiales	Bellerocheaceae	*Bellerochea*	1
	Biddulphiaceae	*Biddulphia*	8
		Eucampia	3
Chaetocerotales	Chaetocerotaceae	*Bacteriastrum*	5
		Chaetoceros	24
	Leptocylindraceae	*Leptocylindrus*	2

(continued)

Table 5.5 (continued)

Order	Family	Genus	Species #
Eupodiscales	Eupodiscaceae	*Odontella*	2
Hemiaulales	Hemiaulaceae	*Climacodium*	1
		Hemiaulus	3
	Isthmiaceae	*Isthmia*	1
Lithodesmiales	Lithodesmiaceae	*Ditylum*	3
		Lithodesmium	1
		Tropidoneis	3
Stephanodiscales	Stephanodiscaceae	*Cyclotella*	7
Thalassiosirales	Thalassiosiraceae	*Coscinosira*	1
		Thalassiosira	17
		Planktoniella	2
	Lauderiaceae	*Lauderia*	2
	Skeletonemataceae	*Skeletonema*	1
		Schroderella	1
Toxariales	Climacospheniaceae	*Climacosphenia*	3
Bacillariales	Bacillariaceae	*Bacillaria*	2
		Cylindrotheca	2
		Giffenia	1
		Nitzschia	18
		Pseudonitzschia	4
Cocconeidales	Cocconeidaceae	*Cocconeis*	2
Cymbellales	Anomoeoneidaceae	*Anomoeoneis*	1
	Cymbellaceae	*Cymbella*	3
		Okedenia	1
	Gomphonemataceae	*Gomphonema*	1
Eunotiales	Eunoticeae	*Amphicampa*	1
		Eunotia	2
Fragilariales	Fragilariaceae	*Fragilaria*	2
		Synedra	2
Licmophorales	Licmophoraceae	*Licmophora*	2
Mastogloiales	Achnanthaceae	*Achnanthes*	3
Naviculales	Amphipleuraceae	*Amphiprora*	2
		Frustulia	1
	Diploneidaceae	*Diploneis*	4
	Naviculaceae	*Navicula*	23
		Haslea	1
	Pinnulariaceae	*Pinnularia*	3
	Pleurosigmataceae	*Gyrosigma*	7
		Pleurosigma	10
	Stauroneidaceae	*Stauroneis*	1
Rhaphoneidiales	Rhaphoneidaceae	*Rhaphoneis*	2
Rhopalodiales	Rhopalodiaceae	*Epithemia*	1

(continued)

Table 5.5 (continued)

Order	Family	Genus	Species #
Surirellales	Entomoneidaceae	*Entomoneis*	2
	Surirellaceae	*Campylodiscus*	2
		Surirella	4
Tabellariales	Tabellariaceae	*Asterionella*	1
		Diatoma	2
Thallasionematales	Thallasionemataceae	*Thallasionema*	1
		Thalassiothrix	2
		Lioloma	2
Thalassiophysales	Catenulaceae	*Amphora*	7
Orders – 29	**Families – 45**	**Genera – 70**	**Species – 275**

Source: In-house study based on literature review

areas. They further comment that earlier tidal water was considered as the only factor that plays a major role in the regeneration and growth of mangroves, research down the years have proven otherwise, and it has been observed that factors like rainfall, atmospheric humidity and moderate temperatures play more significant roles in sustaining this ecosystem.

The entire Sundarbans experiences tropical climate, with precipitation ranging between 200 and 300 cm, atmospheric humidity between 60% and 90%, and temperatures ranging between 19 and 35 °C, these have proven to be ideal for mangrove growth (Blasco 1977; Naskar and Mandal 1999). Added to these is the gentle slope of the low-lying coast, tidal water reaching up to about 110 km inland, and monsoon wind influenced by annual rainfall of 1500–2000 mm (Rahman and Asaduzzaman 2010), that has facilitated gregarious mangrove expansion in the region (Spalding et al. 2010).Tides are an important determinant of the dynamics of Sundarbans and are responsible for inundating the entire Sundarbans twice a day with the tidal currents changing their direction every 6 h in a cycle. The maximum tidal rise and fall is observed in the spring tides of March and April. Tidal inundation contributes to the sustenance of the mangrove forests as transfer of mangrove seeds and propagules are facilitated through this phenomenon of regular inundation.

Nevertheless, an unfortunate realization that holds good regardless of the geographical boundaries between India and Bangladesh is that the coastal regions of this entire delta are among the most vulnerable regions in the world experiencing rapid salinity intrusion and other climate change impacts (IPCC 2007). The rapid and extreme climatic changes, compounded with anthropogenic pressures, are thought to be the principal threats in the form of habitat alterations of the mangrove flora and associated algae together with the faunal components. They also pose threat to wetland dynamics and functions which ultimately affect the valuable ecosystem services provided by this ecosystem. Thus, it becomes very essential to conduct intense scientific study on climate change and associated environmental changes with their multidimensional effect on eco-socio-economic conditions, influencing

Table 5.6 Richness of Cyanobacterial taxa in Sundarbans of India and Bangladesh

Order	Family	Genus	Species #
Chroococcales	Aphanothecaceae	Aphanothece	2
	Cyanothrichaceae	*Johannesbaptistia*	1
	Microcystaceae	*Gloeocapsa*	7
		Microcystis	6
	Stichosiphonaceae	*Stichosiphon*	1
Nostocales	Nostocaceae	*Anabaena*	8
		Anabaenopsis	1
		Nostoc	4
	Aphanizomenonaceae	*Raphidiopsis*	2
	Scytonemataceae	*Scytonema*	3
	Rivulariaceae	*Calothrix*	4
		Gloeotrichia	1
	Hapalosiphonaceae	*Mastigocoleus*	1
Pleurocapsales	Dermocarpellaceae	*Dermocarpa*	3
	Xenococcaceae	*Xenococcus*	3
Pseudanabaenales	Schizotrichaceae	*Schizothrix*	3
Oscillatoriales	Gomontiellaceae	*Katagnymene*	1
	Oscillatoriaceae	*Lyngbya*	14
		Oscillatoria	18
		Phormidium	8
	Microcoleaceae	*Arthrospira*	1
		Hydrocoleum	2
		Microcoleus	3
		Trichodesmium	2
Spirulinales	Spirulinaceae	*Spirulina*	8
Synechococcales	Chamaesiphonales	*Chamaesiphon*	1
	Leptolyngbyaceae	*Leptolyngbya*	4
		Planktolyngbya	1
	Merismopediaceae	*Aphanocapsa*	5
		Merismopedia	4
Orders – 7	**Families – 19**	**Genera – 30**	**Species – 122**

Source: In-house study based on literature review

coastal habitats, amenities, and health (Basu Neogi et al. 2017). In the same context, rising temperature has pronounced effect on phenology, diversity, distribution and dynamics of the communities (Walters et al. 2008). According to Mitra and his associates (Mitra et al. 2009; Chatterjee et al. 2015) the rate of increasing surface water temperature in the Sundarbans region (0.05 °C per year) is much higher than in the Pacific (0.01–0.015 °C per year) and in the tropical Atlantic Ocean (0.01–0.02 °C per year). However, some reports suggest that increased temperature has favoured the growth of mangroves (Rahman and Asaduzzaman 2010) and sometimes the phytoplankton (Manna et al. 2010).

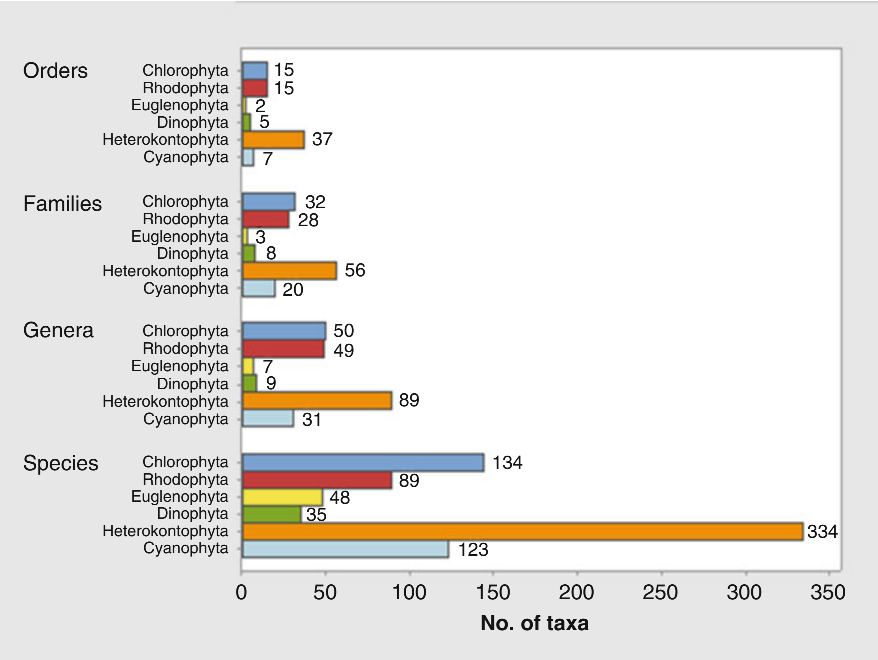

Fig. 5.1 Estimates of different algal taxa in different available publications or reports from Sundarbans of India and Bangladesh. (Source: In-house study)

Annual salinity of the Sundarbans region is greatly varied and can be correlated with fresh water influx. During monsoon, fresh water flow is maximum due to high precipitation in the order of 2000–1600 mm (Rahman and Asaduzzaman 2010) and the salinity remains low which gradually increases from post-monsoon period and reaches the maximum during summer. Besides this monsoon driven salinity alteration, there exist several forces which are known to change the salinity regimes.

Estimates and averages of selected water physico-chemical parameters *viz*., pH, dissolved oxygen, temperature and salinity, which are known to greatly influence algal diversity of all the four zones being considered here, show that the annual variations of pH is between 7 and 9, dissolved oxygen between 3.85 and 10 mgl^{-1}, surface temperature between 20 and 34°C, and salinity between 2.5 and 30.5 dSm^{-1} (Hoque et al. 1999; Manna et al. 2010; Bhattacharjee et al. 2013; Rahaman et al. 2013; Mukherjee et al. 2015; Bir et al. 2015; Sekh et al. 2016).Obviously, with annual averages of the above physico-chemical variables taken into consideration, Sundarbans behaves more like a single system in entirety, although, however, with only considerable gradients observed in terms of dissolved oxygen and salinity. This understanding pertains to the estuarine system within the entire deltaic mass of mangrove land spread over India and Bangladesh. It is beyond the scope of this chapter to discuss parameters other than the above that have synergies amongst them

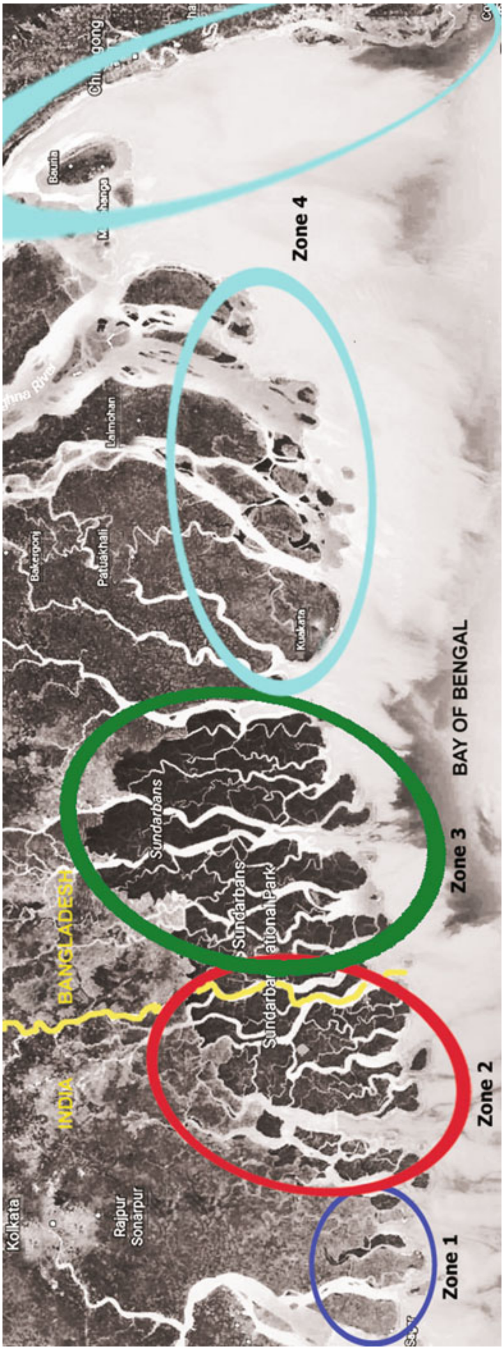

Fig. 5.2 Sundarbans of India and Bangladesh divided into four zones; zone 1-spill over mangrove area in India, zone 2-mangrove forest zone in India, zone 3-mangrove forest zone in Bangladesh, zone 4- spill over mangrove area of Bangladesh. (Source: In-house study)

and dictate on the dynamics of this ecosystem and perpetually influence the dynamics of all biota that inhabit this land including the algae.

5.2.2 Algal Dynamics

Studies on dynamics of algae have numerous perspectives and have been dealt and defined world-wide on scales and patterns of various thrust areas and magnitude. The common perspectives of studies on algal dynamics include diversity dynamics, population dynamics, community dynamics, ecosystem dynamics, patch dynamics, landscape dynamics, spatio-temporal dynamics, nutrient dynamics, and evolutionary dynamics. The entire Sundarbans has documented representation of 6 algal lineages out of the 9 reported lineages. These algae occupy different habitats and niches in the ecosystem. These organisms are responsible for modifying the system, are vulnerable towards the changes in the ecosystem, and are capable of indicating the structures, processes, and health of the habitats they occupy. These along with other characters of the algae inhabiting the Sundarbans contribute to defining their dynamics. Algal dynamics in terms of diversity dynamics on a spatio-temporal scale will be discussed further.

The distributional records of all the 762 algal species (Annex Table 1) reported from the entire Sundarbans spread over India and Bangladesh indicate only 29 species reported as having common distribution over the four zones and interestingly 23 species out of these are diatom species (Table 5.7, Fig. 5.3). About 258 species are reported from zone 1,319 species from zone 2, 152 species from zone 3, and 307 species from zone 4 (Table 5.8). The algal taxa representation in this entire stretch of Sundarbans includes 81 orders, 147 families, 235 genera, and 762 species.

Species distribution models are particularly useful in mapping such organism distributions over spatial and/ temporal scales to develop an understanding of the distributional gradients and also get an insight into ecological consequences or inversely ecological influences over such organisms of interest. A Pearson correlation test was conducted on the algae reported zone-wise, (Table 5.9) to find how the zones correlate with each in terms of algal species assemblage reported at each site. This was followed by a spatial representation of the 762 algal species using the binary data for presence or absence of a species as reported in each of the four zones following which autocorrelation has been generated (Fig. 5.4).

Zone 4 correlates well in terms of species assemblage with all the three other zones. In fact, the strong negative correlation of zone 4 with zones 1 and 2 imply the mounting differences in species assemblages in these three different zones. On the other hand, zone 4 positively correlates with zone 3 suggesting similarities in species assemblages in the two zones. Zones 1 and 2 correlate negatively with each other in terms of their reported algal assemblages. The algal dynamics is further reflected in the species distribution pattern in Fig. 5.4.

The distribution relates with space-lag distribution of the algal species as binary data which is at random. The patterns of distribution based on autocorrelation are

Table 5.7 Common species of algae reported from all the zones of Sundarbans in India and Bangladesh

Sl. no	Algal species	Habitat	Zone			
			1	2	3	4
1	*Chaetomorpha gracilis*	Alongwith *Ulva* sp. on bricks, beaches, or marine	✓	✓	✓	✓
2	*Rhizoclonium riparium*	On pneumatophores in high saline areas	✓	✓	✓	✓
3	*Catenella nipae*	On barks of mangroves in upper littoral zones	✓	✓	✓	✓
4	*Ceratium furca*	Marine phytoplankton	✓	✓	✓	✓
5	*Ceratium tripos*	Marine phytoplankton	✓	✓	✓	✓
6	*Coscinodiscus centralis*	Estuarine phytoplankton	✓	✓	✓	✓
7	*Coscinodiscus eccentricus*	Planktonic from high saline river water	✓	✓	✓	✓
8	*Coscinodiscus gigas*	Planktonic from high saline river water	✓	✓	✓	✓
9	*Coscinodiscus jonesianus*	Marine phytoplankton	✓	✓	✓	✓
10	*Coscinodiscus oculus-iridis*	Marine phytoplankton	✓	✓	✓	✓
11	*Coscinodiscus radiatus*	Marine phytoplankton	✓	✓	✓	✓
12	*Rhizosolenia setigera*	Planktonic from high saline river water	✓	✓	✓	✓
13	*Triceratium favus*	Marine phytoplankton	✓	✓	✓	✓
14	*Biddulphia mobiliensis*	Planktonic from high saline river water	✓	✓	✓	✓
15	*Biddulphia sinensis*	Planktonic from high saline river water	✓	✓	✓	✓
16	*Bacteriastrum cosmosum*	Planktonic from high saline river water	✓	✓	✓	✓
17	*Bacteriastrum delicatulum*	Marine phytoplankton	✓	✓	✓	✓
18	*Planktoniella sol*	Estuarine phytoplankton	✓	✓	✓	✓
19	*Skeletonema costatum*	Marine phytoplankton	✓	✓	✓	✓
20	*Nitzschia closterium*	Estuarine phytoplankton	✓	✓	✓	✓
21	*Nitzschia sigma*	Estuarine phytoplankton	✓	✓	✓	✓
22	*Synedra ulna*	Estuary and brackish water	✓	✓	✓	✓
23	*Pleurosigma elongatum*	Marine phytoplankton	✓	✓	✓	✓
24	*Pleurosigma normanii*	Marine phytoplankton	✓	✓	✓	✓
25	*Asterionella japonica*	Planktonic from high saline river water	✓	✓	✓	✓
26	*Thallasionema nitzschioides*	Marine phytoplankton	✓	✓	✓	✓
27	*Thalassiothrix frauenfeldii*	Marine phytoplankton	✓	✓	✓	✓
28	*Thalassiothrix longissima*	Marine phytoplankton	✓	✓	✓	✓
29	*Lyngbya confervoides*	Bottom biota of high saline brackishwater fishery	✓	✓	✓	✓

Source: In-house study

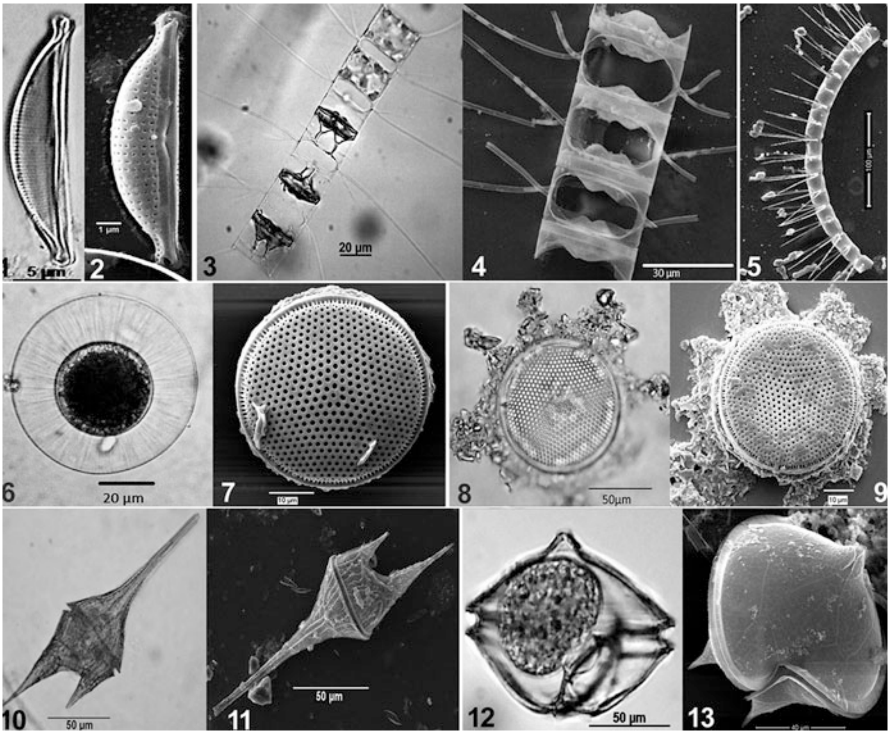

Fig. 5.3 Diatoms and Dinoflagellates of Sundarbans. Diatoms – 1. *Amphora* sp. (LM); 2. *Amphora* (SEM); 3. *Chaetoceros lorenzianus* (LM); 4. *Chaetoceros lorenzianus* (SEM); 5. *Chaetoceros pseudocurvisetus* (LM); 6. *Planktoniella sol* (LM); 7. *Planktoniella sol* (SEM); 8. *Planktoniella blanda* (LM); 9. *Planktoniella blanda* (SEM); Dinoflagellates – 10. *Ceratium furca* (LM); 11. *Ceratium furca* (SEM); 12. *Protoperidinium* sp. (LM); 13. *Protoperidinium* sp. (SEM). (Source: In-house study)

reflective of the Pearson correlation coefficients, but the former gives a better insight on the extent of differences in algal population distribution over the spatial expanse of zone 1–4. Maximum correlation in species distributional trends in all the four zones is observed near correlation 0 implying independence of species in terms of their distribution over the spatial scale or in adjacent or near-adjacent zones of observance. At low space-lag value high correlation is observed and distinctiveness of species assemblages can be observed. At higher space-lag, species distribution takes on negative correlativity and is overlapping in nature. To get a better understanding of algal dynamics in the four different zones, cluster analysis for Euclidean distance and Bray-Curtis similarity of the four zones was performed (Fig. 5.5).

The cluster analysis performed yielded a single-link dendrogram in case of Euclidean distance and a complete–link dendrogram in case of Bray-Curtis similarity. This implies that in case of Euclidean distance the distance calculated between two clusters is equal to the shortest distance from any member of one cluster to any member of the other. Thus, according to our species assemblage data, only one

Table 5.8 Representation of algal taxa in the Sundarbans of India and Bangladesh

	Orders				Families				Genera				Species			
Lineage	Z 1	Z 2	Z 3	Z4	Z 1	Z 2	Z 3	Z4	Z 1	Z 2	Z 3	Z4	Z 1	Z 2	Z 3	Z4
Chlorophyta	11	13	7	4	17	20	7	8	16	38	12	17	47	66	16	43
Rhodophyta	2	3	4	14	2	5	5	28	4	7	6	46	6	12	9	86
Euglenophyta	2	2	2	2	2	2	2	3	2	6	2	4	8	37	11	9
Dinophyta	4	2	3	3	4	2	6	4	6	2	4	5	20	6	8	14
Xanthophyceae	0	1	2	1	0	1	2	1	0	1	2	1	0	2	4	3
Phaeophyceae	0	2	1	6	0	2	1	9	0	2	1	17	0	2	1	53
Bacillariophyceae	27	28	21	21	38	33	26	28	58	40	33	39	159	87	94	95
Cyanophyta	5	7	4	2	8	21	8	2	10	31	5	2	18	107	9	4
Total in each zone	51	58	44	53	71	86	57	83	96	127	65	131	258	319	152	307
TOTAL TAXA	**81**				**147**				**235**				**762**			

Source: In-house study

Table 5.9 Pearson correlation coefficients of algal species assemblage in the four zones of Sundarbans in India and Bangladesh

	Zone 1	Zone 2	Zone 3
Zone 2	−0.179**		
Zone 3	0.031	−0.023	
Zone 4	−0.263**	−0.296**	0.084**

**Significant at 0.01 level
Source: In-house study

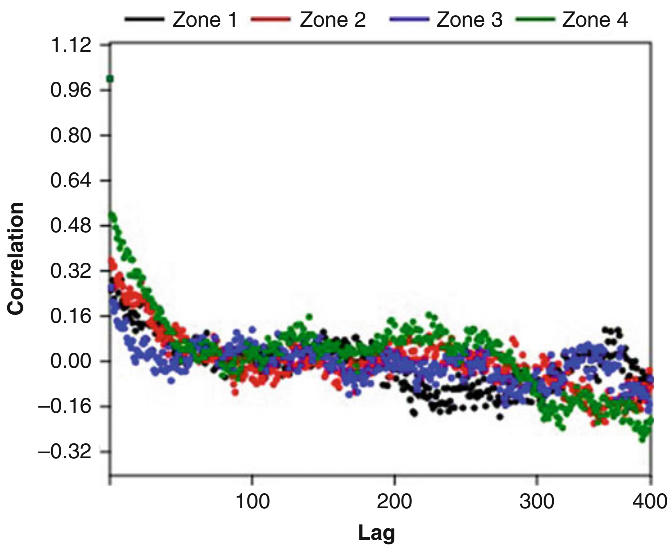

Fig. 5.4 Autocorrelation based Spatial Distribution Model of the algae in the four zones of Sundarbans in India and Bangladesh. (Source: In-house study)

clustering is considered significant, that gives high bootstrap value of 100 and is at an Euclidean distance of ~24. This clustering separates zone 2 as a separate cluster and zone 1, zone 3, and zone 4 as a separate cluster. In terms of the dendrogram obtained for Bray-Curtis similarity, though all the bootstrap values for the clusters are high, the Bray-Curtis similarity values are very low. Thus, only the clustering of zone 3 and zone 4 is considered as significant.

As such, a clear gradient of species assemblage is not perceivable through the different zones of Sundarbans, which agrees with the finding of non-existence of such gradient in terms of physico-chemical parameters over the entire stretch as well. Nevertheless, it has to be kept in mind that all works considered for these analyses have been taken up at different times under different stretches, and by different groups working on the Sundarbans in India and Bangladesh. So, the studies cannot be claimed to be *in sync* with each other. Albeit such studies over the years have yielded a plentitude of data, the focus or objectives of such studies have witnessed tremendous variations, with some studies concentrating only on phytoplankton,

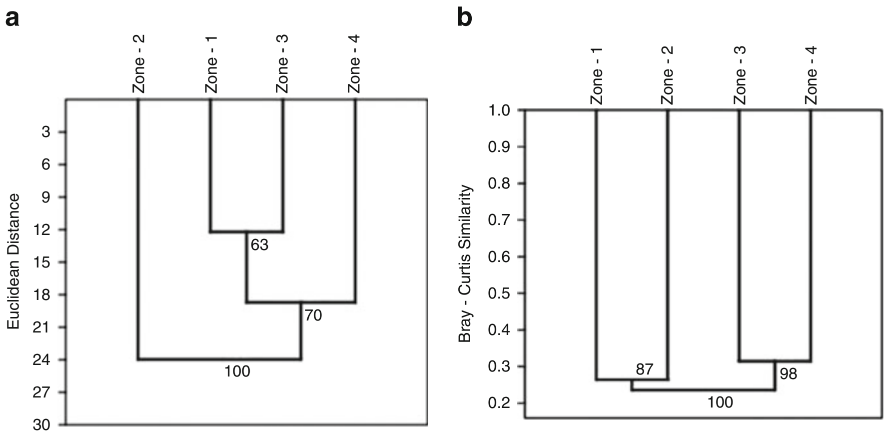

Fig. 5.5 Cluster analysis of species assemblage-based data to determine extent of similarity between the four zones in Sundarbans of India and Bangladesh. (**a**) Euclidean distance based on Ward's method; (**b**) Bray-Curtis similarity based on UPGMA. (Source: In-house study)

some others on benthic forms, and some on the macroalgal species of the forest floors and littoral regions. This is also the cause of getting differences in our expected behaviour of species richness in the four different zones. With maximum studies having been undertaken in zone 2 and zone 4 in terms of phytoplankton analysis as well as macropytic algae on forest floors, the results are indicative in explaining such anomalies too.

5.2.3 Algae as Climate Change Proxies

Different organisms used for interpreting ecological or climatic history of an area and for reconstructing the chronology of environmental changes that the area has experienced are included in the broad category of palaeoecological proxies. These organisms are also capable of serving as tools to make long-term predictions of ecosystem stability and sustenance. Recent times have seen the prevalence of diatoms as one of the most favoured proxy for reconstruction as well as predictions of environment and climate, especially of Holocene period (Mandal et al. 2015b). One noteworthy study belongs to Holocene palaeoclimate research on Lake Baikal in southeast Siberia. This happens to be a strategic site in terms of its closeness to the boundaries of Siberian high pressure and Asian monsoon weather zone, that is also away from the oceanic influences. Many studies have attempted the use of diatom assemblages of Lake Baikal to reconstruct Holocene climate variability in this region (Bradbury et al. 1994; Mackay et al. 1998; Bangs et al. 2000). Subsequent studies have established relationship between diatoms and environmental parameters in closed-lake basin systems to Holocene climates from around the world e.g., North

America (Cumming and Smol 1993; Wilson et al. 1994, 1996; Laird et al. 1998; Last and Scheweyn 1985), Central America (Metcalfe 1995), Africa (Gasse et al. 1997), Australia (Gell 1997), Europe (Reed 1998), Antarctica (Roberts and McMinn 1998), and Greenland (Ryves et al. 2002). Many other studies have resorted to multivariate approaches, while attempting to find climatic or environmental relationships between diatoms in surface sediments of marine environment and environmental variables. Such studies are predominantly on sea-surface temperatures. A study on the relationships between environmental variables and diatom species executed off the north Icelandic shelf suggests a distinct period of cooling since around 2200 cal yrs. BP up to the present, which is coincident with neo-glacial cooling in other regions (Jiang et al. 2002). A very conclusive study on marine diatom assemblage as evidenced for Holocene climate variability relates to a multi-proxy study undertaken in the Antarctic Peninsula that use multiple regression analysis of diatom data and environmental variables of the sediments (Taylor and McMinn 2002).

Studies have been able to indicate that araphidinate diatoms increase substantially with rising eutrophication accompanied by a decrease in centric diatom species (Stockner 1971, 1972; Stockner and Benson 1967). The inverse relationship between *Fragilaria crotonensis* and *Melosira italica* has been reported as a common phenomenon in a vast majority of temperate lakes that have recently undergone cultural eutrophication (Stockner 1971) rendering *Fragilaria crotonensis* as an accepted and reliable character-form of eutrophic waters. A study on diatom palaeoecology undertaken in the Everglades National Park puts forth interesting observations that validate the efficiency of soil diatoms in inferring past ecological history of areas under study (Cooper 1995; Pyle et al. 1998). The study also dwells upon the interesting finding of the significance of Centric: Pennate (c:p) ratio as a useful indicator of the relative availability of planktonic and benthic habitats (Cooper 1995). It also reveals an increase in the ratio over time. The factors attributed as responsible for such increase in c:p ratio include increased nutrient concentration, increased levels of suspended sediments, and increased depths of water column. Interestingly, many such changes in diatom species abundance were found to be preserved between 40 and 50 cm depths and many such trends even reversed between 10 and 20 cm. This study on diatom assemblages conclusively points towards an indication of increasing salinity trends in the Florida Bay.

A study by the authors' group Mandal et al. (2015a) in the Indian Sundarbans on sediment cores (~50 cm depth) from areas falling within zone 2, reports, for the first time, presence of 15 species of diatoms from sediment samples. Only 4 species out of these have previously been reported from the estuarine waters, namely *Cyclotella striata*, *Diploneis smithii*, *Coscinodiscus radiatus* and *Coscinodiscus wailesii*. The rest of the 11 species are first reports made not only from the sediments but also from this system. The study highlights that three of the newly reported species of this region, *Aulacoseira granulata*, *Amphicampa eruca*, and *Epithemia turgida* are interestingly freshwater species. The presence of such indicator species in the sediments of this saline environment is attributed to loss of freshwater conditions and increasing salinity of this area.

Mandal et al. (2015a) have also recorded the presence of *Giffenia cocconeiformis* for the first time from Indian Sundarbans. This rare species is also interesting in terms of deciphering changes in the ecosystem with diatom indicators. It has earlier been reported as part of the marine and brackish diatom assemblages of Nanaura mudflats in Japan (Park et al. 2012). The species has also been reported as a diatom fossil species in marine mud facies in Holocene sediment samples of Dobadia, Bangladesh (Rashid 2014), where the species is reported to co-occur with *Coscinodiscus radiatus* and *Cyclotella striata*, and this holds similarity with the diatom assemblages obtained by Mandal et al. (2015a). According to Rashid (2014), pollen grains of mangrove *Xylocarpus* sp. and *Lumnitzera racemosa* are found within these assemblages implying that the mud was deposited in an intertidal mudflat though the collection site is in central Bangladesh (zone 3), bearing evidence of coastal deposition in such mud facies. Incidentally, Rashid (2014), however, attributed such depositions primarily to tectonic activity. The diatom assemblages in the sediment profiles at the sampling sites considered by Mandal et al. (2015a) (the authors' group) also suggest the presence of a freshwater environment at some point of time during the genesis of this deltaic region. This could only have been possible with higher influx of freshwater during the said period. Thus, the indicator diatom assemblages from zone 2 of Indian Sundarbans also substantiate the findings of Morgan and McIntire (1959), Naskar and Guha Bakshi (1987), Dasgupta et al. (2012), which indicate a very slow tilting of the coast in the north-western part of Sundarbans (within zone 2) owing to tectonic movements. Simultaneous subsidence of the eastern part of Sundarbans (within zone 3) is also observed. Mandal et al. (2015a) also report about the cumulative effect which is presently experienced in the form of decreased freshwater influx in the western part of Sundarbans.

In another study by the authors' group, investigation has been carried out on a seasonal diatom genus – *Planktoniella* (Sekh et al. 2016). The study highlights the fact that the organism dominant in phytoplankton samples throughout the year also exert significant influence on the seasonal species, *Planktoniella* spp. In this case, species like *Coscinodiscus* - *C. argus* and *C. centralis* are found to be dominant during the period when both the species of *Planktoniella* are absent from the phytoplankton samples. Although *Protoperidinium pallidum* as a bloom species in the studied site did not exert any perceivable influence on the presence of *Planktoniella* and both the species were found to be present in their usual limited numbers in the samples. Similarly, species like *Chaetoceros lorenzianus* and *C. pseudocurvisetus* dominant in phytoplankton samples were observed to promote the presence of *Planktoniella* and exhibit strong positive correlation. Similar accounts of co-existence of *Planktoniella* with numerous other phytoplankton forms are found in the literature.

The study also shows that the genus has proven to be a good indicator of even slight variations in temperature, turbidity, and DO in the estuarine system of Indian Sundarbans acting as excellent response variables. The study could generate two regression models for the two-different species of *Planktoniella* which included temperature, turbidity, and DO as predictor variables.

The regression equation generated for *P. blanda* with *p* value = 0.000:

$$P.blanda \;=\; -2.6 - 0.425\text{Temp.} - 0.00082\ \text{Turb.} + 0.255\text{DO}$$

The regression equation generated for *P. sol* with *p* value = 0.000:

$$P.sol = 29.4 \;\; - 0.302\text{Temp.} - 0.00161\text{Turb.} - 0.682\text{DO}$$

In the context of associated climate change effects, the study showed that temperature, turbidity, and DO can effectively serve as predictor variables for the two species of *Planktoniella* as response variables. The equation in case of *P. blanda* predicts that with each unit decrease in temperature, *P. blanda* counts can increase by 0.425 considering the interaction with other predictor variables. Similarly, in case of *P. sol*, a single unit decrease in temperature can increase *P. sol* count by 0.302 in consistence with other predictor variables.

Findings of significant importance that address future climate change effects on diatoms can be found worldwide. Boeff et al. (2016) have highlighted different responses recorded in the sediments of three large lakes in northeast USA to climate-driven changes using a diatom-based thermal stratification index and support the use of diatoms as indicator species in reconstructing lake thermal stratification patterns when paired with site-specific morphometric and ecological data. Barron et al. (2013) report an extensive study related to response of diatoms and silicoflagellates to climate change in the California Current in Santa Barbara Basin over about 250 years spanning over a period since 1748 through 2007. They studied diatoms and silicoflagellate assemblages for the purpose of determining the timing and impact of possible twentieth century warming on several different components of the plankton. Their findings highlight the decline of *Thalassionema nitzschioides* and *Distephanus speculum*s, in the 1920s, with both the species being indicative of cooler waters, these results prove to be consistent with the influence of twentieth century warming on marine ecosystems. Interestingly, a cooling of surface waters coincident with the one of the strongest La Niña events of the twentieth century in the late 1998 brought about a return to pre-1940 values of these cool water taxa. Diatom response to recent climatic change in a high arctic lake was studied by Michelluti et al. (2003). The study was conducted in Char Lake for studying physical, chemical and biological variables. The water quality data did not reveal much in terms of change but with the application of a diatom-based palaeolimnological analysis revealed a subtle, yet distinct species assemblage shift 1987 onwards. Of interest to note is that the timing of this species shift corresponds with recent climatic changes during 1988–1997 as documented by local meteorological data. Such findings reinstate the importance of paying increased attention to algae, particularly diatom flora in our system of interest, i.e., Sundarbans, while inferring climate change effects in the past, and also for the purpose of predicting future climate dynamics and possible impacts of climate change on the system.

5.3 Conclusions

Sundarbans, spread across India and Bangladesh, is reportedly quite rich in terms of its algal flora with the presence of 762 species of algae. Their dynamics in the ecosystem are dependent on many different environmental variables. It is important to pay increased attention to algae, particularly diatom flora in Sundarbans, while inferring climate change effects in the past, for the purpose of predicting future climate dynamics, and also for possible impacts of climate change on the system.

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Part IV
Production and Productivity of Major Enterprises under Stressed Environment

Wetland manual rice transplanting in progress (Courtesy D. Burman)

Chapter 6
Soil and Water Resources of Sundarbans

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Abstract The people of the Sundarbans, spread over India and Bangladesh, depend mainly on agriculture, the productivity of which is low due to several constraints related to soil and water resources. The soils of the Sundarbans region are generally occupying deltaic geomorphic position and have developed on alluvium. The soils are affected by salinity, while acid sulphate soils having pH <4 are also found in patches in the region. Soils are generally low in available N and organic carbon, low to high in available P, and high in available K. The soils are usually well-supplied with micronutrients, except Zn. Acid sulphate soils are deficient in P, and very high in water soluble Fe, Al, and Mn. Rivers are all tidally fed as these rivers have lost their upstream connections with the Ganges due to heavy siltation and solid waste disposal. This region experiences significant long-term variation in quality of river water, such as the surface water temperature, salinity, pH, dissolved oxygen. The salinity of river water increases gradually from post-monsoon to pre-monsoon period and thereafter decreases to a lowest value in monsoon, and the cycle repeats annually. The top saline water bearing aquifers are generally separated from the underlying fresh water group of aquifers by a thick impermeable clay layer. The arsenic contamination problem in groundwater has been reported in the Sundarbans. In general, there is seasonal fluctuation of salinity in the groundwater too, salinity is higher in dry season than in monsoon.

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6.1 Soils

The soils of the Sundarbans region are generally occupying deltaic geomorphic position and have developed on alluvium and affected by salinity. The major taxonomic groups of soil in the salt affected coastal region of Sundarbans are: *Typic Endoaquepts*, *Fluventic Endoaquepts*, *Aeric Endoaquepts*, *Sulfic Endoaquepts*, *Fluvaquentic Endoaquepts*, *Vertic Endoaquepts*, *Typic Ustifluvents*, *Typic Fluvaquents*, and *Sulfic Endoaquents*. The soils have Hyperthermic temperature and Aquic moisture regime. The region is having a flat topography with elevation of about 1–12 m from mean sea level (MSL). The soils are usually heavy-textured and it varies from clay to silty loam. However, light textured soil, i.e. sandy to sandy loam soils are also found at places. The soils of the mangrove forest area are wetlands and are characteristically different from the those of the cultivated soils. The major soil groups form management points of view are acid sulphate soils and saline soils.

6.1.1 Acid Sulphate Soils

6.1.1.1 Formation and Distribution

Acid sulphate soils encountered in patches have pH below 4 that is directly or indirectly caused by sulphuric acid formed by oxidation of pyrites(FeS_2) (or other oxidizable sulphidic materials) present in the soils. Under strongly oxidizing and acidic condition in presence of metallic cations $FeS_2$the soils may also be oxidized forming jarosite ($KFe_3(SO_4)_2(OH)_6$) and free acid. Presence of jarosite mottles along with low pH is the most characteristic feature of acid sulphate soils. However, there are many acid soils visibly without jarosite mottles. The acid sulphates soils are broadly grouped into two types, i.e. actual and potential acid sulphate soils (Pons1973). Actual acid sulphate soils have a low pH (<4.0) and high amount of sulphate, about 5 g kg^{-1} water soluble sulphate (Ponnamperuma and Solvias 1982). Potential acid sulphate soils are poorly drained soils with high content of pyrites. The pH of the soil may be neutral or slightly acidic in the field. Upon drainage, the soil becomes strongly acidic, which directly affects the growth of plants asa result of aluminum and iron toxicity, and indirectly decreases the availability of phosphorus and other nutrients.

In Sundarbans region in both India and Bangladesh, acid sulphate soils are found in patches (Rahman et al. 1990; Bandyopadhyay and Maji 1995; Bandyopadhyay et al. 2003). These soils are locally known as 'Koimuro' or 'Kosh' soil in India and Bangladesh, respectively. About 71, 000 ha of acid sulphate soils have been reported from the coastal zone of Bangladesh (Rahman et al. 1990). These soils are very poor to poorly drained with colour ranging from dark grey to grey. The texture is silty clay loam to clay, and the soil pH is less than 4.

The strong acidity of soil is developed due to oxidation of pyrite (FeS_2) and other oxidizing sulphidic materials present in the soil. Zerosite mottle is generally found in the soil profile. Potential acid sulphate soils in Bangladesh have no jarosite mottle. However, jarosite mottles have been found within the profile at different depths in actual acid sulphate soils. Soil reaction values (pH) in Indian Sundarbans varies generally from 6.0 to 8.5, however, pH of acid sulphate soil in this area is less 4.5. A thematic map sowing soil pH status of surface soils in North 24 Parganas and South 24 Parganas districts in Sundarbans in India is presented in Fig. 6.1 depicting acid sulphate soils having pH <4.5.

6.1.1.2 Physicochemical Properties

Profile characteristics of a representative acid sulphate soil in North 24 Parganas district in India are given in Table 6.1. The acid sulphate soils in Sundarbans areas are widely variable in organic C content with high value at the surface because of deposition of organic matter and it decreases with depth. In some areas, high organic C at lower depth indicates early deposition of organic matter in the soil. The CEC value ranges from 5 to 28 C mol kg^{-1} or more. The variation in CEC values is related to variation in organic matter and clay content in the soil. In general, exchangeable Mg^{+2}concentrations is very high in the profile compared to Ca^{+2} concentration, which suggests old marine deposits and Ca^{+2} largely leached from the exchangeable complex. These soils are low to medium in available N content, poor in available P content, and high in available K content. These soils contain very high quantity of water soluble Fe, Al, and Mn. The pH of soil increases, while water soluble Al decreases following submergence of soil. Due to high content of soluble Fe, Al and Mn the soils show high P-fixation capacity and toxicity of Fe and Mn particularly under waterlogged condition. High K status in the soil is due to presence of K-containing illitic materials and K-containing salts, like KCl and K_2SO_4. The high S content in the soil is attributed to presence of sulphuric horizon within the soil profile. These soils are generally poor in Zn and Cu contents.

6.1.2 Saline Soils

6.1.2.1 Formation and Distribution

Most of the Sundarbans areas in Indian and Bangladesh are affected by salinity. The salinity development in the soils is primarily attributed to tidal flooding, frequent

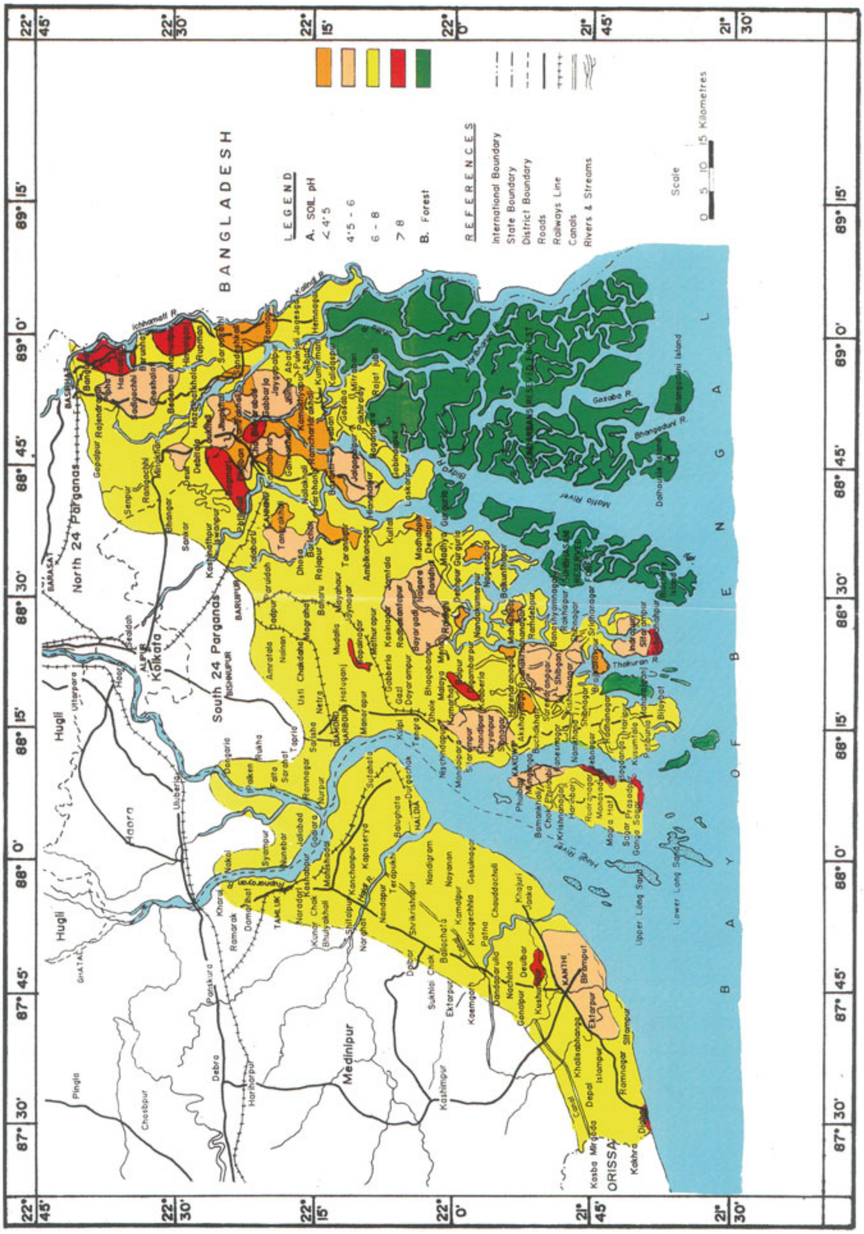

Fig. 6.1 pH status of surface soils in Sundarbans (South & North 24 Parganas districts), India. (Source: Bandyopadhyay et al. 2003, free access)

Table 6.1 Morphological, physical and physico-chemical characteristics of acid sulphate soils

(a)

Horizon	Depth (cm)	Colour (moist)		Texture	Clay(%)	pH (1:2)	ECe (dSm^{-1})	SAR	ESP	Org.C (%)
		Matrix	Mottles							
Ap	0–20	5Y 5/1	7.5YR 5/6,mlp	sic	46	4.1	14.5	3.9	11.6	1.25
BA	20–71	5Y 4/1	2.5YR 3/6,mlp	sicl	38	4.4	7.7	4.4	13.2	1.28
Bwg1	71–125	5Y 4/1	2.5YR 3/6,mlp	sic	46	4.3	7.0	5.4	15.8	0.55
Bwg2	125–240	5Y 4/1	2.5YR 3/6,flp	sic	46	6.1	7.5	5.2	20.6	0.34

(b)

Horizon	Ionic composition of saturation extract of soil (me l^{-1})							CEC (cmol (p+) kg^{-1})	Base sat. (%)
	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-		
Ap	50.1	1.3	6.2	13.9	20.0	35.1	1.0	26.6	63.9
BA	25.1	0.5	1.7	2.2	6.7	13.4	1.0	23.4	64.9
Bwg1	46.7	1.2	2.0	2.5	11.7	6.7	0.5	22.1	70.1
Bwg2	33.4	1.2	2.0	2.8	10.0	8.4	1.0	19.4	88.1

Source: Bandyopadhyay et al. 2003, free access
Pedon: Nirdeshkhali, P.S. Basanti, district South 24 Parganas, India
Soil classification: *Fine, mixed hypothermic Fluvaquentic Endoaquepts*

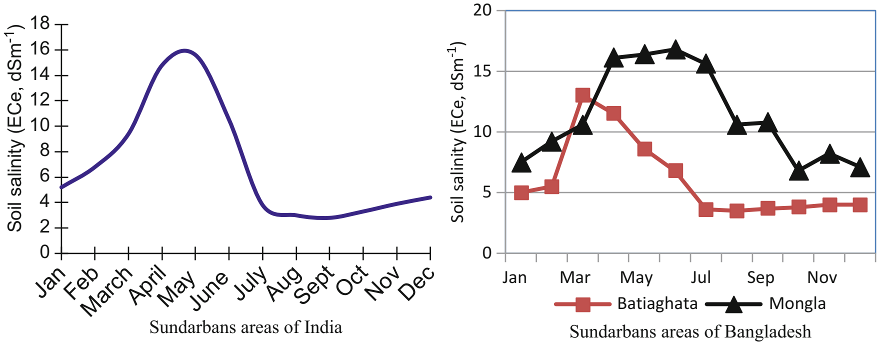

Fig. 6.2 Variation in soil salinity in different months of the year in Sundarbans. (Sources: Bandyopadhyay et al. (2003), free access (1st graph) and SRDI (2003), Mondal et al. (2006), free access (2nd graph))

inundation of saline water from sea or river coupled with drainage congestion during monsoon (June to October), and upward capillary movement of saline water from brackish groundwater located at shallow depths (usually around 1 m depth throughout the year) during post-monsoon period. Soil salinity showed a large temporal and spatial variation across the coastal zone (Bandyopadhyay et al. 2003; SRDI 2010). It is highest in summer and lowest in monsoon season (Fig. 6.2). During monsoon, the salinity levels in soils are within the safe limits due to leaching and washing of salt through monsoon rains. After monsoon, the salinity starts increasing due to upward capillary movement of salt following evaporation. In top soil, salinity (ECe) varies from 0.5 to 50 dSm^{-1} or more in Indian parts of Sundarbans, while in Bangladesh part it is reported to vary from 0.3 to 70.0 dSm^{-1}. The salt distributions in soils in the Sundarbans region of India is presented in Fig. 6.3. The soil salinity increases from northern to southern part and from west to east. The Ganges tidal floodplains, i.e. Sundarbans constitute about 49% of the coastal areas in Bangladesh. Among the four physiographic units (Ganges tidal floodplain, Lower Meghna estuarine floodplain, Ganges river meander floodplain and Peat basin), the highest salt accumulation is observed in the Ganges tidal floodplain in Bangladesh (SRDI 2000). Electrical conductivity (ECe) of almost all the soils decreases with depth and then increases again due to the influence of saline groundwater. The highest total soluble salt concentrations (3122 mg l^{-1}) are found under brackish water shrimp cultivation due to flooding with high saline water for a considerable time in each year.

6.1.2.2 Profile Characteristics

Soils of the Sundarbans are mostly non-sodic. SAR varies from 1.54 to 1.66 in Khulna region in Sundarbans in Bangladesh (Mondal et al. 2001). Salts are dominated by Cl^- and SO_4= of Na, Mg, Ca and K (SRDI 2000; Bandyopadhyay et al. 2003). In Bangladesh, for most of the saline soils the ionic preponderance decreases

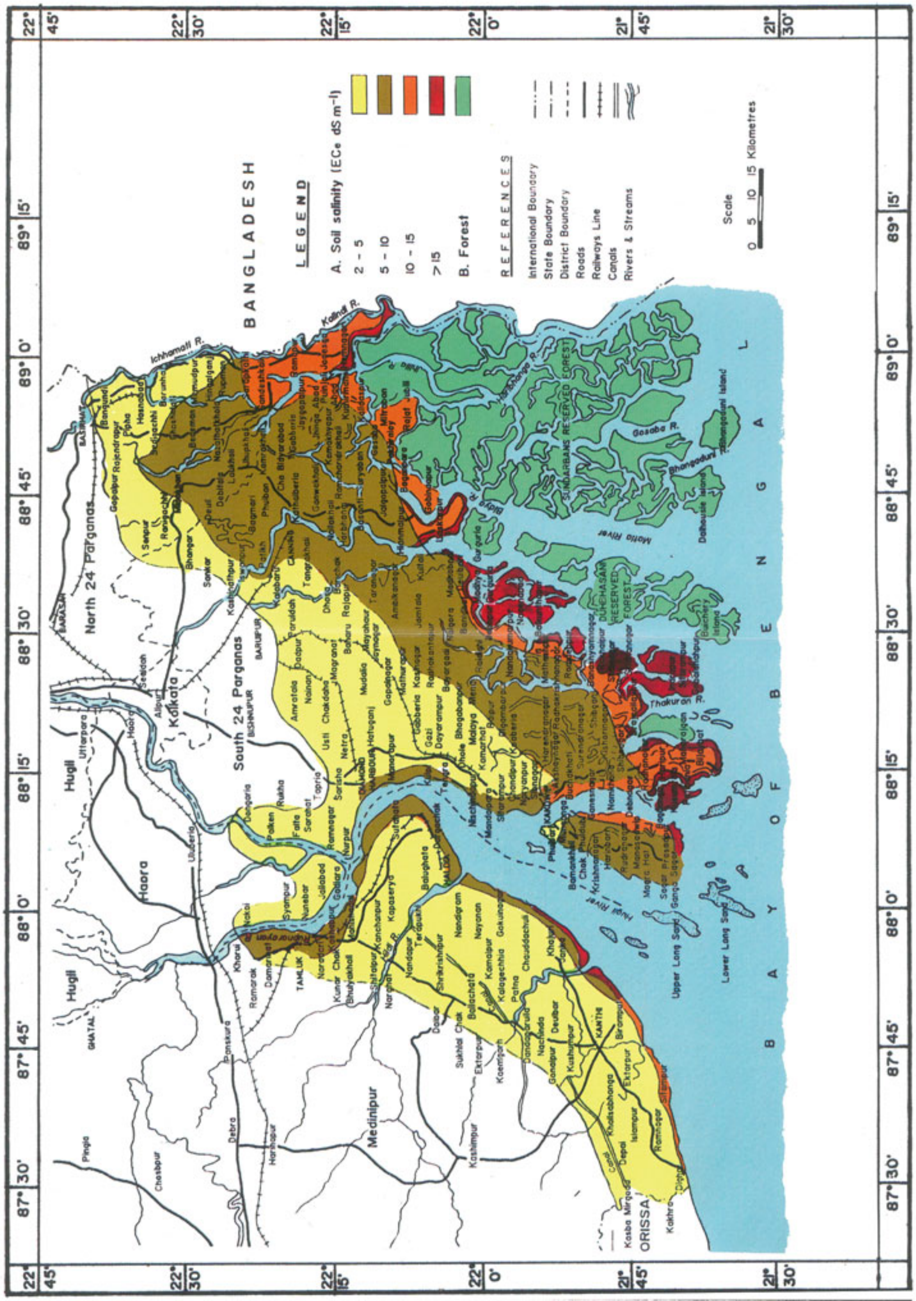

Fig. 6.3 Soil salinity status in Sundarbans (South & North 24 Parganas districts, India). (Source: Bandyopadhyay et al. 2003, free access)

in the order of $Na^+ > Ca^{2+} > Mg^{2+} > K^+$. But in the soils under prolonged brackish water shrimp cultivated areas, ionic preponderance decreases in the order of $Na^+ > Mg^{2+} > Ca2^+ > K^+$.

In general, saline soils in Indian Sundarbans are low in fertility status. They are usually rich in available K and micronutrients (except Zn), low to medium in available N, and are having variable available P status (Bandyopadhyay et al. 1985; Bandyopadhyay 1990; Maji and Bandyopadhyay 1991). The profile characteristics of saline soils of Sundarbans in India are given in Table 6.2.

In Bangladesh part of Sundarbans, the dominant soil texture of the upper soil layer (10–20 cm) is silty clay and silty clay loam (Table 6.3). Mondal et al. (2001) reported similar soil texture at two sites in Dumuria upazila in Khulna district. The subsoil texture is almost similar to topsoil, while sporadic clay is found in the sub-layers in the region. In all cases, silt and clay fractions dominated over the sand fraction. This is typical for the parent materials of delta soils because larger particles, including most of the sand fraction, are deposited further upstream, and many of the remaining fine particles (silt and clay particles) are deposited in the delta area due to the back and forth movement of water in the tidal zone (Saleque et al. 2010). Fine textured delta soils are expected to be highly suitable for lowland rice farming because of their high nutrient content and high water holding capacity. However, the fine textures of delta deposits, especially when occurring in the subsoil, indicate the possibility of poor internal drainage, retarded salt leaching during the wet season, and considerable salt input with capillary rise during the dry season (Panaullah 1993). But horizontal salt leaching or washing salts from the topsoil by the tidal river water and rainfall in the deltas is a common phenomenon suggesting desalinization of surface soil to cultivate rice in the *aman* (monsoon or *kharif*) season in the Sundarbans region (Mondal et al. 2006).

6.1.2.2.1 Soil Nutrient Status

Organic matter (OM) status of coastal Ganges delta soils of Sundarbans region in Bangladesh ranges from 1.7% to 3.8% (Table 6.3). Slightly higher organic matter contents in the upper soil layers are found in Sundarbans than in other parts of the coastal zone of Bangladesh, and this may be because of less intensive cropping in case of the former (SRDI 2000). The high OM concentrations could also be attributed to the prolonged submergence (June–December) and growth of natural aquatic plants during the period when the soil remains flooded for long. In addition, the fine texture of delta soils may also favour OM accumulation. Tidal sediments often contain high OM concentrations (3.4% OM and 700 ppm soluble organic carbon), thereby contributing to the observed high OM concentrations of these tidal flooded delta soils that normally remain underwater for 4–5 months each year (Saleque et al. 2010).

Total N contents of the topsoil in the coastal Ganges delta in Bangladesh vary from 0.06% to o.17% (Table 6.4), which is generally considered low to very low for the crop production (SRDI 2000). Total N contents decrease with the depth. The

Table 6.2 Morphological, physical and physico-chemical characteristics of saline soils

(a)

Horizon	Depth (cm)	Colour (moist)		Texture	Clay (%)	pH (1:2)	ECe (dSm^{-1})	SAR	ESP	Org. C (%)
		Matrix	Mottles							
Ap	0–15	2.5 Y 7/2	_	s1	14	5.9	7.5	5.6	7.2	0.36
Bw1	15–51-	2.5Y 5/2	10YR4/4,c1d	sc1	26	7.0	2.5	3.4	5.6	0.27
Bw2	51–72	2.5Y 7/4	10YR4/4,c1d	sc1	31	6.7	2.5	4.4	6.4	0.20
2C	72–125	2.5Y 8/2	10YR4/4,m3d	ls	4	6.6	10.0	5.3	6.1	0.14

(b)

Horizon	Ionic composition of saturation extract ($me\ l^{-1}$)							CEC (c mol (p^+) kg^{-1})	Base Sat. (%)
	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-		
	33.2	0.50	10.6	11.6	36.5	3.3	2.6	18.1	77.8
Bw1	13.3	0.33	6.0	6.0	11.6	3.3	1.7	14.4	85.8
Bw2	11.7	0.33	3.0	5.3	10.0	1.7	1.0	13.8	82.2
2C	18.3	0.17	4.6	6.0	29.0	1.7	1.6	6.3	81.7

Source: Bandyopadhyay et al. 2003, free access
Pedon: Ghonarban, P.S. Minakhan, district North 24 Parganas, India
Soil classification: Fine-loamy, mixed hyperthermic Aeric Endoaquents

Table 6.3 Physiochemical properties of the upper layer (~15 cm) of Sundarbans soils in Bangladesh

District	Location	Soil texture	CEC (meq100 g^{-1} soil)	Organic matter (%)	CaCO3 (%)	Bulk density (gcc^{-1})
Khulna	Dumuria	Silty clay	18.4	3.82	3.5	1.37
	Batiaghata	Silty clay	26.4	2.22	0.5	1.33
	Paikgacha	Silty clay loam	13.6	1.72		
Bagerhat	Mongla	Silty clay	24.8	3.82	0.5	1.35
	Morrelgonj	Silty Caly	16.8	1.93	0	
Satkhira	Kaligonj	Silty clay	17.0	2.23	0	
	Satkhira	Silty clay loam	20.8	2.16	5.5	
	Shyamnagar	Silty clay	17.6	3.40	0	

Source: SRDI 2000, free access

poor N status of the delta soils is due to high rate of decomposition of OM, inadequate application of N, and high loss due to volatilization and denitrification.

Available P (Olsen-P) in the coastal Ganges delta soils of Sundarbans region in Bangladesh varies from 2.72 to 11.35 mg kg^{-1} (Table 6.4). Most soils in this region suggest P deficiency. According to Fairhurst et al. (2007), P deficiency is highly likely at Olsen P below 5 mg $kg^{-1}$and probable at values ranging between 5 and 10 mg kg^{-1}. SRDI (2000) mentioned that in some areas P was found well below the critical level for most agricultural crops. Acute P deficiency was observed in low-saline zone of the Sundarbans. Saleque et al. (2010) mentioned that tidal flooded delta soils were replenished with P through tidal sediments, which contained considerable amounts of total and available P (763 $mgkg^{-1}$ total P and 28 mg kg^{-1} available P). Moreover, 8–14 mg kg^{-1}P is generally adequate for moderate yield of lowland rice and response to P application of lowland rice in delta soils is therefore expected to be relatively low, especially in *aman* rice, because of tidal sediments.

The exchangeable K concentration in most of the coastal delta soils is relatively high (Table 6.4) in Bangladesh. Higher exchangeable K content has been observed in medium and high saline coastal zone of the region (0.15–7.2 mg g^{-1} soil). In non-saline delta areas, the exchangeable K concentrations vary from 0.02 to 0.07 mg g^{-1}soil. Most of the soils in low saline coastal zone are found deficit in potassium (Fairhurst et al. 2007) due to higher cropping intensity, inadequate application of K, and limited tidal water inundation (SRDI 2000). Given the observed concentrations of exchangeable K and the reported threshold values (K deficiency is highly likely at exchangeable K below 0.15 mg g^{-1}soil and probable at values between 0.15 and 0.45 mg g^{-1} soil), lowland rice in delta soils would rarely respond to the application of K (Saleque et al. 2010). Moreover, considerable K inputs from tidal sediments (SRDI 2000) can further contribute to the K nutrition of rice crops in the Sundarbans area.

Table 6.4 Nutrient status of the uppers soil layer (15 cm) of the coastal zone of Bangladesh

District	Location	pH	Macronutrient				Micronutrient				
			N (%)	P (mg kg^{-1})	S (mg kg^{-1})	K (meq 100 g^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	B (mg kg^{-1})	Mn (mg kg^{-1}	Zn (mg kg^{-1})
Khulna	Dumuria	7.0	0.17	3.16	319	0.21	5.44	69	1.60	21.7	0.60
	Batiaghata	7.6	0.10	2.64	151	0.10	6.49	46	0.94	10.4	0.23
	Paikgacha	5.1	0.07	5.04	341	7.20	8.08	106	1.87	6.4	1.58
Bagerhat	Mongla	4.7	0.15	3.53	514	1.34	7.56	364	1.91	43.7	0.63
	Morrelgonj	6.7	0.09	6.44	118	0.88	8.48	88	0.86	29.9	0.31
Satkhira	Kaligonj	6.5	0.10	11.35	189	0.88	5.14	79	1.12	16.5	0.42
	Satkhira	8.0	0.10	7.00	16	0.15	3.39	28	0.56	11	0.56
	Shyamnagar	4.6	0.15	6.20	506	2.63	7.96	165	1.14	6.6	1.46
Eastern Sundarbans	Chandpai	8.2	0.06	2.72	69	0.31	7.00	18	0.74	18	0.08
	Andharmanik	8.5	0.09	10.12	174	0.61	15.0	35	1.10	89	0.20
	Kotka	7.8	0.11	4.92	59	0.61	14.0	66	4.37	44	Traces
	Harintana	6.9	0.07	5.25	74	0.56	10.0	81	2.77	2	0.18

Source: SRDI 2000, free access

Available S concentrations in the coastal Ganges delta soils of the Sundarbans region in Bangladesh range from 16 to 514 $mgkg^{-1}$ (Table 6.4). Critical soil levels for occurrence of S deficiency in rice are suggested as below 9 mg kg^{-1}soil (Fairhurst et al. 2007). The S content of the top soils of this region was found medium to very high. Therefore, none of the soils in the Sundarbans region are deficient in S for wetland rice, since considerable S inputs from the deposition of tidal sediments could be expected.

SRDI (2000) reported appreciate amounts of micronutrients (Cu, Fe, B and Mn), except for Zn, in almost all the coastal Ganges soil including Sundarbans region, meaning thereby that there is no deficiency of Cu, Fe, B and Mn (Table 6.4). Available Zn concentrations in almost all delta soils are below 2.0 $mgkg^{-1}$ soil, which is below the critical level suggested by Fairhurst et al. (2007). High pH values and excessive wetness/waterlogging, as often experienced in these soils, further enhance the limit for Zn availability for rice. Therefore, widespread Zn deficiency and response to Zn application could be expected. However, there are also considerable differences in tolerance to Zn deficiency amongst different rice varieties, and only field tests with widely used varieties in the region may recommend the need for Zn application (Saleque et al. 2010).

Saleque et al. (2010) investigated the relation between the soil fertility indicators and established correlation matrices for saline and non-saline soils and for the combined dataset (Table 6.5). All three matrices indicated that higher pH values were related to lower OM concentrations and possibly related to a higher mineralization rate at higher pH. They mentioned limited availability of the plant nutrients in the poor soils of the Sundarbans region due to positive correlation among P, K, S and Zn (except in non-saline soil). In non-saline soils, the soil pH was correlated negatively with available K, S and Zn, suggesting better nutrient availability occurred near neutral pH values.

Soil nutrient status for the Sundarbans region in India has been covered by Sarangi and Islam in another chapter in this book.

6.2 Water

6.2.1 Surface Water

6.2.1.1 Rivers, Estuaries and Occurrences of Tides

Sundarbans, a tide-dominated wetland, is comprised of a complex network of estuaries, tidal inlets, tidal creeks, and a large number of islands. Sundarbans is influenced by several numbers of rivers in a criss-crossed way and the tidal river system or estuaries. Most of the creeks act as the pathway for the to and fro movement of tidal water and downstream flow of river systems. There are seven most important rivers in the Indian Sundarbans, out of which two western sectors rivers, viz. Hooghly and Muriganga are connected to the Himalayan glaciers through

Table 6.5 Correlation matrix and coefficients for soil characteristics: pH, organic matter (OM) and soil nutrients (Olsen P, exchangeable K, available S and Zn) in saline and non-saline delta soils of the Ganges coastal zone of Bangladesh

	OM	Olsen P	Exchangeable K	Available S	Available Zn
Non-saline soil (n = 41)					
pH	−0.35*	0.61**	−0.45**	−0.51**	−0.39*
OM		−0.44**	0.32*	0.18ns	−0.04ns
Olsen P			−0.54**	−0.35*	−0.24ns
Exchangeable K				0.41**	0.24ns
Available S					0.35*
Saline soil (n = 19)					
pH	−0.20ns	−0.31ns	0.09ns	−0.13ns	0.01ns
OM		−0.17ns	−0.04ns	−0.25ns	0.01ns
Olsen P			0.02ns	0.36ns	0.78**
Exchangeable K				0.36ns	0.32ns
Available S					0.49*
Combined (saline and non-saline) soil (n = 60)					
pH	−0.38**	−0.01ns	0.18ns	0.02ns	−0.03ns
OM		−0.22ns	−-0.14ns	−0.20ns	−0.20ns
Olsen P			0.06ns	0.29*	0.66**
Exchangeable K				0.49**	0.35**
Available S					0.43**

Source: Saleque et al. 2010, free access
*, **- significant at p = 0.05%, 0.01%, respectively; ns- non-significant

the Ganges, and the five eastern sector rivers, viz. Saptamukhi, Thakuran, Matla, Gosaba and Harinbhanga are all tidally-fed as these rivers have lost their upstream connections with the Ganges due to heavy siltation and solid waste disposal from the adjacent cities and towns (Chakrabarti 1998). During the fifteenth and sixteenth centuries, Bidyadhari river was a flourishing branch of the Bhagirathi but now it is almost in dying condition since the river bed is completely silted up and serves only as a sewage and excess rainwater outlet from the city of Kolkata. The spatio-temporal variations of the tidal water level were observed at different observation stations, spread over more than 3600 km^2 area, and covering seven estuaries, viz. Saptamukhi, Thakuran, Matla, Bidya, Gomdi, Harinbhanga, and Raimangal in Indian Sundarbans region (Chatterjee et al. 2013). The predominantly semi-diurnal tides are observed to amplify northwards along each estuary, with the highest amplification observed at Canning, situated about 98 km north of the sea-face on the Matla. The first definite sign of decay of the tide was observed only at Sahebkhali on the Raimangal, 108 km north of the sea-face. The degree and rates of amplification of the tide over the various estuarine stretches were not uniform and followed a complex pattern. A least-squares harmonic analysis of the data performed with eight constituent bands showed that the amplitude of the semi-diurnal band was an order of magnitude higher than that of the other bands and it doubled from mouth to head.

The diurnal band showed no such amplification, but the amplitude of the 6-hourly and 4-hourly bands increased head-ward by a factor of over 4.

There are five potential river estuaries, viz. Raimangal estuary, Malancha estuary, Kunga estuary, Bangra estuary, and Baleswar estuary located in the southern Sundarbans in Bangladesh (Fig. 6.4) and these are affected due to tidal inundation and high salinity intrusion (Islam et al. 2011). The availability of freshwater in Sundarbans is mainly dependent on upstream river water flows. The lower part of Gorai (major tributaries of the Ganges), called Madhumati, carries fresh water to the Baleswar river estuary in Sundarbans. Besides these, there are five other rivers, like Kobadak, Kholpetua, Passur, Sibsa and Baleswar, which carry fresh water into the Sundarbans estuaries. Kholpetua and Kabadak rivers receive fresh water mainly from the local run-off, in addition to that from the Gorai inflows. Passur and Sibsa rivers receive fresh water from Gorai offtake, while Baleswar is fed partially by Gorai and also from right bank spill channels of the Ganges and Meghna rivers.

6.2.1.2 Water Quality: Seasonal Variations

6.2.1.2.1 Salinity and Other Physicochemical Properties

A study conducted by Mitra et al. (2009) indicated that Sundarbans in India experienced significant long-term variation in water quality of river water, such as the surface water temperature, salinity, pH, dissolved oxygen, and transparency over a period of 27 years (1980–2007). The temperature in these waters has risen by 6.14% in the western sector (Hooghly and Muriganga), and by 6.12% in the eastern sector (Saptamukhi, Thakuran, Matla, Gosaba and Harinbhanga) at the rate of approximately 0.5 °C per decade, much higher than that observed globally as well as for the Indian Ocean. The western rivers showed a significant and continuous decrease in salinity (1.67 PSU/decade), whereas the eastern sector showed an increase in salt (~6 PSU over 30 years) (Fig. 6.5). The trends are similar in both pre-monsoon and monsoonal periods. The waters of the western rivers are fresher now than in the 80s and 90s, probably, and primarily due to the increased amount of melt water from the Gangotri Glacier. At the same time, salinity has increased on the eastern sector, where the connections to the melt water sources have become extinct due to heavy siltation of the Bidyadhari Channel.

Two decades of pre-monsoon data (1990–2012) showed a significant and continuous decrease in salinity in the western rivers (Muriganga, Saptamukhi, Jambu, Lothian, Sagar, Prentice), and eastern rivers (Arbeshi, Jhilla, Harinbhanga, Katuajhuri, Chamta, Chandkhali), whereas the central-eastern rivers (Thakuran, Dhulibasani, Chulkathi, Goashaba, Matla, Pirkhali) showed an increase in salinity (Banerjee 2013) in India (Fig. 6.6). The rivers in the western sectors of the Indian Sundarbans (Hooghly and Muriganga), being continuations of the River Ganges, receive the snow-melt water of the Himalayas, which might result in decrease in water salinity level (~2.0 PSU/decade). The eastern region, which has shown a decrease in salinity levels (1.71 PSU/decade), is due to the influx of the large

Fig. 6.4 Location of the estuaries in the Sundarbans region in Bangladesh. (Source: Islam et al. 2011, free access)

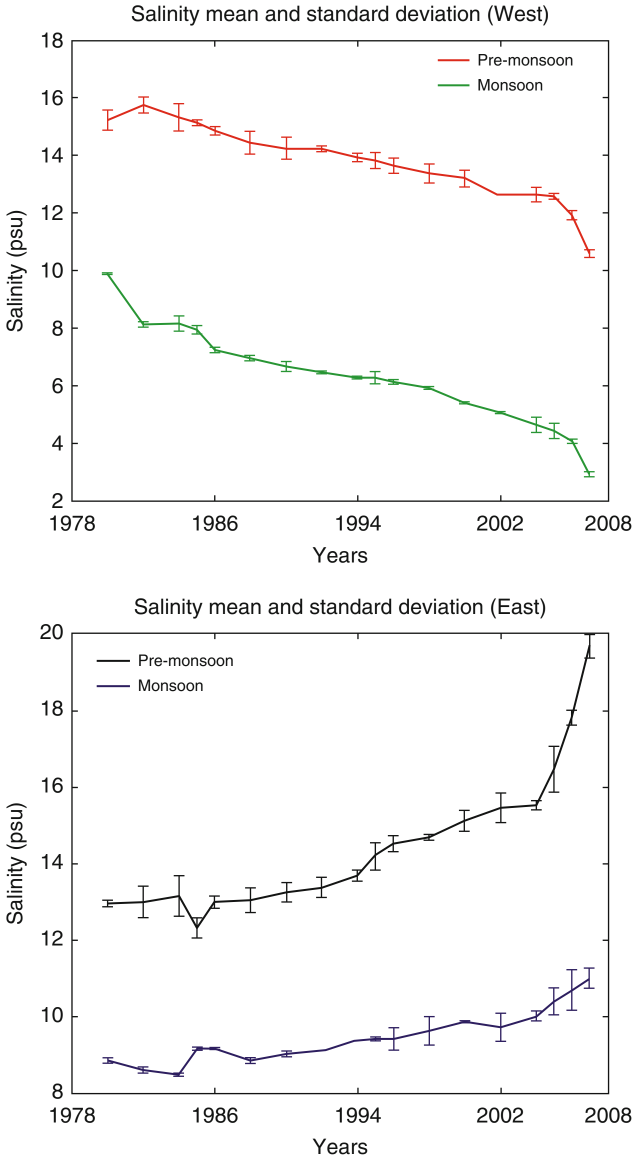

Fig. 6.5 Salinity decreased during the last 30 years on the western (left) sector whereas it increased on the eastern (right) sector of the Indian Sundarbans. Trends are similar in both pre-monsoon and monsoonal periods. (Sources: Mitra et al. 2009, free access)

discharges of the Padma river from Bangladesh. The salinity has been increased (1.3 PSU over two decades and ~2.8 PSU/decade) in the central sector, where most of the salinity increase (2.8 PSU/decade) happened during the last 13 years. This increase,

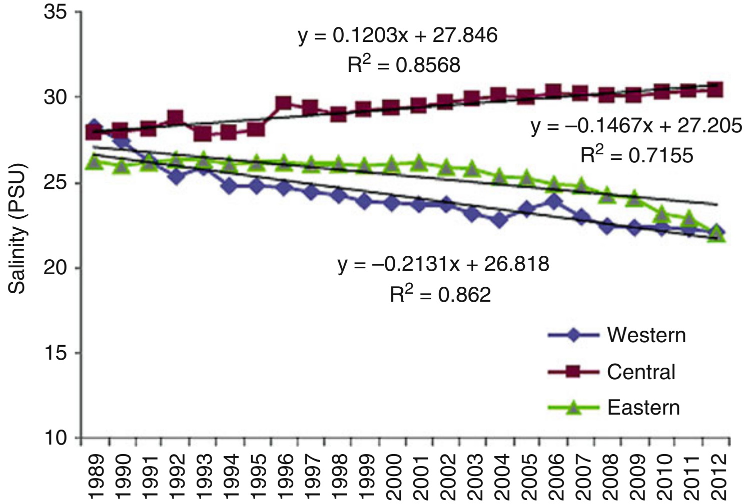

Fig. 6.6 Trendline showing the increasing salinity in the central sector and decreasing salinity in the western and eastern sectors of Indian Sundarbans. (Source: Banerjee 2013, free access)

on other hand, may be due to the clogging of the connections to the melt water sources from Ganges on account of heavy siltation of the Bidyadhari Channel.

During 1980 and 2007, the waters in the western sector in India became gradually warmer, fresher and lighter with lesser pH concentration (more absorbed CO_2), incurred more DO, and became less transparent, while its water quality has increased. During the same three decades, the eastern waters became warmer, saltier, denser and less transparent, whereas their water quality has deteriorated considerably. The signals for pH and DO are complicated with a shifting from no-trend to near-trend or significant trend behaviour in the mid-nineties.

Physicochemical parameters of surface water (0.5 m depth) studied during November, 2008 to October, 2011in Jharkhali estuary, which is a part of Hoogly-Matla estuary in India, surrounded by the mangrove forests, showed that temperature of the estuary was lowest in post-monsoon in the month of January (21.5 °C) and highest in pre-monsoon in the month of June (33.5 °C) (Table 6.6) (Chaudhuri et al. 2012). The pH of water was weakly alkaline and more or less constant throughout the study period (8–8.15). The salinity of water increased gradually from post-monsoon (17.3 PSU) to pre-monsoon period (24.5 PSU), and decreased to a lowest value in monsoon (12.6 PSU). Highest salinity was observed in June (24.5 PSU) and lowest in October (12.6 PSU). Moderate to high DO concentration (6.5–9.8 mg l^{-1}) was observed throughout the year, highest in January (9.8 mg l^{-1}), and lowest in June (6.5 mg l^{-1}). Maximum aquatic turbidity was observed in monsoon in the month of October (125 NTU), followed by post-monsoon in the month of November (55 NTU) and pre-monsoon in the month of March (25 NTU), also evidenced by SPM concentrations (248.4 mg mg l^{-1}, 172.1 mg l^{-1} and 87.8 mg l^{-1}), respectively.

Table 6.6 Monthly variation of physical and light availability parameters in Sundarbans estuary in India

Month	Temperature (°C)	pH	Salinity (PSU)	DO (mg l^{-1})	Suspended particulate matter (mg l^{-1})	Turbidity (NTU)	Secchi disc index (cm)	Light attenuation coefficients
November	27.5 ± 0.1	7.90 ± 0.1	14.9 ± 0.2	8.4 ± 0.15	172.1 ± 5.6	55 ± 5.0	52.2 ± 2.2	0.030
December	24.5 ± 0.1	8.0 ± 0.15	15.5 ± 0.1	8.5 ± 0.12	144.5 ± 4.2	48 ± 5.5	61.5 ± 2.1	0.025
January	21.5 ± 0.1	8.10 ± 0.1	16.6 ± 0.1	9.2 ± 0.2	129.4 ± 3.6	39 ± 4.8	70.0 ± 2.6	0.022
February	25.0 ± 0.1	8.20 ± 0.1	17.3 ± 0.1	9.8 ± 0.18	117.3 ± 4.6	25 ± 5.3	78.0 ± 1.8	0.020
March	27.5 ± 0.1	8.10 ± 0.12	21.2 ± 0.2	7.1 ± 0.1	87.8 ± 5.4	25 ± 0.6	137.5 ± 3.9	0.011
April	32.5 ± 0.1	8.05 ± 0.1	22.3 ± 0.2	7.0 ± 0.12	95.8 ± 5.6	24 ± 0.4	169.6 ± 4.2	0.009
May	33.5 ± 0.1	7.95 ± 0.14	23.6 ± 0.1	6.7 ± 0.2	73.4 ± 3.2	23 ± 0.4	174.1 ± 4.5	0.009
June	34.0 ± 0.1	7.90 ± 0.1	24.7 ± 0.1	6.5 ± 0.15	57.5 ± 6.2	20 ± 0.8	185.3 ± 5.6	0.008
July	33.5 ± 0.1	7.95 ± 0.15	15.0 ± 0.2	6.6 ± 0.14	186.5 ± 6.9	57 ± 4.8	51.2 ± 2.2	0.030
August	32.0 ± 0.1	7.90 ± 0.14	14.1 ± 0.1	6.9 ± 0.12	230.8 ± 2.7	110 ± 3.2	24.5 ± 1.1	0.060
September	30.5 ± 0.1	7.90 ± 0.1	13.3 ± 0.2	7.6 ± 0.15	234.2 ± 5.9	114 ± 2.5	22.6 ± 1.2	0.069
October	29.0 ± 0.1	7.85 ± 0.11	12.7 ± 0.1	7.8 ± 0.18	248.4 ± 6.9	125 ± 6.2	20.0 ± 1.1	0.078

Sources: Chaudhuri et al. 2012, free access
Each value represents mean of 180 samples

This observation was also reflected in Secchi disc indices (20.0 cm, 52.3 cm, 137.5 cm) and light attenuation co-efficient (0.078, 0.030, 0.011). Highest aquatic turbidity and suspended load (SPM) concentration were evidenced in October (125 NTU, 248.4 mg l^{-1}), and lowest in June (20 NTU, 57.5 mg l^{-1}) (Table 6.6).

Nutrient concentrations, i.e. total nitrogen (TN), ammonia nitrogen, total phosphate (TP), and silicate showed higher concentration in post-monsoon and monsoon compared to those in pre-monsoon period. TN and ammonia-nitrogen were estimated to be 34.14 μmol l^{-1}, 2.06 μmol l^{-1}in post-monsoon, 20.52 μmol l^{-1}, 1.24 μmol l^{-1} in pre-monsoon, and 28.22 μmol l^{-1}, 1.36 μmol l^{-1} in monsoon (averaged), respectively. Highest TN and ammonia-nitrogen concentration were observed in the month of February (36.25 μmol l^{-1}) and January (2.3 μmol l^{-1}), respectively.

In another study in Jharkhali, India, Mitra et al. (2015) observed that DO value decreased gradually over a period of three decades (1984–2015). The average values of DO are 3.82 ppm during pre-monsoon, 4.56 ppm during monsoon, and 4.15 ppm during post-monsoon. The data reflect the seasonal order of DO in the sequence, monsoon > post-monsoon > pre-monsoon. A sharp rise in DO level during pre-monsoon 2009 in the study site may be attributed to *Aila*, a super-cyclone that passed across Sundarbans. The gradual decreased in DO values may be attributed to high salinity in the central part Sundarbans in India due to complete blockage of fresh water as a result of siltation of Bidyadhari channel since late fifteenth century.

Salinity is a major problem for agriculture as well as for drinking water in the high saline Sundarbans areas of Bangladesh (Satkhira District). Salinity in the Ichhamoti and Kakshiali rivers rises to about 30 dSm^{-1} in the dry season, starts decreasing from mid-June, and drops to below 10 dS m^{-1}in mid-July, but remains above 3 dS m $^{-1}$ throughout the year (Fig. 6.7). In the medium saline Sundarbans region (Khulna and Bagerhat districts), salinity starts to increase from December with the decrease in upstream fresh water flow in the Rupsha, Kazibacha and Pussur river systems.

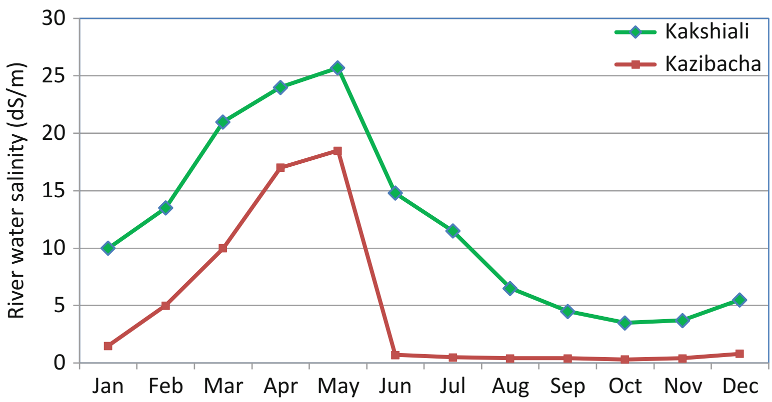

Fig. 6.7 River water salinity in medium (Kazibacha river) and high (Kakshiali river) saline Ganges coastal zone of Sundarbans region of Bangladesh in 2013. (Source: SRDI 2014, free access)

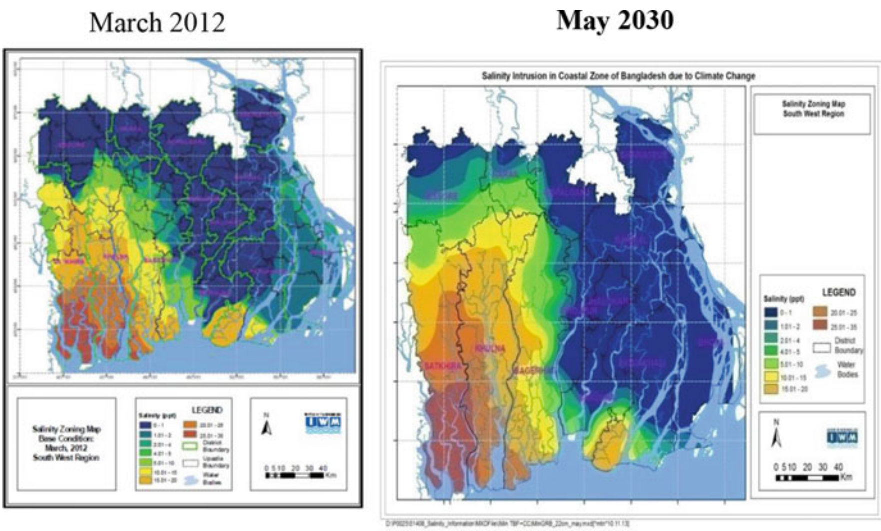

Fig. 6.8 Simulation of the changes in river water salinity (2012 vs 2030) in the coastal Ganges basin in Bangladesh. (Source: Khan et al. 2015a, b, co-author and open access)

Salinity varies seasonally and remains below 4 dS m^{-1}from mid-June to mid-February, reaches the peak value of 20–25 dSm^{-1}in April/May (Mondal et al. 2006; Mondal et al. 2010; Khan et al. 2015a). Khan et al. (2015a,b) mentioned that EC of the river water will increase further in the Sundarbans region even under moderate climate change (scenario A1B) and with 22 cm sea level rise up to 2030 (Fig. 6.8).

Khan et al. (2015a) reported from field observations that the river water salinity of the Kazibacha river in Khulna district started to increase from December and reached the peak (~20 dS m^{-1}) in April/May, decreased rapidly in June, and remained below 4 dS m^{-1}until mid-February (Mondal et al. 2010). But scarcity of fresh water is acute in Satkhira district. The salinity in the river systems remains above 3 dS m^{-1} throughout the year and the peak salinity reached up to about 26 dS m^{-1} in Kakshiali river in 2013. Khan et al. (2015a) mentioned that the river water in the Satkhira area was never suitable for agricultural crops; however, it is a valuable resource for shrimp cultivation.

6.2.1.2.2 Hydrographic and Time Series Data Analysis: Effect of Cyclone *Aila*

The hydrographic and time series data in June (pre-monsoon season) for 30 consecutive years (1984–2013) during high tide period in six selected stations in the western Indian Sundarbans (Chemaguri, Saptamukhi, Jambu Island, Lothian Island, Harinbari, Prentice Island) exhibit acidification of estuarine water (Jana et al. 2014). The pH has decreased within the range 0.24% to 1.44% over a period of 30 years in the study area. The rate of decrease per decade varies from 0.007 to 0.048. The significant reduction in levels of surface water pH can be attributed to factors like seawater intrusion into the estuary from Bay of Bengal, sewage discharge (from point and nonpoint sources), and photosynthetic activity by the mangrove vegetation that exhibit variable biomass and area around the selected stations. However, sudden rise of pH recorded during 2009 was the effect of *Aila* cyclone in the Sundarbans region in 2009. This cyclone caused significant rise of surface water salinity and pH in the estuaries of the Indian Sundarbans (Mitra et al. 2011).

6.2.2 Groundwater

6.2.2.1 Aquifer Zones and Soil Strata

The Sundarbans region is the most vulnerable area for groundwater use in respect of quality and quantity. It is mostly used for drinking purpose, although sporadic utilization for dry season cropping is also observed in Sundarbans region. In the Indian part of Sundarbans, the top saline water bearing aquifers are generally separated from the underlying fresh water group of aquifers by a thick impermeable clay layer. The fresh groundwater occurs under confined condition, where piezometric surfaces lie between 0.50 and 2.00 m below msl and hydraulic gradient tends towards sea. There are three aquifer zones in the Indian Sundarbans (Fig. 6.9), the first upper aquifer occurs within 60 m below ground level (bgl) which is mostly saline. The second zone occurring between 70 and 160 m bgl is also saline. The third aquifer zone, fresh in nature, occurs between 160 m and 400 m bgl. The saline water aquifers at the top are separated from the underlying freshwater group of aquifers by a thick clay layer varying in thickness from 4 m at Gangasagar to 120 m at Kultali; the general thickness of the intervening clay blanket is between 20 and 50 m (Sinha Ray 2010).

The salinity problem in Sundarbans aquifers of India is mostly due to the presence of seawater (as connate water) with different degrees of salinity getting entrapped during marine transgression or through deposition of sediments under marine depositional environment. Slow movement of groundwater in the area with a long residence time in contact with a stationary coast-ward salt water body also causes quality deterioration. The Sundarbans areas are prone to frequent cyclonic storms. During the cyclonic storms, high tidal waves enter deep inland and also along the tidal creeks, the influent seepage from which also deteriorates the quality of groundwater.

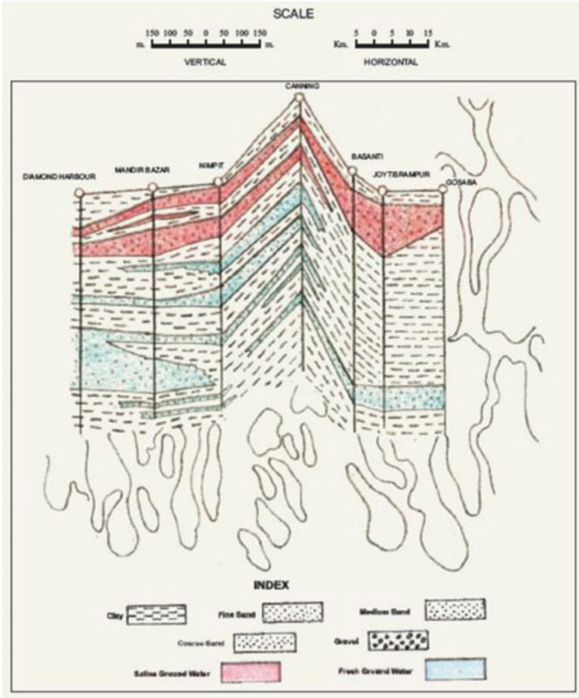

Fig. 6.9 Disposition of sub-surface fresh/saline aquifers from Diamond Harbour in the northwest to Gosaba in the east, is depicted with the aid of lithological and hydro-chemical data from seven bore holes as observed by the Central Groundwater Board, India. (Source: Sinha Ray 2010, free access)

6.2.2.2 Aquifer Water Quality

The top saline/ brackish aquifer lies within the depth of 160 m bgl. The important chemical types of groundwater are Ca-Mg-HCO_3 type and Na-HCO_3 type in North 24 Parganas and South 24 Parganas districts in Sundarbans, respectively. However, Ca-Mg-Cl type of groundwater is also found in some isolated patches in the region. In general, Cl content in South 24 Parganas is high (< 1000 mgl^{-1}) in upper aquifer (20–150 m depth range) with specific conductance at high value (< 1500 dSm^{-1} at 25 °C). However, aquifers at deeper depth (115–350 m) in this district is relatively fresh and Cl content is within permissible limit. Owing to the sub-marine and estuarine environment in which sediments are deposited and also owing to saline water intrusion as a result of proximity to the sea and tidal influence, the Cl content in upper aquifer of South 24 Parganas district is at high level. The salinity in groundwater in this district is also higher (< 3000 μS cm^{-1} at 25 °C). The iron content in groundwater in Sundarbans areas is at high level (< 1.0 mgl^{-1}). The arsenic contamination problem in groundwater area has been reported in Sundarbans. Arsenic content of groundwater has been found to be beyond permissible limit of 0.01 ppm in sporadic manner in Haroa block in North 24 Parganas district and Joynagar-I and Magrahat II blocks in South 24 Parganas district of Sundarbans. The status of groundwater in total 19 blocks of North 24 Parganas and South 24 Parganas district of Sundarbans is given in Table 6.7.

Table 6.7 Status of groundwater development in Indian part of Sundarbans (Block-wise)

Block	Occurrence of aquifer and its potentiality (as per the data available with CGWB)	Feasibility of groundwater structure	Remarks
South 24 Parganas district			
Joynagar I	The upper shallow unconfined aquifer system occurs within 50 m bgl. The lower confined aquifer system occurs in between 70 and 160 m bgl and occurs in between 170 to 360 m bgl. Each aquifer system consists one of more granular zones which are more or less interconnected. The transmissivity (T) ranges from 500 to 2000 m^2/day and co-efficient of Storativity (S) ranges from 0.3×10^{-1} to0.5 $\times 10^{-2}$ in the second i.e., upper confined aquifer system; and in the deper confined aquifer system 'T' ranges from 915 to 3000 m^2/day and 'S' ranges from 0.3×10^{-3} to 1.1×10^{-3}	Low duty shallow tubewells with yield of 20 to 40 m^3 hr^{-1}, and heavy duty deep tubewells with yield of 50 to 150 m^3 hr^{-1} are feasible	Sporadic occurrence of arsenic beyond permissible limit of 0.01 mgl^{-1}
Joynagar II			Fe – 0.11 to 7.82 mg l^{-}1, cl – 124 to 149 mg l^{-1}, EC – 1070 to 1300 μscm^{-1} at 25 °C
Canning I	The upper confined aquifer system occurs in between 80 and 150 m bgl containing brackish water, and the deeper second group of confined aquifer occurs in between 160 and 360 m bgl containing fresh water. Each aquifer system consists one or more granular zones which are more or less interconnected. The transmissivity (T) ranges from 500 to 2000 m^2/day and co-efficient of Storativity (S) ranges from 0.3×10^{-1} to 0.5×10^{-2} in the second i.e., upper confined aquifer system; and in the deper confined aquifer system 'T' ranges from 915 to 3000 m^2/day and 'S' ranges from 0.3×10^{-3} to 1.1×10^{-3}	Heavy duty deep tubewells with yield of 50 to 150 m^3 hr^{-1} are feasible	Fe – 0.61 mg l^{-1},Cl – 53 mg l^{-1},EC – 900 μscm^{-1} at 25 °C
Canning II			–
Mathurapur I			–
Mathurapur II			Fe – 0.04 to 12.27 mg l^{-1},Cl – 138 to 869 mg l^{-1},EC – 1180 to 3500 µs cm^{-1}at 25 °C
Basanti			Fe – 0.06 to 0.63 mg l^{-1}, Cl – 110 to 124 mg l^{-1},EC – 930 to 1150 µs cm^{-1}at 25 °C
Gosaba I			Fe – 0.27 mg l^{-1},Cl – 85 mg l^{-1},EC – 1030 µs cm^{-1}at 25 °C
Kultali			Fe – 0.42 mg l^{-1},Cl – 117 mg l^{-1},EC – 1060 µs cm^{-1}at 25 °C

(continued)

Table 6.7 (continued)

Block	Occurrence of aquifer and its potentiality (as per the data available with CGWB)	Feasibility of groundwater structure	Remarks
Kakdwip			Fe – 0.65 to 10.3 mg l^{-1},Cl – 103 to 450 mg l^{-1},EC – 940 to 2050 μs cm^{-1}at 25 °C
Namkhana			Fe – 0.33 mg l^{-1},Cl – 227 mg l^{-1},EC – 1330 μs cm^{-1}at 25 °C
Pathar-pratima			–
Sagar			Fe – 1.73 to 2.57 mg l^{-1},Cl – 99 to 131 mg l^{-1},EC – 860 to 1050 μs cm^{-1}at 25 °C
North 24 Parganas district			
Haroa	In general, in the depth span of 2–27, 36–78, 122–161 mbgl, T of the aquifers is about 1200–2000 m^2/d	Low duty (20–40 m^3 hr^{-1}), and heavy duty (50–150 m^3 hr^{-1}) tube wells are generally feasible	Safe block, arsenic affected in down to depth of 80mbgl
Hasnabad	In general, in the depth span of 24.00–60.00	Low to medium (50–100 m^3 hr^{-1}), tube wells are generally feasible	Confined aquifer. In few places the aquifers down to 300 mbgl are brackish to saline in nature. Fresh groundwater bearing
Hingalganj	In general, in the depth span of 180–208, 250–280 mbgl	Low to medium duty (50–100 m^3 hr^{-1}), tube wells are generally feasible	Confined aquifer. Above 180 mbgl saline
Minakhan	In general, in the depth span of 115–125 and 170–190 mbgl	Low to medium duty (50–100 m^3 hr^{-1}), tube wells are generally feasible	Confined aquifer. Above 125 mbgl brackish to saline
Sandeshkhali I	In general, in the depth span of 150–160 and 230–290 mbgl	Low to medium duty (40–100 m^3 hr^{-1}), tube wells are generally feasible.	Confined aquifer. Above 150 mbgl saline
Sandeshkhali II	In general, in the depth span of 150–160 and 230–290 mbgl	Low to medium duty (40–100 m^3 hr^{-1}), tube wells are generally feasible	Confined aquifer. Above 150 mbgl saline

(Source: Central Ground Water Board: http://cgwb.gov.in/District_Profile/WestBangal_districtprofile.html, free access)

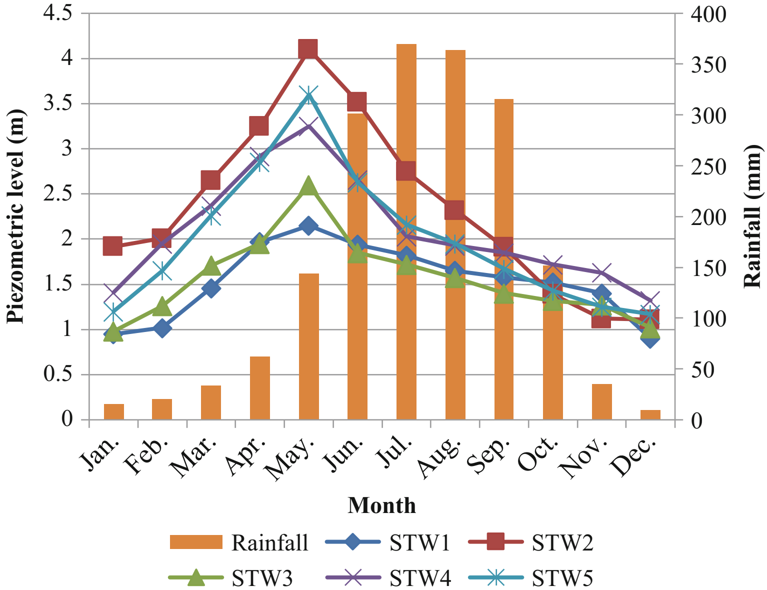

Fig. 6.10 Variation of rainfall and depth (below ground level) of the piezometric level in selected STWs in Dumki village. (Source: Burman et al. 2015, in-house study by the senior author)

6.2.2.3 Groundwater Use for Irrigation

Scarcity of fresh surface water for irrigation during the post-monsoon period is the main constraint on growing *rabi* (post-monsoon *boro*) rice and other crops in the Sundarbans region. Therefore, there is increasing exploitation of groundwater through shallow tube wells (STWs) in Indian Sundarbans region. A series of surveys was conducted on the status of STWs in South 24 Parganas and North 24 Parganas districts from 2000 to 2014 (Burman et al. 2015). The depth of STWs varied from 67 to 128 m below ground level (bgl). A study throughout 2003 showed variation of piezometric level and salinity in groundwater with rainfall during the year, showing drop in the salinity with rise of piezometric and increase of rainfall during monsoon (June to October), and increase in salinity with the reverse trend in piezometric level and rainfall during post-monsoon period (November to May) (Figs. 6.10 and 6.11).

The findings suggest that there is an urgent need to characterize the aquifers of the region and to develop a plan for the sustainable use of groundwater for irrigation.

The tubewells in the Sundarbans area in Bangladesh were generally installed at depths between 150 m and 350 m. In the Khulna region, Haskoning and Iwaco (1981) found that the upper aquifer contains brackish to saline water and that the fresh-saline groundwater interface lies at a depth between 200 and 300 m below ground level. Saline pockets also occur in both shallow and deep aquifers due to the presence of paleo-brackish water that was entrapped in small areas during rapid

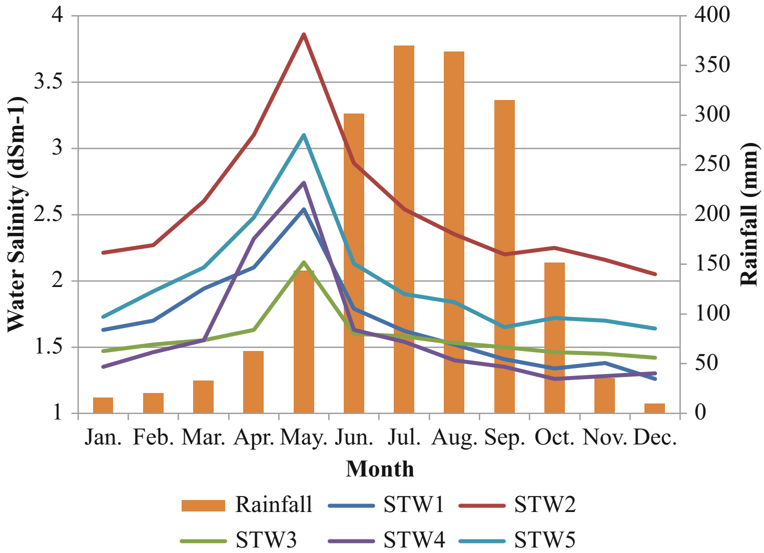

Fig. 6.11 Variation of rainfall and salinity of the groundwater in selected STWs in Dumki village. (Source: Burman et al. 2015, in-house study by the senior author)

regressive events, the latter having occurred between 12,000 and 10,000 years after a transgression period between 18,000 and 12,000 years ago (Acharyya et al. 1999).

Hasan et al. (2015) conducted study on the quality of groundwater in the medium and high saline coastal zone of Sundarbans areas of southwest Bangladesh. They collected water samples from 130 shallow hand tubewells (SHTW) and 115 deep hand tubewells (DHTW). The SHTWs had screen depths varying from 35 to 120 m and in the DHTW it varied from 150 to 340 m below the ground level. Quality of groundwater was variable ranging from good to poor, meaning some aquifers of the southwest coastal zone was suitable for drinking and some were saline for agricultural development and drinking as well.

SRDI (2014) also analysed the suitability of groundwater collecting water samples from the HTWs across the coastal zone of the Ganges delta. The groundwater salinity of Khulna area in the southwest coastal zone over the period 2009 to 2014 varied from 1.2 to 2.8 dS m^{-1} (SRDI 2014).

Observations taken during February 2005 to December 2007 from wells installed at about 50–60 m depth at Polder 30, Batiaghata upazila in Khulna district and Jetua-Kanaidia sub-polder in Tala upazila in Satkhira district in Bangladesh indicated that the phreatic levels at Batiaghata and Tala fluctuated seasonally (Fig. 6.12) (Mondal et al. 2008). The groundwater level at Batiaghata remained at or above the ground surface until November, whereas it remained near the soil surface until September at Tala. The full recharge at both sites and no change in water level between years suggests that there was no "mining" of the groundwater. The elevation of the

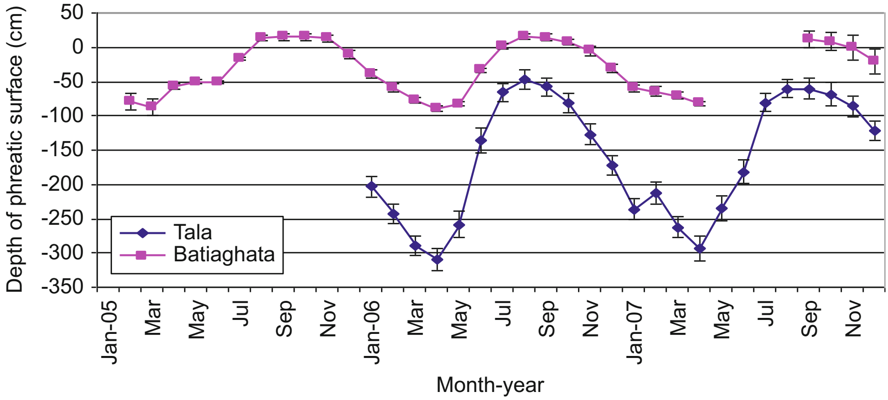

Fig. 6.12 Mean monthly depth of phreatic surface from the ground level in Batiaghata and Tala upazilas of Khulna and Satkhira district, Bangladesh, respectively (vertical and capped bars indicate standard errors of the means of 11–56 values per month). (Source: Mondal et al. 2008, in-house study by second author and free access)

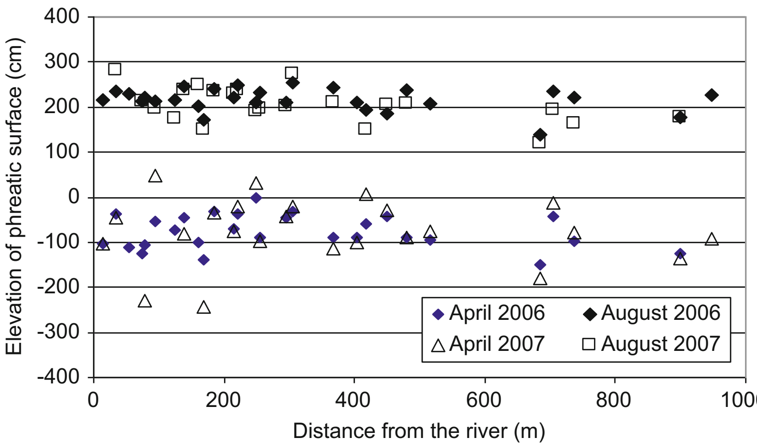

Fig. 6.13 Elevation (in cm above mean sea level) of the phreatic surface at drawdown (April) and recharge (August) periods as a function of the distance from the Kobadak river at Jetua-Kanaidia sub-polder in Tala upazila of Satkhira district, Bangladesh. (Source: Mondal et al. 2008, in-house study by second author and free access)

phreatic level of different STWs at Tala during the drawdown (in the first half of April) and recharge (third week of August) periods is shown in Fig. 6.13.

Mean monthly EC of the groundwater varied between 2 and 5 dSm^{-1} at Batiaghata (Khulna district) and 1–2 dSm^{-1} at Tala in Satkhira district in Bangladesh (Fig. 6.14). In general, there was some seasonal fluctuation of EC, but there was no clear annual increase in EC in the study period. Mondal et al. (2008) argued that the relatively low EC at Batiaghata during November 2005 to May 2006

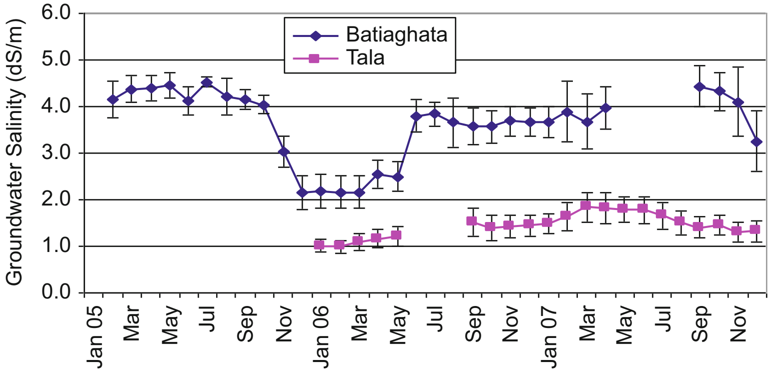

Fig. 6.14 Mean monthly electrical conductivity (EC) of groundwater at Batiaghata and Tala (vertical and capped bars indicate standard error of the means of 8–24 values per month). (Source: Mondal et al. 2008, in-house study by second author and free access)

was unusual; since it is expected that EC would be higher in the dry season than in the rainy season. In a separate study, Mondal et al. (2006) observed EC of groundwater at Kismat Fultola village at Batiaghata varied from 3.5 to 12.7 dS m^{-1}. Such variation and level of salinity indicated non-suitability of groundwater for irrigation development. But in two locations at Dumuria upazila in Khulna district, EC remained within 2.0 dS m^{-1} and SAR was 1.22 meaning thereby that the groundwater at both sites was non-saline and non-sodic (Mondal 1997; Mondal et al. 2001), and considered suitable for irrigation. SRDI (2000) reported variable SAR of groundwater (0.3–4.2) collected from shallow and deep hand tubewells from different locations of the southwest coastal zone of Bangladesh. Although there are suitable aquifers found in the coastal region, utilization of groundwater is risky owing to probability of salt-water intrusion in the coastal aquifers.

6.2.2.4 Change of Water Quality with Distance from River

The change of groundwater EC of the STWs with respect to the distance from the nearest river bank at Tala during the drawdown period (April) is shown in Fig. 6.15. Sixteen STWs (57% of STWs) had EC <1.0 dSm^{-1}, irrespective of their distances from the river. Four STWs had EC in between 3 and 5 dSm^{-1}. The mean monthly EC of these STWs was around 3 dSm^{-1}. Their EC gradually went up to 3–5 dSm^{-1} as the dry season proceeded. Mondal et al. (2008), however, mentioned that it was not possible to conclude that the salt contamination was caused by their proximity to the river. There were other STWs which were nearer to the river for which EC remained <1 dSm^{-1}. It was inferred by them that there was no definite change in the mean elevation of the phreatic water level with distance from the river. This implied

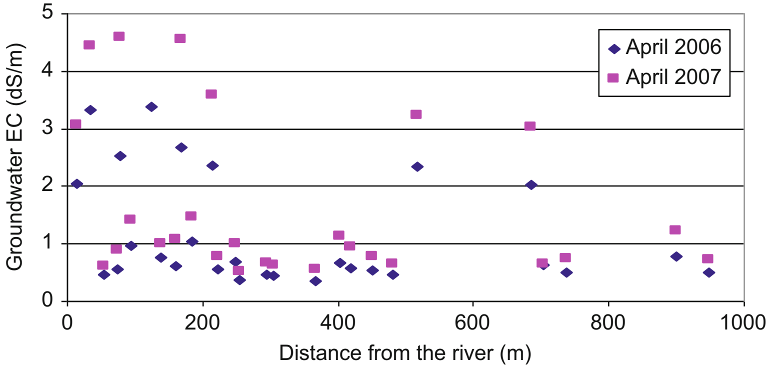

Fig. 6.15 Electrical conductivity (EC) of groundwater as a function of the distance from the adjacent river at Jetua-Kanaidia sub-polder in Tala upazila, Bangladesh. (Source: Mondal et al. 2008, in-house study by second author and free access)

that there were no flows from the river to the inland or vice versa in either period, suggesting there was no direct connection between the aquifer and the surrounding river.

Mondal et al. (2008) further observed that the four contaminated STWs were in places with relatively lower elevation than the surroundings. The contamination might have been due to faulty construction of the wells, which might have allowed vertical leakage, allowing salt water intrusion from the soil surface. The contamination would increase with the drawdown created by pumping groundwater. Faulty construction of the STWs is not uncommon because the wells were often constructed by local untrained personnel.

6.3 Conclusions

Scores of data are being generated on soil and water characteristics in both India and Bangladesh. It is clear from the trend, which are spatio-temporally variable in nature, that rivers and estuaries are tending to become principally tide-fed with time since there appears to be lesser flow of water from the mighty Ganges in the upstream, being common to both countries, due to siltation and poor solid waste management. While, this is a matter of serious concern in so far as surface water hydrology and the related soil characteristics, leaving aside the frequent occurrence of climatic hazard and its influence in the eco-region, very little progress has been made on the groundwater and its utilization having tremendous potential otherwise from the point of view of its capacity along the coastal tract. It is indicative, though not conclusive so far from the limited studies, contrary to the observations from other coastal ecosystems in the globe, that the groundwater in Sundarbans is possibly not influenced by the adjoining rivers and the sea. In order of planning for exploitation of the coastal groundwater, specific programme needs to be undertaken, preferably in transboundary mode, to arrive at a definite conclusion and plan for the mode and nature of its use for irrigation and domestic purposes without affecting the ecology of the region.

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On-farm rainwater harvesting for improved water management (Courtesy S. K. Ambast)

Chapter 7
Managing Land and Water Resources in Sundarbans India for Enhancing Agricultural Productivity

S. K. Ambast

Abstract Agriculture in Sundarbans is plagued with adverse land and water conditions. The answer to the problem of improving agricultural production and productivity in this region primarily lies with the tackling of problem of surface drainage in the monsoon season and through water availability during post-monsoon season. The various strategies suggested in this chapter from the points of view of improved land and water management under the existing situations in India narrated above include (i) rainwater management through storage in on-farm reservoir, derelict channels, other canals, etc., (ii) channelization of the catchment and regulated operation of the sluice gates, (iii) land management through levelling, *bunding*, raising of crop beds, and (iii) improved crop planning against constraints due to drainage congestion during monsoon as well as to limited irrigation water availability during dry periods. Simulation studies using a soil water balance model for rainfed lowland rice is used for estimating excess rainwater to design on-farm reservoir (OFR) and to assess surface drainage improvement due to storage in OFR. Weekly rainfall at 2 and 5 year-return periods are used to optimize the size of OFR and to simulate surface drainage improvement, respectively. It is recommended to convert 20% of the farm area into OFR to harvest excess rainwater, and also to reduce surface waterlogging to the extent of 75%. Further, a simple linear programming model is used to propose optimal land allocation for *rabi* (winter) crop cultivation to increase the agricultural profit under various limitations of land and water.

Keywords Sundarbans delta · Rainwater management · Crop planning · On-farm reservoir · Optimal land and water allocation

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7.1 Introduction

Integrated natural resource management, watershed management or farming system approach are the terms often used synonymously though their dimensions of area vary from basin to farm scale (Fig. 7.1). The integrated natural resource management is good for planning strategy, watershed management is good for programme

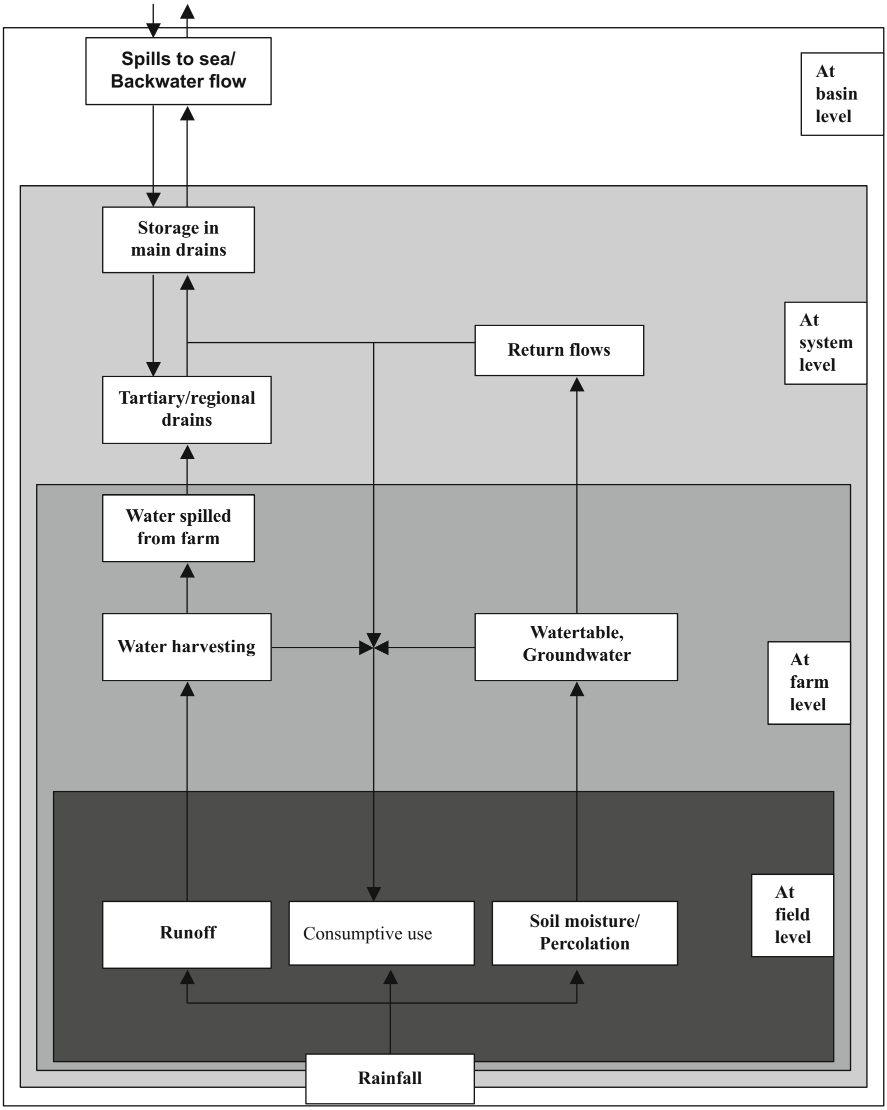

Fig. 7.1 A framework of hydrological processes at different scales in Sundarbans. (Source: Ambast 2007, In-house study)

implementation, while farming system approach suits more to the beneficiaries. In all these approaches, rainwater management forms the basis of improvement. However, looking to the small land holdings in Sundarbans, in particular, farming system approach seems to be more appropriate. It is an integrated approach on rainwater management dealing with on-farm storage of excess rainwater during monsoon season and recycling the same for irrigation of crops during deficit periods in dry season with the objective to introduce multi-cropping in the otherwise predominantly mono-cropped areas.

7.1.1 Strategies towards Enhancing Agricultural Productivity

The Sundarbans is one of the largest deltas in the world and is shared by India and Bangladesh. The region is criss-crossed by innumerable tidal rivers and creeks forming 54 islands. As per the present status in India, the region is predominantly mono-cropped with more than 80% area under *kharif* (June–November) rice cultivation and about 62% of the area is low-lying (Anonymous 1988). The region is more or less flat with undulations having an average ground level 1.2 m above the mean sea level, whereas the average high tide level is 2.75 m above MSL. The area is surrounded by protective earthen embankments provided with one-way sluice gates for drainage of excess inland water and to prevent ingress of tidal water. The field level drainage network is inadequate in the region (Ambast 1996). In the years of high rainfall, it gets severely waterlogged or occasionally flooded during monsoon due to impeded natural drainage. On the other hand, ground water quality, being saline, and due to lack of assured means of water supply, *kharif* rice crop often suffers under prolonged drought spells particularly in the later period of crop growth. This compels the farmers to resort to prefer local low yielding (1–1.4 t ha^{-1}) tall varieties. The practice of rainwater storage in an on-farm reservoir (OFR) is quite common but their design is not based on scientific principles. Also, there is no information available on the extent of surface drainage improvement due to rainwater storage in OFR. The use of stored water for second crop cultivation during *rabi* (December–April) is not judiciously practised for the lack of recommendations on crop selection and water allocation at different stages, and this often results in crop failure or low net returns during rainfall deficit years.

The agricultural water management strategies in terms of rainwater management, land management and improved weather-based crop planning are the possible options to improve agricultural production and productivity in this region. Studies were made for weather-based crop planning, land management through fish-cum-paddy farming, and rainwater management through optimal design of OFR, simulation of surface drainage improvement due to OFR, and supplemental irrigation demand in Sundarbans delta region of West Bengal, India, which are discussed in the subsequent text. Similar strategy can be planned for other parts of eastern coast in India.

7.2 Agricultural Land Drainage

Most of the coastal low-lying areas in Sundarbans are frequently inundated due to ingress of seawater through tidal estuaries. These estuaries are slowly silting up due to high silt load carried along with the river flows causing congested drainage system leading to flooding of agricultural fields. It has been suggested that earthen embankments, preferably brick-pitched, having side slope of 3:1 on the river side and 2:1 on the country side, with 1 m free board above the high tidal level, are appropriate for protection against flooding (Rao 1981). In order to facilitate quick removal of excess rainwater and to stop the ingress of seawater into the low-lying areas, construction of peripheral embankments with provision of one-way sluice gates, and construction of drainage network will be necessary. In general, a three-tier system of surface drainage, described below, is recommended for effective and economic view (Gupta et al. 2006).

1. Rainwater is allowed to accumulate and remain in the fields till such time and extent as will not be harmful to crop.
2. Excess water from the fields is led to the dugout ponds of sufficient capacity. The stored water can be utilized subsequently during dry spells or for irrigating winter season crops.
3. Rainwater in excess of these two components of storage is taken out of the area to the creeks/sea through appropriately located one-way sluice gates/structures.

7.3 Rainwater Management

A comprehensive work on rainwater management in Sundarbans delta, West Bengal is presented by Ambast et al. (1998).

7.3.1 Analysis of Rainfall and Evaporation Data

Historical daily rainfall (1963–1992) and evaporation (1967–1992) data for Canning (India), which is a representative block for Sundarbans delta, are collected and analyzed. The region receives an average annual rainfall of 1768 mm ranging from 1030 mm to 2462 mm with a coefficient of variation of 21.2%. Of that, 82% rain occurs during June–October in monsoon season (Fig. 7.2). The average monthly rainfall and evaporation are shown in Fig. 7.3. Weekly rainfall and evaporation data are analyzed for different probability distributions, i.e. Normal, Log Normal, Extreme value I and Log Pearson type III (Chow 1964). The Extreme value I distribution is found suitable for the observed rainfall data, whereas Log-Pearson type III is found closely fitting to the evaporation data, and therefore, used as input parameter for further estimation. The weekly rainfall at 2 (50% probability) and

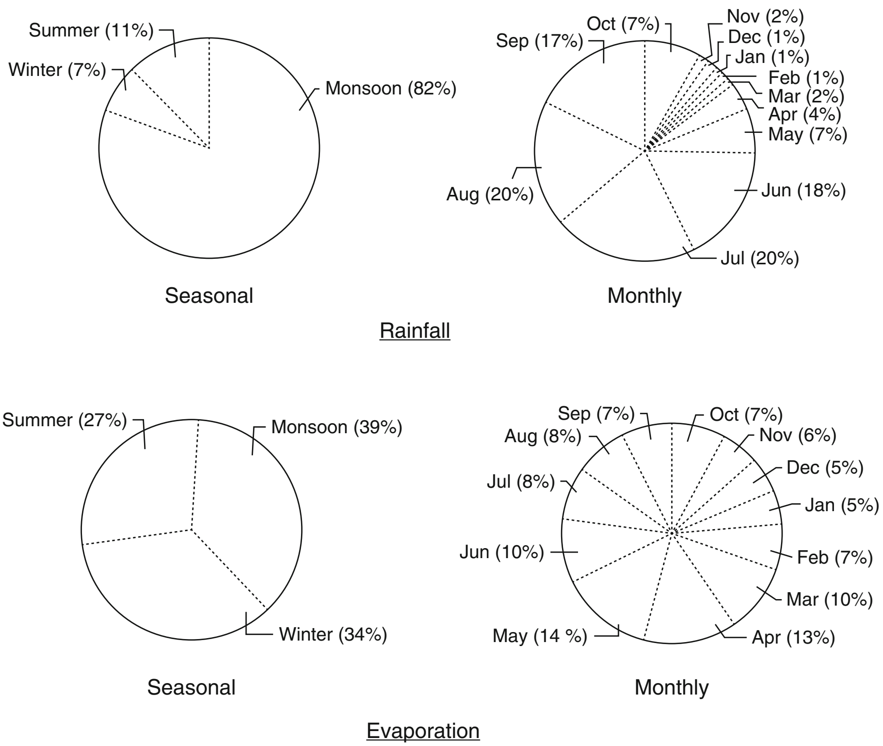

Fig. 7.2 Average monthly rainfall (1963–1992) and evaporation at Canning Town. (Source: Ambast et al. 1998, In-house study)

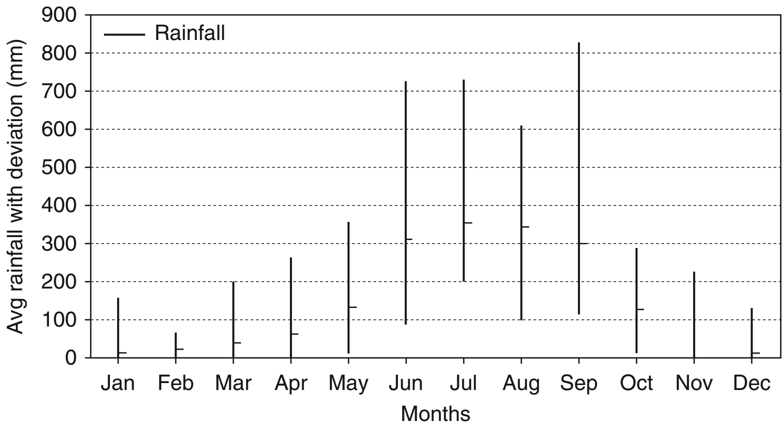

Fig. 7.3 Average monthly rainfall and its variation at Canning Town. (Source: Ambast et al. 1998, In-house study)

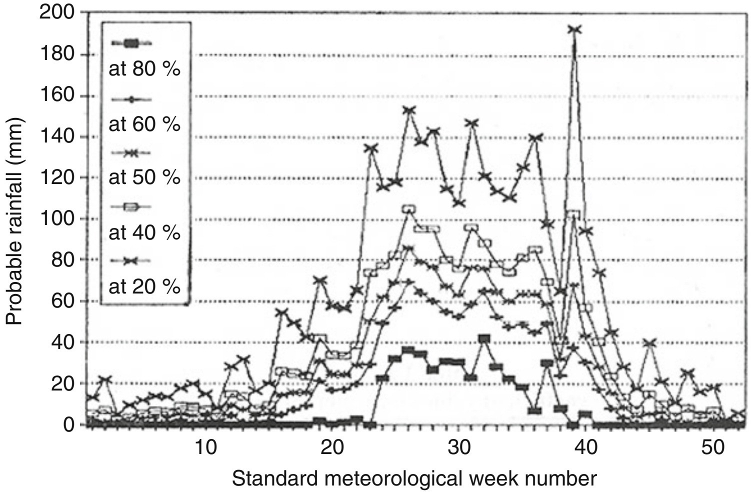

Fig. 7.4 Weekly probable rainfall at different return periods. (Source: Ambast et al. 1998, In-house study)

5 year (20% probability)-return periods are given in Fig. 7.4. It is estimated that, on an average, about 5-week drought (no water stands on surface) for rice crop may occur during the season and about 3-week continuous drought may be expected during the ripening stage, compared to none, during both vegetative and reproductive stages (Ambast et al. 1998).

7.3.2 Crop Planning

Crop planning involves selection of crops, varieties and planting schedules to suit the land topo-sequences, and availability of water and its use. Since more than 80% cultivated area in the region is medium to low-lying, scope of *kharif* crops, other than rice, hardly exists in this region. Therefore, planning involves selection of rice varieties and their planting schedules during *kharif* and crop diversification during *rabi*. Probable rainfall and evaporation, as a measure of crop water demands, has been made to develop a crop calendar for Sundarbans delta region for optimal farming operations with the objectives of stabilizing production and minimizing recurrent production losses due to uncertain weather (Ambast et al. 1996).

To determine the time of pre-sowing and sowing operations for *kharif* rice, probability of onset of monsoon was assessed. The expected onset of monsoon is from 24th week and the rainfall at all probability levels increases after 23rd week onward (Fig. 7.5). It also indicates that there are seven chances out of ten of receiving at least 50 mm rain during pre-monsoon period (19th–23rd week). Therefore, it is suggested to initiate off-season tillage practices from 19th week onwards.

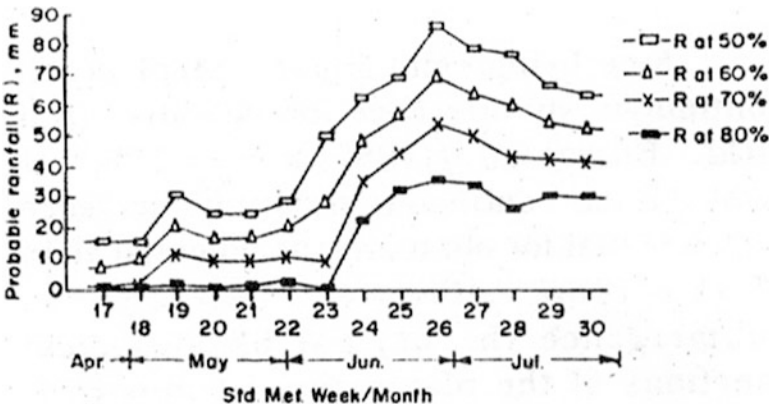

Fig. 7.5 Probable onset of monsoon. (Source: Ambast et al. 1998, In-house study)

Since the area is generally saline in nature, it was recommended to allow the rain during 19th–23rd week to flush/leach down the salts accumulated in the soil surface/profile during the dry season.

7.3.2.1 Optimal *Kharif* Planting

In order to make the best use of the expected weekly rainfall potential and its distribution at critical growth stages, sowing time of rice were adjusted for different duration varieties keeping the problems prioritized under various farming situations to stabilize the crop yield. The critical stages were worked out based on the growth pattern of short, medium and long duration varieties (Tanaka 1976). The analysis indicates that there are 50% chances of waterlogging in the early part of monsoon and/or moisture stress in the later period of crop growth. Keeping the agronomic requirements for potential rice production (Pandey 1976; Biswas et al. 1982), rainfall (R) – potential evapotranspiration (PET) diagrams were prepared for optimal planting schedule of different duration varieties (Figs. 7.6, 7.7, 7.8).

The suitability of different duration rice varieties for different rainwater availability constraints and their optimal planting schedules for various farming situations during *kharif* season for Sundarbans delta region are given in Table 7.1.

7.3.2.2 Optimal *Rabi* Planting

For *rabi* planting, planning is made by assessing the probability of pre-monsoon showers at the time of crop harvest. It indicates that there are fair chances of occurrence of rain of more than 60 mm at 5 year- return period after 16th week. The problem area, in general, is having heavy textured soil and therefore, accumulation of water of more than 60 mm damages the crop. Land preparation for *rabi*

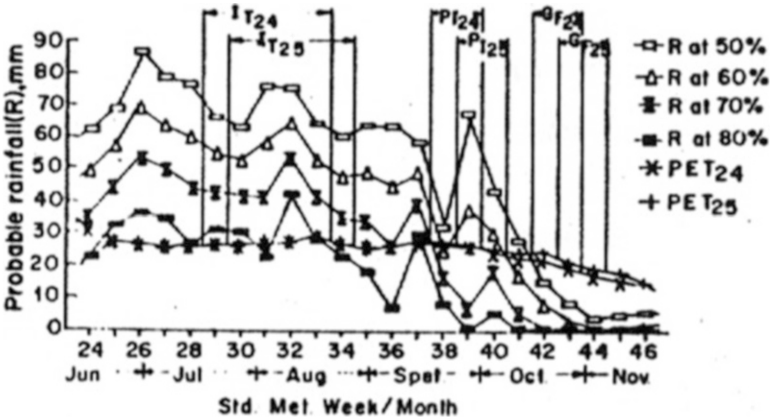

Fig. 7.6 R-PET diagram for short duration rice. (Source: Ambast et al. 1998, In-house study)

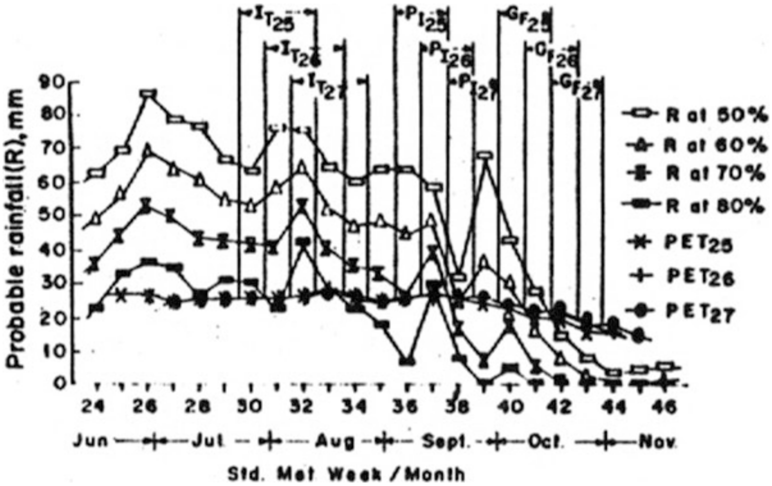

Fig. 7.7 R-PET diagram for medium duration rice. (Source: Ambast et al. 1998, In-house study)

cultivation from 46th to 48th week, followed by sowing in 49th week and harvesting of crop before the 16th week in the following period, is suggested. This leaves scope for a third short duration summer crop (green manure or fodder) after the *rabi* harvest.

Based on probable weekly water balance, planting schedule for *kharif* and *rabi*, crop suitability, and their agronomic management practices, a crop calendar is suggested for Sundarbans region (Fig. 7.9).

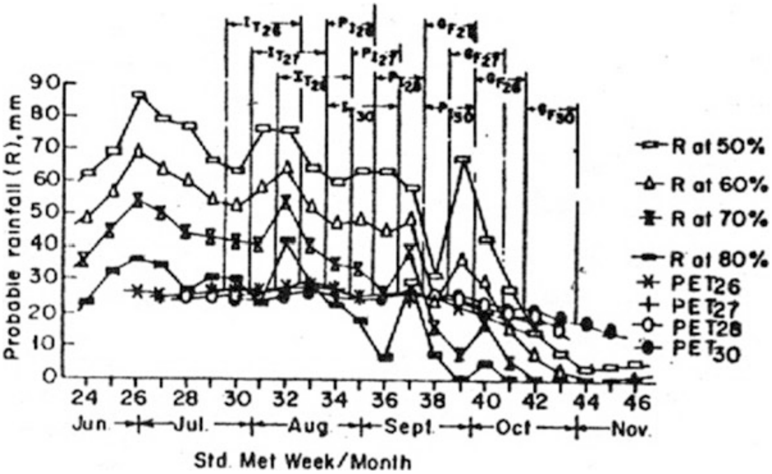

Fig. 7.8 R-PET diagram for long duration rice. (Source: Ambast et al. 1998, In-house study)

Table 7.1 Duration and planting schedule for *kharif* rice in different farming situations

Farming situation	Availability of irrigation (OFR)	Recommended duration	Time of sowing
Upland	Yes	Short duration	26th week (26 Jun – 02 Jul)
	No	Short duration	26th week (26 Jun – 02 Jul)
Medium land	Yes	Short duration	30th week (23 Jul – 29 Jul)
	No	Medium duration	25th week (19 Jun – 25 Jun)
Low land	Yes	Medium duration	25th week (19 Jun – 25 Jun)
	No	Long duration	24th week (12 Jun – 18 Jun)

Week refers to meteorological week
Source: Ambast and Sen 1995a, In-house study

7.3.3 Optimizing On-Farm Reservoir (OFR)

7.3.3.1 Soil Water Balance Model

A soil water balance model based on physical parameters is used to estimate the excess rainwater availability in lowland rice paddies (Ambast and Sen 1995c; Ambast and Sen 1998). The schematic diagram for a typical rainfed rice lowland system is shown in Fig. 7.10. The soil water balance equation to estimate the depth of standing water in rainfed rice lowlands is expressed as follows:

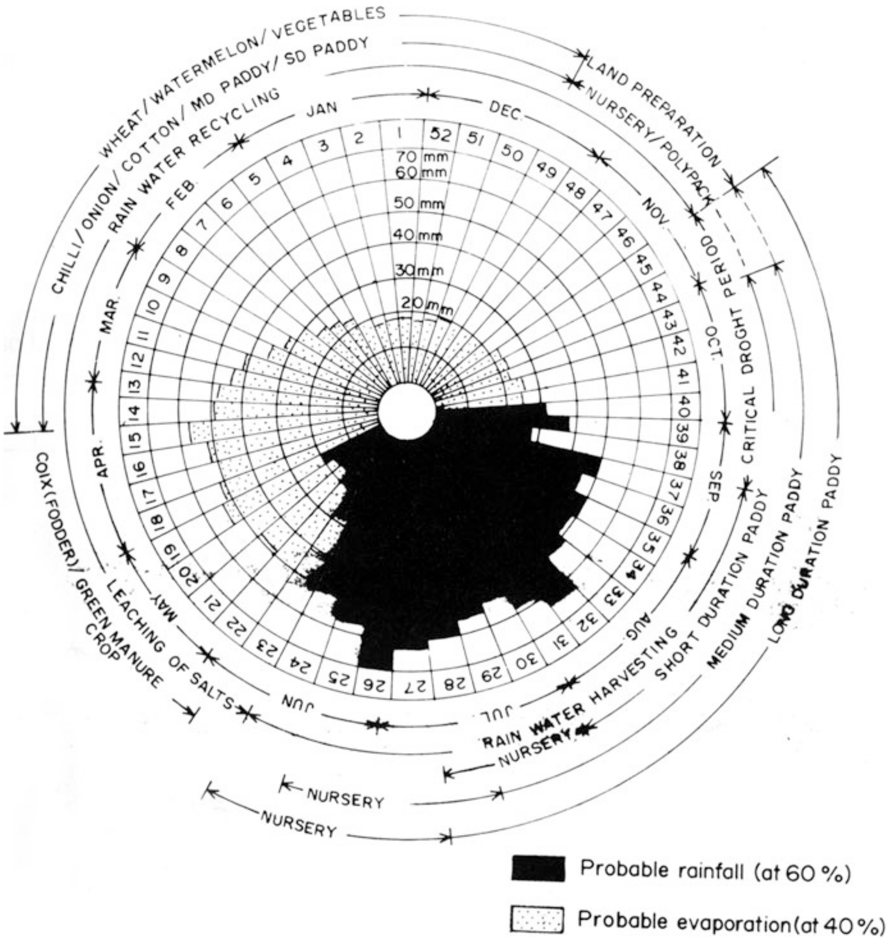

Fig. 7.9 Recommended crop calendar for Sundarbans delta region. (Source: Ambast and Sen 1995b, In-house study)

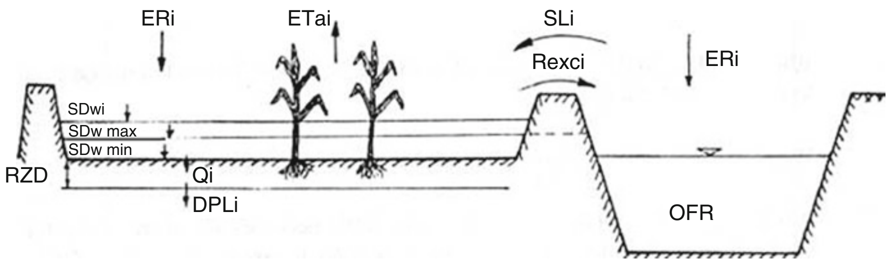

Fig. 7.10 Components of water balance for a typical rainfed lowland system. (Source: Ambast and Sen 1998, In-house study)

$$SDW_i = SDW_{i-1} + R_i - ET_i - DPL_i + SI_i \tag{7.1}$$

where, i is the time index, week; SDW the depth of standing water at surface, mm; R the rainfall, mm; ET the crop evapotranspiration, mm; DPL the deep percolation loss, mm; SI the depth of supplemental irrigation, mm.

The following conditions are used to estimate the amount of excess rainwater in rainfed rice lowlands:

- At the beginning of the computation, SDW_{i-1} is set to zero.
- When $SDW_{min} < SDW_i < SDW_{max}$, SDW_i becomes actual water depth for the period.
- When $SDW_i > SDW_{max}$, the amount SDW_i-SDW_{max} is diverted to the OFR and SDW_i is set to SDW_{max}.
- When $SDW_i < SDW_{min}$, the SI_i (50 mm), if available in OFR is provided.
- When VOL > V_{OFR}, the SDW_i becomes actual water depth up to the height of field dyke (700 mm) and any excess rainwater beyond SDW_i spills to drainage system.

where, SDW_{min} is the minimum depth of standing water for optimal growth of rice, mm; SDW_{max} the maximum depth of standing water for rice crop, mm; VOL the volume of rainwater storage in OFR, m^3; and V_{OFR} the volume of OFR, m^3.

In Sundarbans region, the onset of monsoon occurs at 24th standard meteorological week (SMW) (Ambast and Sen 1995b). It is assumed that the soil cracks may be filled during pre-monsoon rains. The weekly rainfall values at 2 and 5 year-return periods are taken as R from 24th week onward to design OFR and to assess surface drainage improvement, respectively. As water availability is fairly good during *kharif* season weekly ET values are estimated using the pan evaporation method as proposed by Doorenbos and Pruitt (1977).

$$ET_i = Kc_i \, Kp \, Evp_i \tag{7.2}$$

where, Kc is the dimensionless crop coefficient value for rice (Table 7.2); Kp the dimensionless pan coefficient value (0.8 valid for humid climate with moderate wind velocity); and Evp_i the open pan evaporation, mm.

The DPL (deep percolation loss) beyond the root zone occurs when soil moisture exceeds field capacity. The equivalent depth of soil moisture at field capacity is estimated by taking root zone depth for rice and percentage moisture content at field capacity for silty clay loam soil (Michael 1978). A maximum of 14 mm weekly DPL (subject to moisture availability) is taken on the basis of daily DPL (2 mm d^{-1}) measured in the farmer's field under puddled rice condition by ponded basin method (Rao and Dhruvanarayana 1979). A simple book keeping approach is used to estimate the soil moisture storage in the root zone. As rice requires an optimal submergence of 50 ± 20 mm for potential production (Biswas et al. 1982), the SDW_{max} and SDW_{min} are taken as 100 mm and 0 mm (moisture at saturation), respectively. SI is provided only when water equivalent to a SI is available in the OFR.

Table 7.2 Crop coefficient (Kc) values for rice

Percentage crop growth	Kc	Percentage crop growth	Kc
0	1.00	55	1.21
5	1.02	60	1.22
10	1.03	65	1.22
15	1.05	70	1.22
20	1.07	75	1.21
25	1.09	75	1.19
30	1.11	80	1.16
35	1.13	85	1.10
40	1.16	90	1.03
45	1.18	95	0.96
50	1.20	100	0.86

Source: Michael 1978, In-house study

7.3.3.2 Design and Construction of OFR

The low cost of construction has made OFR increasingly popular in the Sundarbans region. The design parameters are shape, size, depth, side slope, capacity and location. The prevailing dugout trapezoidal OFR with and without *bund* are considered for optimization. The length-width ratio of OFR is taken 1:1 as it is having minimum perimeter and therefore, attains maximum storage. As groundwater is at shallow depth and saline in nature in this region, the depth of OFR is restricted to 3 m on the basis of observed water quality in the OFR at the end of *rabi* season. The standard side slope of 1:1 is taken for silty clay loam soil.

The following equations are used to optimize the size of an OFR:

$$RA = WA\ (S/100) \tag{7.3}$$

$$W = (A/Y)^{½} \tag{7.4}$$

$$L = W\ Y \tag{7.5}$$

$$L_s = L - 2\ ((2\ Z_b\ \ H_b) + TW_b + W_b) \tag{7.6}$$

$$W_s = W - 2\ ((2\ Z_b\ \ H_b) + TW_b + W_b) \tag{7.7}$$

$$AL_s = \left[L_s + \left\{L_s - \left(2\ Z_p\ \ D\right)\right\}\right]/2 \tag{7.8}$$

$$AW_s = \left[W_s + \left\{W_s - \left(2\ Z_p\ \ D\right)\right\}\right]/2 \tag{7.9}$$

$$V_{OFR} = AL_s\ \ AW_s\ \ D \tag{7.10}$$

Where, RA is the surface area of OFR, m^2; WA the farm area, m^2; S the size of OFR, % WA; W the width of OFR at surface, m; Y the ratio of length to width, mm^{-1}; L the length of OFR, m; L_s the length of submergence at surface of the OFR, m; Z_b the side slope of the *bund*, mm^{-1}; H_b the *bund* height, m; TW_b the top width of *bund*, m;

W_b the width of berm, m; W_s the width of submergence at surface of the OFR, m; AL_s the average (at surface and bottom of OFR) length of submergence, m; AW_s average width of submergence, m; Z_p the side slope of OFR, mm^{-1}; and V_{OFR} the volume of OFR, m^3.

The rainwater storage in OFR is computed using the equations expressed as:

$$Rexc_i = SDW_i - SDW_{max} \tag{7.11}$$

$$VOL_i = \sum_{i=1}^{n} \{(Rexc_i/1000)\ (WA - RA) + ((R_i/1000)\ RA)\} \tag{7.12}$$

where, Rexc is the excess rainwater diverted from field to OFR, mm. The evaporation and seepage losses from OFR are not considered during *kharif* season because shallow water table (0.5–1.5 m below surface) contributes water to OFR whereas, losses take place on account of evaporation. However, these losses are considered to compute available water storage in OFR for irrigation during *rabi* season due to deeper water table (2–3 m).

7.3.3.3 Computation of the Programme: Comparison with Field Data on Flood Water Depth

A flow chart for development of computer programme is given in Fig. 7.11. The model is verified by comparing simulated and observed depth of standing water in rice lowlands without OFR. The weekly rainfall and evaporation data for *kharif* 1994 are used for generation of simulated depth of standing water. Two fields; one at the tail end (lowland) and the other at the head end (upland) in the catchment of sluice no 2 of East Mograhat Drainage Outfall Division in Sundarbans delta are selected. The maximum depth of standing water in lowland and upland are 600 mm and 100 mm, respectively beyond which excess water spilled out to the drain. The depths of standing water are observed at different growth stages during *kharif* 1994. The regression analyses indicated a good agreement ($r^2 = 0.97$ for lowland and 0.95 for upland) between simulated and observed values (Fig. 7.12) and therefore, may be faithfully used to simulate excess rainwater availability in rice paddies.

For computation purpose the initial size of OFR is assigned the maximum area (40% of farm area) which may be converted into OFR, whereas the location of OFR is varied to allow runoff from 10% to100% of farm area. At the end of computation, if storage in OFR is found less than its capacity, a decrement to the size of OFR is provided for further computation. When OFR gets filled the size is considered as optimal and the process is terminated.

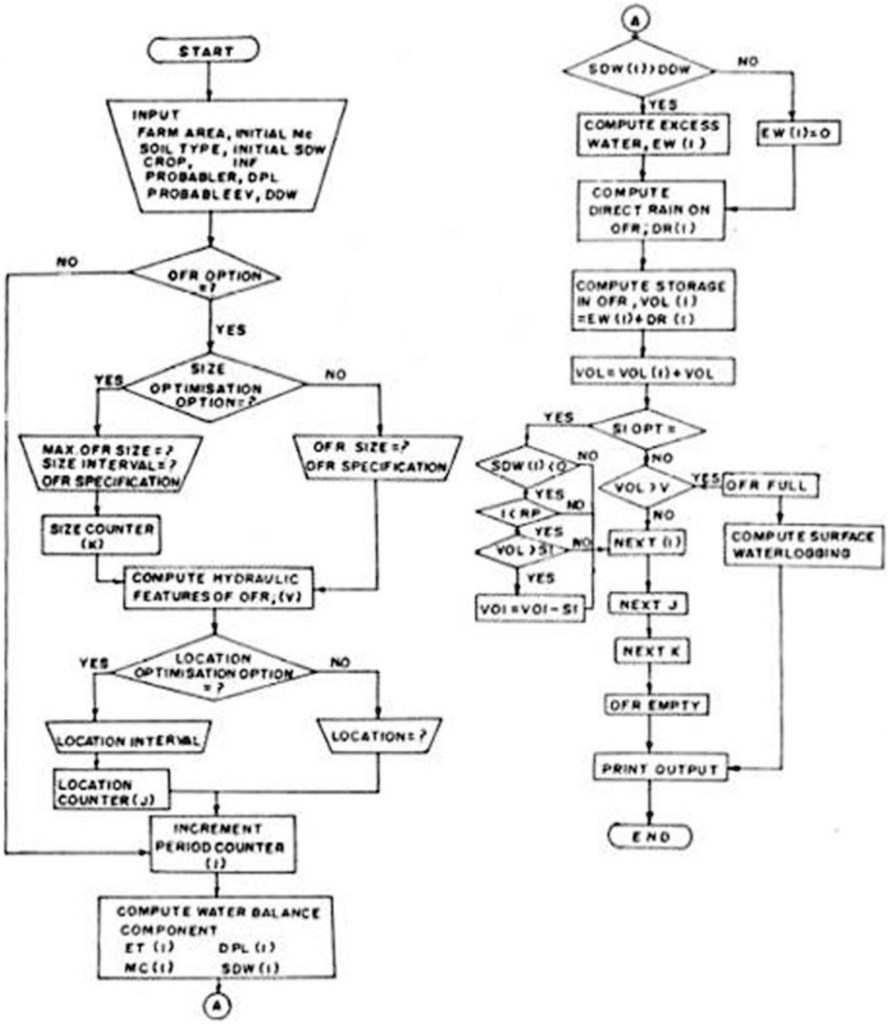

Fig. 7.11 Flowchart for optimizing size of on-farm reservoir. (Source: Ambast et al. 1998, In-house study)

7.3.3.4 Hydrologic and Hydraulic Features of an OFR: Developing a Nomograph

A nomograph is developed to determine the hydrologic and hydraulic features of OFR in unit farm area (1 ha) for various combinations (Fig. 7.13). It represents three type of curves, i.e. the design dimension curve, OFR capacity curves, and rainwater availability curves. Since OFR is considered square in shape, the design dimension curve represents the equal length and width of the selected size of OFR. The OFR

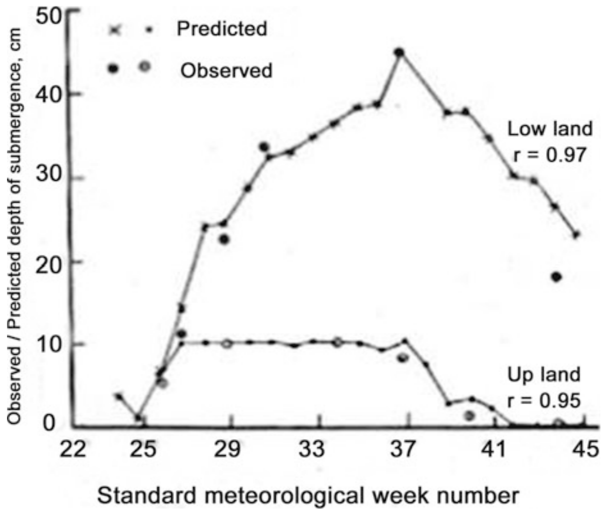

Fig. 7.12 Model verification by observed – simulated submergence in Mograhat drainage division, Sundarbans, India. (Source: Ambast et al. 1998, In-house study)

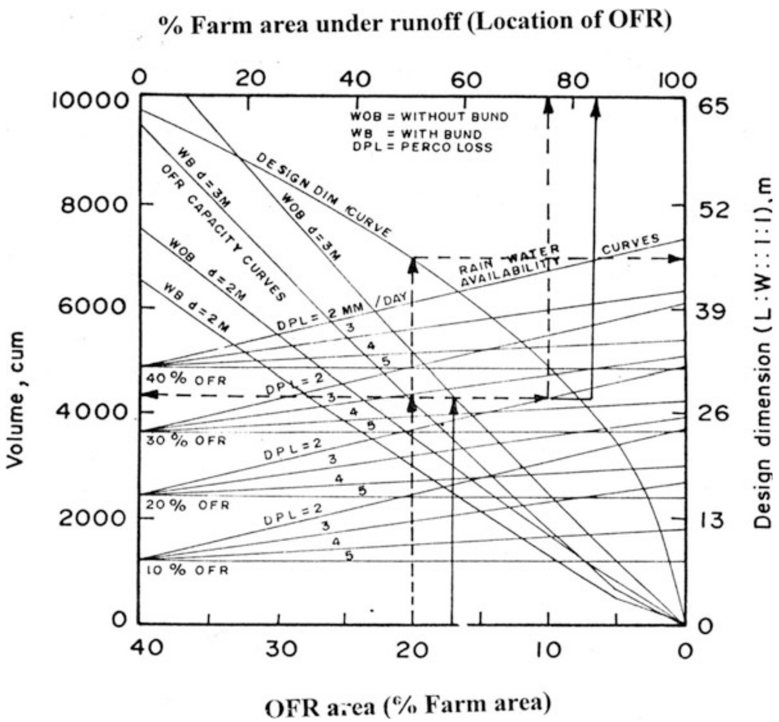

Fig. 7.13 Nomograph for determining optimal size of farm reservoir. (Source: Ambast and Sen 1995c, In-house study)

capacity curves give the information of the total volume that can be stored in the OFR of different sizes. The capacity curves are plotted for OFR with and without *bund* for 2 and 3 m depths. The rainwater availability curves for different size of OFR i.e. 10%, 20%, 30% and 40% of farm area are generated for construction of OFR at different locations, i.e. 10%, 50% and 100% below farm area, which contribute runoff from 10%, 50% and 100% farm area, respectively.

The basic steps to use the nomograph are (i) note the volume of a particular size of OFR by projecting vertical line to OFR capacity curves and extending it towards volume, (ii) note the location of OFR to meet the rainwater availability curve for that particular size of OFR and for known deep percolation rate, and (iii) note the dimension of OFR by projecting vertical line to design dimension curve. For example, the dotted line in Fig. 7.13 represents an optimal 3 m deep OFR with *bund* in 20% farm area in soils with percolation loss rate 2 mm d^{-1} to be placed at 75% below the farm area. Similarly, the solid line represents an optimal size of 3 m deep OFR without *bund* in 17% farm area for such soils and placed at 83% below the farm area to meet rainwater to its designed capacity of 4268 m^3. The length and width of OFR in 20% area of a hectare should be 44.7 × 44.7 m. Therefore, it is suggested to convert 20% or 17% of the farm area into OFR with or without *bund*, respectively. However, for recommendation purposes, it is suggested to convert 20% of the farm area into OFR. The design features of OFR for a unit farm area (1 ha) in Sundarbans delta is shown in Fig. 7.14.

7.3.3.5 Surface Drainage Improvement

In low-lying areas of the region, the scope for cultivation of high yielding dwarf rice varieties (HYV) is almost negligible due to surface waterlogging during *kharif* season (Rao and Ambast 1996). The simulation study is made to assess the reduction in weekly surface waterlogging by diverting excess rainwater into the OFR (with and

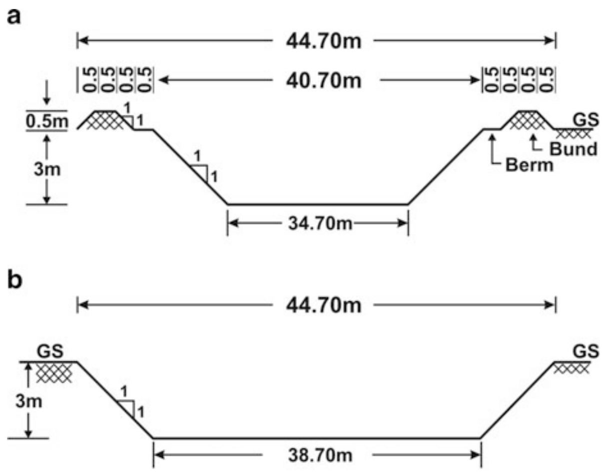

Fig. 7.14 Design dimension of on-farm reservoir for 1 ha area in Sundarbans delta. (Source: Ambast and Sen 1995b, In-house study)

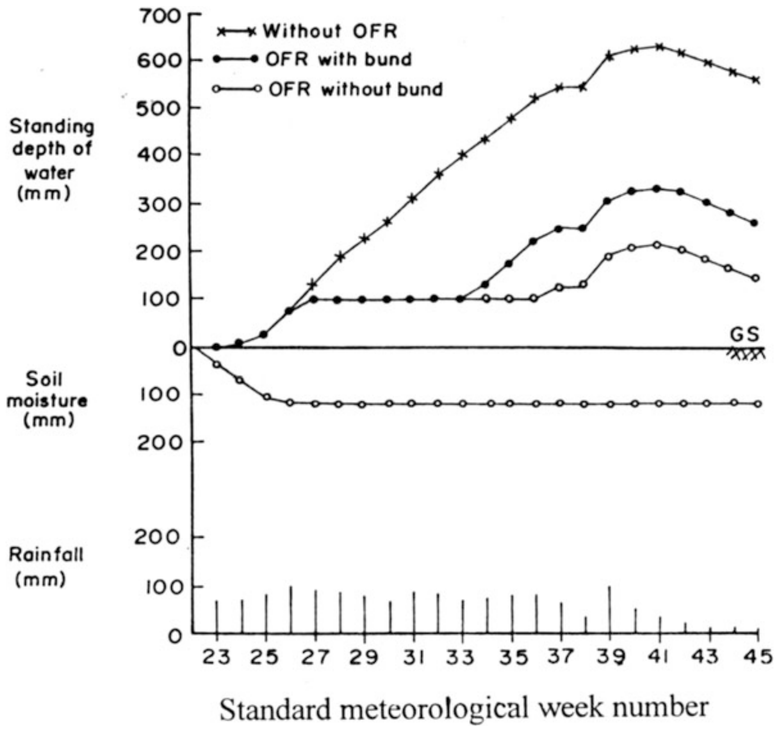

Fig. 7.15 Simulation of surface drainage improvement due to on-farm reservoir. (Source: Ambast et al. 1998, In-house study)

without *bund*) in 20% of farm area over low-lying area without OFR. The surface water depth hydrographs are generated with probable weekly rainfall at 5 year-return period (Fig. 7.15). It is estimated that in a lowland catchment with no drainage, the water depth may reach as high as 0.63 m and therefore the cultivation of HYV rice crop is not possible under the existing condition. The water depth, in case of OFR with *bund*, remains at required water depth for rice up to 33rd SMW till OFR gets filled. However, the water depth increases to 0.35 m at panicle initiation and flowering stages, which are critical to excess water and affect crop production adversely. It is estimated that surface waterlogging during the season may reduce to about 45% in case of OFR with *bund*. In case of OFR without *bund*, the depth of water remains as required for a major growth period up to 37th SMW. The maximum depth of water may reach to 0.18 m at the beginning of grain formation stage but for a short period. Though, some reduction in crop yield may occur due to excess water at this stage that may not be significant. In this case the reduction in surface waterlogging is to the extent of 75%. Therefore, construction of OFR not only provides water for irrigation but also improves surface drainage and thus, makes it possible to grow HYV of rice in lowlands of Sundarbans delta.

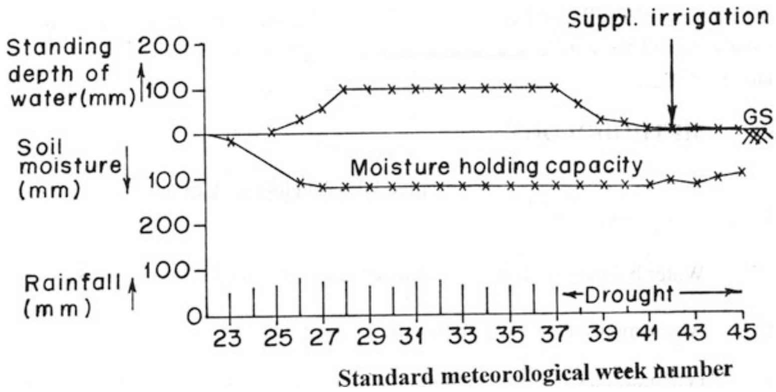

Fig. 7.16 Simulation of supplemental irrigation requirement in kharif season. (Source: Ambast et al. 1998, In-house study)

7.3.3.6 Supplemental Irrigation Demand

In order to assess the requirement of supplemental irrigation (SI) during *kharif* rice and to formulate water availability constraint for optimal land allocation in *rabi* season, simulation study was made. The preconditions for supplemental irrigation (50 mm) are defined as (1) storage in the OFR should be more than one SI for cultivated land, and (2) soil moisture in subsurface should reach below the saturation level. On the basis of weekly values at 80% annual rainfall (no rainfall after 37th week), it is estimated that at least one supplemental irrigation is needed at the time of grain formation stage in two out of 10 years (Fig. 7.16). This will stabilize the crop production against the weather uncertainty.

7.3.3.7 A Computer Software

Further, user-friendly computer software RAINSIM (Rainwater Simulation Modelling) was developed (Fig. 7.17).

7.3.4 Optimal Land and Water Allocation for Maximizing Profit

Rainwater harvesting through OFR can make available only limited quantity of water. To keep the economics of OFR in favourable range, it is imperative that water is used judiciously for crops having high water productivity in terms of economic returns. Linear programming formulations were normally used to arrive at the optimal land and water allocation amongst different crop activities (Palanisami 1991). A simple linear programming model is used in the present case.

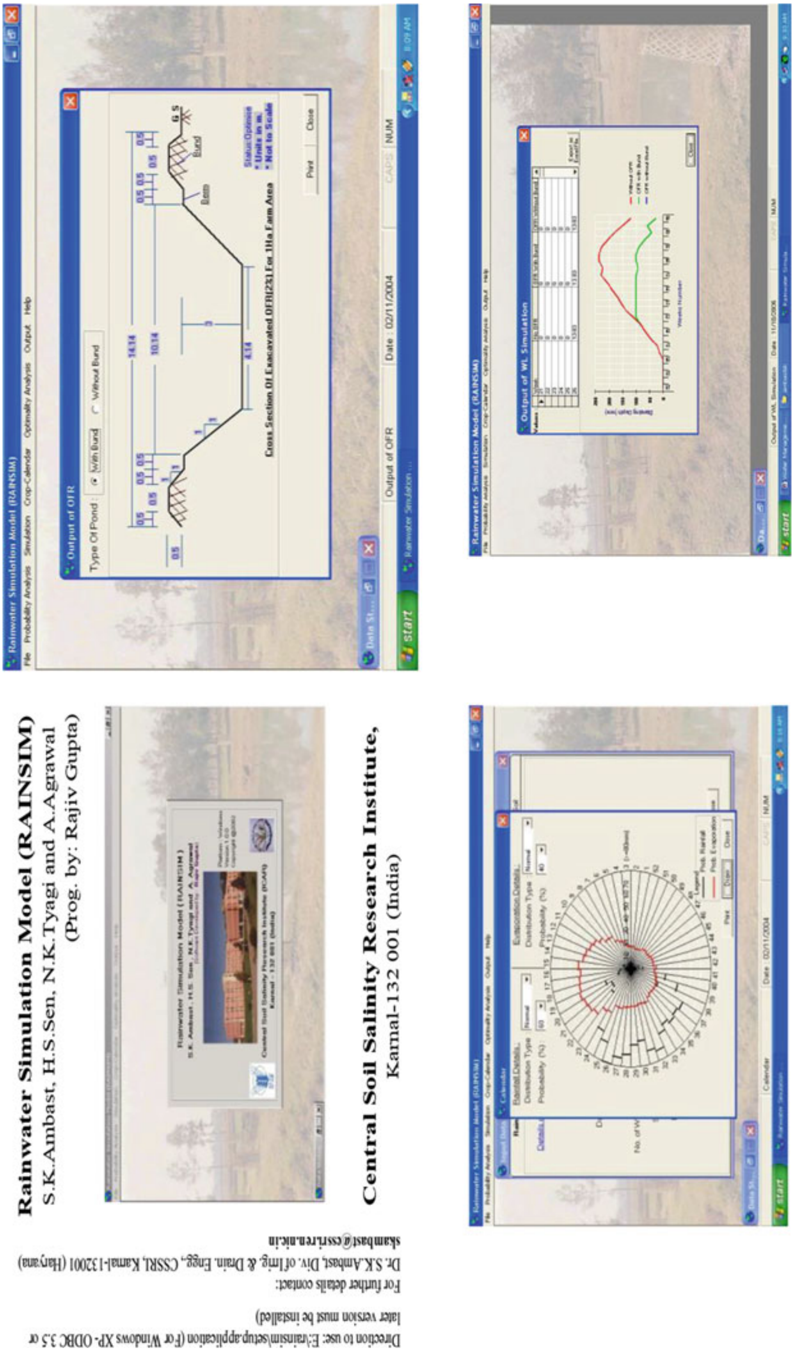

Fig. 7.17 (**a**) RAINSIM software (**b**) OFR design (**c**) crop calendar and (**d**) simulation of drainage improvement. (Source: Ambast et al. 2002, In-house study)

Objective Function The objective function maximizes returns from the irrigated area under different crops through OFR and cost of water stored in OFR (includes cost of OFR and a penalty cost for making OFR area out of production during *kharif* season). It is assumed that inputs other than land, water and labour are at fixed level.

$$\text{Max NP} = \sum_{i=1}^{n} ((C_i Y_i) - P_i)\, A_i - \text{Cs S} \tag{7.13}$$

where, i is the index for crop; NP the net profit, Rs ha^{-1}; A the area under crop, ha; C the unit sale cost of crop, Rs $tonne^{-1}$; P the unit cost of crop production, Rs ha^{-1}; Y the yield per unit area, tonne ha^{-1}; Cs the unit cost of water in OFR, Rs m^{-3} $year^{-1}$; and S the total stored volume in OFR, m^3.

Irrigation Requirement Constraint The sum of water demand of crops should not exceed available water in OFR (Initial storage-Seepage-Evaporation) during the period of growth.

$$\sum_{i=1}^{n} GIR_i\ A_i - (S - WL) < 0 \tag{7.14}$$

where, GIR is the gross irrigation requirement for crop, m^3 ha^{-1}; WL the water losses from OFR observed at the rate of 5 mm d^{-1} for 135 days, m^3.

Land-Use Constraint The percentage acreage under different crops is limited to 80% of the total available area as 20% area is used for OFR.

$$\sum_{i=1}^{n} A_i - L < 0 \tag{7.15}$$

where, L is the total available land area, ha.

The acreage under chilli (A3), cotton (A4) and cucumber (A5) are restricted to a given value due to the risk of crop damage by heavy rainfall at the time of harvest. Rice is the most demanding and safe crop against the weather uncertainty, and therefore, a minimum acreage under rice (A1) crop is placed. The crop activities and the limits placed on crop area are given in Table 7.3.

$$A\,(3) < A_{max}(3) \tag{7.16}$$

$$A\,(4) < A_{max}(4) \tag{7.17}$$

$$A\,(5) < A_{max}(5) \tag{7.18}$$

$$A\,(1) > A_{min}(1) \tag{7.19}$$

Table 7.3 Crop activities and area constraints

Sr. No.	Crop	Maximum area (%)	Minimum area (%)
1	Rice	–	20
2	Wheat	–	–
3	Cotton	50	–
4	Chilli	50	–
5	Cucumber	20	–
6	Watermelon	–	–
7	Pumpkin	–	–
8	Ridgeguord	–	–

Source: Ambast et al. 1998, In-house study

where, A denotes the area under crop, A_{max} and A_{min} denote the maximum and minimum area under the crop, respectively.

Labour Constraint Most of the non-rice crops are labour intensive because irrigation is often applied through pitcher, and the inter-culture operations also require considerable labour. However, labour availability in the area is low. Therefore, a constraint is placed on labour requirements.

$$\sum_{i=1}^{n} A_i Lr_i - La < 0 \tag{7.20}$$

where Lr is the labour requirement for unit area for crops, man-days ha^{-1}; La the total labour availability, man-days.

Two OFR (with bund – Case I and without bund – Case II) at Nikarighata village in South 24 Parganas district of Sundarbans delta are selected for model application. The hydraulic and storage features of OFR are given in Table 7.4. The storage in OFR with and without *bund* is estimated as 1100 and 5225 m^3, respectively. Taking the surface area of OFR, crop duration and observed daily water losses into account, seepage and evaporation losses are estimated to be 270 and 1355 m^3 for OFR with and without *bund*, respectively. The water requirements of different crops are estimated using pan evaporation method (Doorenbos and Pruitt 1977) and the prevailing water application methods. On the basis of 2 years (93–94 and 94–95) of experimentation in the farmer's field, the input on labour, cost of cultivation (includes pumping cost) and net profit per unit area for different crops are generated (Ambast et al. 1998). The inputs on water use, labour requirement and net profit are given in Table 7.5.

In the existing cropping pattern, rice crop is cultivated through OFR that causes shortage of water or crop failure in rainfall deficit years. The optimal area allocation to different crops is shown in Table 7.6. As per the allocation during *rabi* season in the years of normal rainfall, rice should be grown only in 20% of area and the remaining area should be allocated to non-rice crops in farms having OFR with

Table 7.4 Specifications of OFR with and without bund at Nikarighata village, Sundarbans

Sr. No.	Specifications	With *bund* (Case I)	Without *bund* (Case II)
1	Size of OFR (m)	30.0 × 19.4	60.0 × 33.5
2	Area of OFR (m^2)	582	2010
3	Submergence area (m^2)	400	2010
4	Maximum depth (m)	3.00	2.75
5	Estimated volume (m^3)	1100	5225
6	Net cultivated area (m^2)	2325	7933
7	Estimated water losses (m^3)	270	1355

Source: Ambast et al. 1998, In-house study

Table 7.5 Input use per hectare in Sundarbans

Sr. No.	Crop	Water use (ha cm)	Labour (Man-days)	Net profit (Rs)
1	Rice	86	105	7280
2	Wheat	26	94	2910
3	Cotton	32	168	3275
4	Chilli	22	475	6550
5	Cucumber	30	294	4730
6	Watermelon	26	135	4000
7	Pumpkin	26	120	3275
8	Ridgeguord	26	135	2550

Source: Ambast et al. 1998, In-house study

bund. Under non-rice crops 50% area is allocated to chilli crop, whereas 15% area allocated to each cucumber and watermelon. In case of OFR without *bund*, 40% and 60% area to rice and non-rice (chilli-50% and cucumber-10%) crops, respectively showed an optimal allocation to maximize net profit. The increase in cost of rainwater storage in OFR does not change water allocation, and therefore, indicated the stability of the suggested crop allocation.

Effect of Deficit Rainfall on Crop Allocation In rainfall deficit years it is stipulated that SI of 50 mm is to be provided during *kharif* season and thus, water availability in OFR would reduce by same amount during *rabi* season. In case of OFR with *bund*, the optimal allocation indicates that the percentage rice area remains the same because of minimum area constraint but the irrigation intensity (percent area irrigated) is reduced by 20%. In case of OFR without *bund*, the percentage acreage under rice crop reduces by 10% but the irrigation intensity remains same as 10% land allocated to cucumber.

Effect of Labour Inadequacy on Crop Allocation Labour is the major constraint in the region particularly when non-rice crops are irrigated manually with water applied through pitcher. Therefore, the effect of labour availability on crop allocation was studied. Sufficiency of labour is estimated on the basis of average demand for chilli and wheat crop as the most and least labour intensive crop, respectively. In case of

Table 7.6 Optimal crop allocation for OFR at Nikarighata village, Sundarbans

Crop	Area allocation							
	OFR Full		OFR empty to a SI		80% labour		OFR empty to a SI + 80% labour	
	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II
Rice	464 (20)	3173 (40)	464 (20)	2380 (30)	464 (20)	3173 (40)	464 (20)	2777 (35)
Wheat	–	–	–	–	–		793 (10)	–
Cotton	–	–	–	–	–	–	–	–
Chilli	1160 (50)	3967 (50)	1160 (50)	3174 (40)	814 (35)	3174 (40)	928 (40)	3173 (40)
Cucumber	348 (15)	793 (10)	–	1587 (20)	232 (10)	–	116 (5)	–
Watermelon	348 (15)	–	232 (10)	–	812 (35)	793 (10)	348 (15)	1586 (20)
Pumpkin	–	–	–	–	–	–	–	–
Ridgeguord	–	–	–	–	–	–	–	–
Net agric profit in *rabi* (Rs)	759	2420	548	2217	662	2071	496	1867
Net agric profit in *kharif* (Rs)	667	2912	667	2912	667	2912	667	2912
Total agric profit (Rs)	1425	5332	1215	5129	1329	4983	1163	4779

Source: Ambast et al. 1998, In-house study
Data in parenthesis represents percentage acreage to total area
Additional Income from horticulture – Case I @ Rs 440
Additional Income from pisciculture – Case I @ Rs 2525 and Case II @ Rs 12,000
Empty row against cotton, pumpkin or ridgegourd suggests the crops were considered though not qualified for maximizing profit

OFR with *bund* when labour sufficiency is reduced by 20%, the area allocated to rice remains the same due to minimum area constraint but the area allocated to chilli and cucumber crop is reduced by 15% and 5%, respectively. However, the irrigation intensity remains the same as the area of watermelon is increased by 20%. In case of OFR without *bund*, the optimal land allocation to rice crop remains the same but the area under chilli crop reduces by 10%. However, 0% area may be allocated to wheat crop, as it requires minimum labour.

Effect of Interaction of Water and Labour Inadequacy The effect of interaction between reduction in available water during *rabi* due to its use during *kharif* as SI and labour (by 20%) was studied. It is noticed that the rice area remains the same due to lower limit but the area under chilli and cucumber reduced equally by 10% in case of OFR with *bund*. Therefore, irrigation intensity was reduced by 20%. In case of OFR without *bund*, the reduction in rice area was 5%, while chilli and cucumber both were reduced equally by 10%. Since 20% area was allocated to watermelon, a reduction of 5% in irrigation intensity was observed.

Economic Evaluation The economic feasibility of OFR, technical efficiency in terms of cost of water development (includes cost of OFR and a penalty cost for making OFR area out of production during *kharif* season), and productivity per unit water storage were estimated. The life of OFR was taken as 25 years. The annual cost of water harvesting and supply were estimated as Rs 582 10^{-3} m^3 and Rs 557 10^{-3} m^3 for OFR with and without *bund*, respectively. The total agricultural profit per hectare area were estimated at Rs 1295 10^{-3} m^3 and Rs 1020 10^{-3} m^3. Thus, the benefit cost ratio is around 2 in both the cases that justify investment in OFR.

7.3.5 Land-Shaping Interventions

In humid coastal areas, surface waterlogging during *kharif* and non-availability of water during *rabi* is major problem. Land-shaping is the articulation of land arrangement, discussed above, so as to overcome hydrologic problems in agricultural area for potential crop cultivation (Ambast et al. 2007, 2011; Ravisankar et al. 2008). Relevant descriptions of land shaping interventions in Sundarbans are presented by Sarangi and Islam in a separate chapter in this book.

7.4 Conclusions

Following significant achievements have been emerged out of the studies carried out at the Sundarbans delta:

- With an average annual rainfall of 1768 mm and evaporation of 1581 mm, July and August are the wet months having probability of severe crop damage due to waterlogging. On an average, 5-week drought (3-week continuous at ripening) may occur during *kharif* season.
- Based on probable R-PET data, rice-transplanting schedule was developed for reducing climatic hazard in different land topo-sequences. Further, a crop calendar of optimal farming operations is developed for minimizing production losses due to uncertain weather.
- Water balance analysis shows considerable scope of rainwater harvesting in on-farm reservoir (OFR). It was recommended to convert 20% of the farm area into OFR. The procedure may be used for optimal design of OFR in different agro-ecological conditions.
- Simulation of surface drainage improvement with and without OFR indicated surface drainage improvement up to 75% in low-lying rice areas of East Mograhat Drainage Basin. It provides scope for cultivation of HYV of rice in rainfed humid rice lowlands.

- It is estimated that 1-supplemental irrigation might be required at grain formation stage in two out of 10 years that will stabilize rice production in *kharif* season.
- Linear programming model is used for optimal land and water allocation in dry season for various land and water constraints for maximizing profits. Optimal allocation indicated benefit-cost ratio of 2:1 (excluding income from fishery and horticulture), thus justified the investment in OFR.

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Improved crop management under land shaping technique (Courtesy D. Burman)

Chapter 8
Advances in Agronomic and Related Management Options for Sundarbans

Sukanta K. Sarangi and Mohammad Rafiqul Islam

Abstract Agriculture, including livestock, fishery and production of various crops, like rice, maize, sunflower, mustard, vegetables, fruits, etc., is the primary occupation of the people of Sundarbans. However, productivity of crops in this region is low due to preponderance of various factors, which include abiotic stresses like salinity, flooding, occasional drought; biotic stresses, like high infestation with insect pests, diseases, weeds and rodents; and natural calamities, like cyclones, tsunami, etc. For a successful crop production, selection of suitable crops and varieties along with commensurate management practices are essential. In this chapter a succinct account of appropriate salt tolerant crops, varieties and their descriptions, area of suitability with advanced package of practices, crop management practices to reduce salinity, particularly during *boro*/*rabi* (summer/winter) season, are discussed. The cropping pattern in Sundarbans eco-region is mostly mono-cropped, therefore information on suitable cropping patterns/systems with natural resource management strategies are also described.

Keywords Sundarbans · Low productivity · Crop varieties · Cropping system · Agronomic practices · Other management options · Salinity · Water harvesting · Land shaping · Integrated fertility management

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8.1 Introduction

The Sundarbans eco-region possesses saline soils, mud shores, marine streams, rivers, estuaries, coral reefs, mangrove forests, etc. Agriculture and aquaculture are the major occupations for the inhabitants of this region. There are about 2 m ha area of saline soils in Sundarbans including mangrove swamps. Waterlogging during rainy season, moderate to high level of soil salinity along with scarcity of irrigation water during summer/winter (*boro*/*rabi*) season, are the major bio-physical constraints, which result in mono-cropping with traditional rice (*Oryza sativa*) varieties (Sarangi et al. 2014, 2015). The factors which contribute significantly to the development of saline soils are tidal flooding during wet season (June–October), direct inundation by saline or brackish water, and upward or lateral movement of saline ground water during dry season (November–May). Natural calamities, like cyclone, flood, tsunami, storm, ingress of seawater affect agriculture and related activities adversely. All these lead to poor socio-economic status of the farming communities in the coastal region. Most of the holdings (>80%) are small and marginal with holding size for most of 0.5 ha. During recent years, in India, rapid conversion of agricultural land to brackish water fishery tends to aggravate the salinity stress in the adjoining crop fields. In the Bangladesh portion of Sundarbans, similar problems are observed.

The soil salinity starts increasing at the end of the *kharif* (monsoon) season on cessation of rains, and reaches its maximum in the month of May–June before the onset of next monsoon rains (Fig. 8.1).

Ground water in the shallow zones are saline in coastal areas with spatial and temporal variations. With monsoon rains, the ground water is recharged and there is less salinity, and as the summer progresses, the ground water salinity increases with peak salinity during April–May (Fig. 8.2).

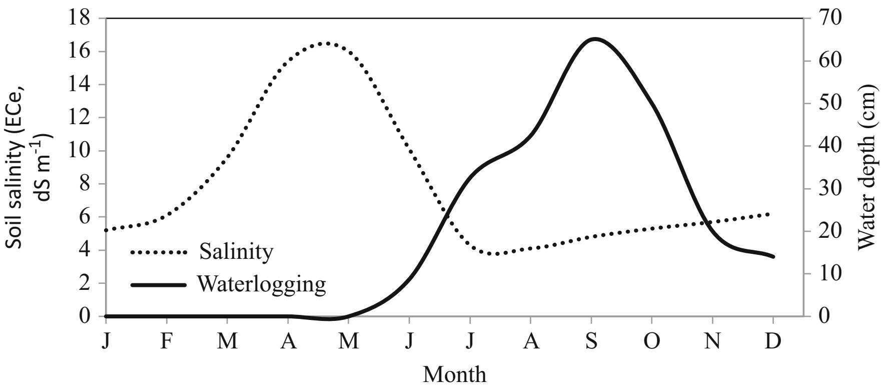

Fig. 8.1 Soil salinity and field water depth in paddy fields at Canning Town, India. (Source: In-house study)

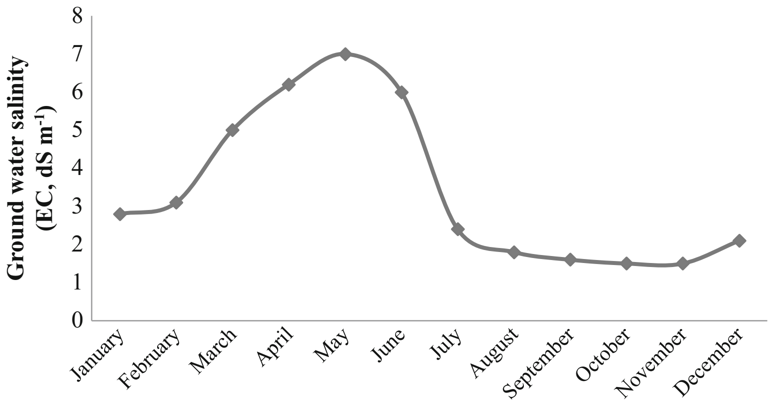

Fig. 8.2 Salinity of groundwater as observed in piezometers at Canning Town, India. (Source: In-house study)

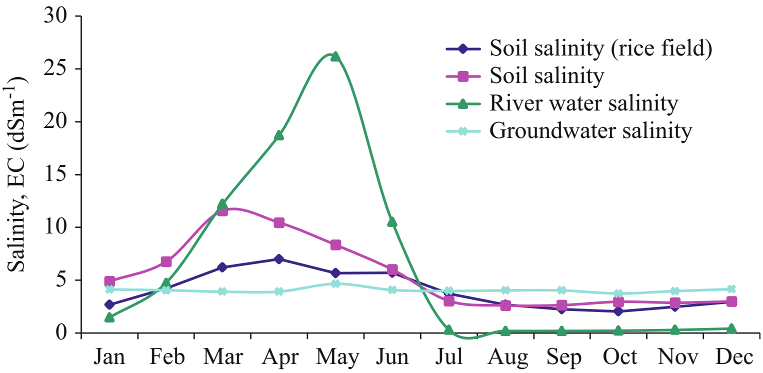

Fig. 8.3 Soil and water salinity dynamics at Batiaghata, Khulna. (Source: In-house study in Bangladesh)

High tidal surges caused by coastal storms increase salt accumulation in soils, and high rainfall during the wet season cause flash-floods and waterlogging. Together, these constraints limit rice productivity in these coastal areas. As a consequence of high salinity and waterlogging, only a small set of local landraces are traditionally grown by farmers in these areas. These traditional varieties are photoperiod sensitive and tall in stature with low yield and poor grain quality.

The soil and water salinity dynamics for coastal saline areas of Bangladesh is shown in Fig. 8.3. In the month of February, the river water (surface water) salinity starts to increase and reaches its peak in the month of June (EC > 25 dS m^{-1}). With onset of monsoon from July, the river water salinity decreases and it remains almost fresh up to December – January. Therefore, farmers can easily grow *aman* (wet) season rice during this period. Thereafter, soil salinity starts increasing from January–February and it reaches EC >10 dS m^{-1} in March – April; and this salinity increase affects rice production in *boro* (dry) season. For increasing interest in rice cultivation in Sundarbans during dry season there is a definite need to develop salt tolerant rice varieties with high yield and improved grain quality.

In the background of the above, attempt is made in this article to discuss improved agronomic and related management options to increase crop productivity for higher income for the inhabitants of Sundarbans.

8.2 Cropping Pattern

The Sundarbans region is primarily mono-cropped with paddy cultivation during wet (*kharif*) season, which accounts for almost 98% of cultivable area and rest used mainly for vegetables and cereals on uplands. Major cropping patterns are rice-fallow, rice-rice and rice-vegetables with very negligible share of other crops like oilseeds and pulses (Fig. 8.4). The *kharif* season (*aman* paddy) covers the period from mid-June to December and dry season (*rabi*/*boro*) spreads from mid-December to May (Sarangi and Maji 2017). Cropping intensity in the area is quite low (120–125%) as most of the cultivated area remains fallow during dry season. Growing crops other than rice is very difficult during *kharif* season due to deep waterlogging/flooding of low-lying agricultural fields by ample monsoonal rains. This is also a constraint for successful rice cultivation, thus the productivity of rice during this season is very low (~2 t ha^{-1}).

Lower cropping intensity is observed in most of the blocks of Sundarbans. In India, moderate cropping intensity is found at Basanti, southern part of Canning, parts of Jaynagar and Kultali blocks. Higher cropping intensity is found in a small pocket covering parts of Kultali and Jaynagar block. *Kharif* paddy is the most important crop, while *boro* paddy ranks second in importance and covers more than 10% of the area in the season. Vegetables are grown both in *rabi* and *kharif* seasons covering about 8% of the total cropped area. Comparatively the share of area

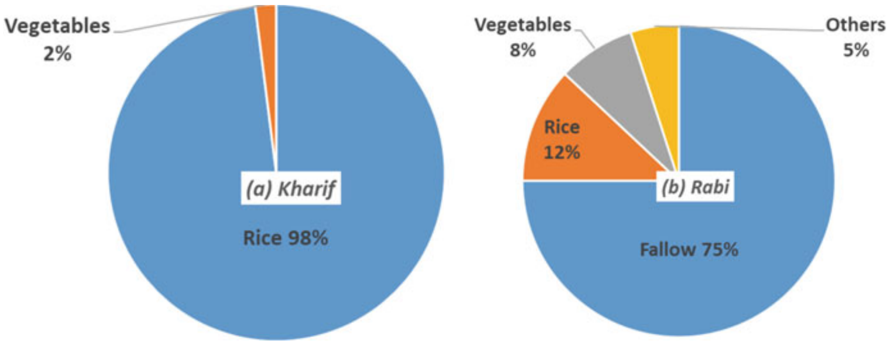

Fig. 8.4 Cropping pattern in Sundarbans region (**a**) *kharif* and (**b**) *rabi* seasons. (Source: In-house study at Canning, India)

Fig. 8.5 Relay/*paira* cropping of grass pea with *aman* rice. (Source: In-house study at Canning, India)

under *rabi* vegetables is higher than that under *kharif*. Besides *aman* and *boro* paddy, aus (summer/pre-*aman*) paddy is also grown but in insignificant amount in Indian Sundarbans. Farmers prefer to grow *boro* paddy because of lower risks than *aman*, besides, the productivity of the former is much higher, especially when high yielding varieties are used (Sarangi et al. 2014). The higher productivity of *boro* may be attributed to the use of high yielding variety seeds, feasibility of improved water management practices, and presence of conducive climate, etc. Cultivation of *boro* paddy is fully dependent on the availability of irrigation facility during the dry periods. However, cultivation of *boro* paddy is more capital intensive, though more remunerative, than *aman*.

During *rabi* season, in India there is scope for cultivation of field crops like maize (*Zea mays*), potato (*Solanum tuberosum*), sunflower (*Helianthus annuus*), rapeseed (*Brassica napus*) and vegetables if improved management practices are followed. During recent years, with introduction of improved production technologies, like raised bed sowing, paddy straw mulching, zero tillage, solar powered drip irrigation, etc. by ICAR-CSSRI, RRS, Canning Town, the areas under maize, potato, rapeseed and vegetable cultivation is increasing, particularly in Canning, Gosaba, and Basanti blocks. Relay cropping (*paira/utera*) of grass pea (*Lathyrus sativus*) locally called *khesari* are promoted in Gosaba island of Indian Sundarbans (Fig. 8.5). Though potato is an important *rabi* crop it occupies less than 1% of the total cultivable area. Cultivation of potato is mainly concentrated in the northern part of Gosaba block. Potato is also grown, though in small quantity, at Basanti, Kultali, Canning-I, Mathurapur, Kakdwip, Namkhana, Sagar and Patharpratima blocks. In recent years, lady's finger (*Abelmoschus esculentus*) has become popular and is grown in considerable area in Sundarbans throughout the *kharif* season. Chilli (*Capsicum* *annuum*) is one of the important cash crops of this region. Sagar, Canning, Namkhana and Jayanagar blocks have moderate concentration of area under chilli. In general, chilli is now being grown in almost all blocks. However, due to the incidence of viral diseases after the cyclone *Aila* in May 2009, the area under chilli is decreasing in some of the blocks.

In the saline soils of Bangladesh part of Sundarbans, various crops, like rice, maize, jute (*Corchorus* spp.), sugarcane (*Saccharum officinarum*), pulses, oilseeds, spices, vegetables and fruits are grown, but their contributions to cropping intensity vary greatly with regions. In salt affected highlands of Barisal, Khulna and Patuakhali regions, local transplanted *aman* rice (July–November) is the dominant crop, whereas in the same land type of Chittagong region HYV, *aman* rice is the major crop. In medium highlands of Barisal, Khulna, Noakhali, Patuakhali and Chittagong regions, the dominant crop is local transplanted *aman* rice. The dominant crop in the medium lowlands of the former three regions is broadcast *aman* rice, whereas in Chittagong region broadcast *aus* rice is the dominant crop.

During *kharif* season, local *aman* paddy is grown extensively in the coastal saline areas with normal yields between 2.5 and 3.0 tons per hectare. Transplanted *aman*-fallow is the most dominant cropping pattern in Khulna, Barisal and Patuakhali regions. In Noakhali and Chittagong, *aus*-local transplanted *aman* pattern covers 25–28% area. Next to this is the transplanted *aman*-fallow pattern, which represents about 18–20% area. Winter crops, such as wheat (*Triticum aestivum*), potato and vegetables are grown, which cover a small area (11.5%). This is practiced in the district of Noakhali with transplanted *aman*-winter crop cropping pattern. Crops during *rabi* season vary from place to place depending upon depth and duration of flooding, soil texture and salinity. Relay cropping of *khesari* or *mung* (*Vigna radiata*), sole cropping of sesame (*Sesamum indicum*) or mustard (*Brassica juncea*) are found in Patuakhali, Barisal, Satkhira and Khulna, whereas soyabean (*Glycine max*) and chilli are *rabi* crops in Noakhali (Shoaib 2013).

8.3 Strategies to Enhance Crop Productivity

8.3.1 Salt Tolerant Rice Varieties

During 1990s (1994–1998) four most significant salt tolerant rice varieties, viz. CSRC 2-1-7 (IET No. 13428), CSRC(S) 11-5-0-2 (IET No. 13422), CSRC(S) 5-2-2-5 (IET 12855) and CSRC(S) 7-1-4 (IET No. 14199) were developed; these were released in the names of Sumati, Utpala, Bhutnath and Amal-Mana in 2003, 2003, 2005 and 2008, respectively in India. After 2008, large scale evaluation of rice varieties was conducted for salt tolerance and flood tolerance under on-farm condition at ICAR-CSSRI, RRS Canning as well as in the farmers' fields in the Sundarbans region during dry and wet seasons, respectively. The significant salt tolerant varieties identified were WGL 20471 (Lal-minikit), Bidhan 2, Binadhan-8, BRRI dhan47, Annada, Boby, Lalat, Canning 7 for dry season. The promising flood tolerant rice varieties were Amal-Mana, Swarna-Sub1, CSRC(D) 7-0-4 and CSRC (D) 12-8-12 for cultivation in the flood-prone areas of Sundarbans region during wet season. The on-station or on-farm experiments on varietal evaluation in Sundarbans region suggested that there is considerable potential for increasing rice production in the coastal zone of West Bengal through replacement of locally grown wet and dry season varieties with improved stress tolerant varieties (Sarangi et al. 2015, 2016b). With adoption of promising stress tolerant HYVs and matching agronomic management practices, grain yields of 4.0–5.0 t ha^{-1} can be achieved in these areas (Sarangi et al. 2015).

Collaborative efforts between International Rice Research Institute (IRRI) and local research institutions in Bangladesh resulted in the development and release of several varieties that are tolerant of salt stress. These include the moderately tolerant wet season varieties BR23, BRRI dhan40, BRRI dhan41, and BRRI dhan54. These varieties can tolerate salt stress up to an EC of 8 dS m^{-1} at reproductive stage, in addition to their high yields (> 4.0 tha^{-1}); while these varieties are also lodging-tolerant and shorter in maturity duration by 10–38 days than the traditional varieties (Islam et al. 2008).

Major impacts of breeding salt tolerant rice varieties in Bangladesh became apparent after the development and release of the highly salt tolerant varieties for the *boro* season. These varieties include BRRI dhan47, BINA dhan8, BRRI dhan53, BRRI dhan55, BINA dhan10, BRRI dhan61, BRRI dhan67 and BRRI dhan73 (BRRI 2016; Islam et al. 2013). Most of these varieties (BRRI dhan47 and 61, BRRI dhan67, BINA dhan8 and 10) can tolerate salinity stress of EC 12 to 14 dS m^{-1} at seedling stage and 6–8 dS m^{-1} for the entire duration of the crop. Other varieties can tolerate salt stress of EC 8 dS m^{-1} at seedling stage and EC 4–5 dS m^{-1} for their whole life cycle. The attainable yield of these varieties ranges from 4.0 to 7.0 t ha^{-1} in salt affected areas.

8.3.1.1 Improved *Aman* Varieties with Salient Characteristics

Sumati (IET 13428) This is a derivative of the cross Pankaj× NC 678, released by Central Variety Release Committee (CVRC) of Government of India in 2003. It is photoperiod sensitive, salt tolerant (EC 6.0–8.0 dS m^{-1}), and suitable for medium land situations, however, it can be grown under 30–40 cm water depth situation. It matures in 140–145 days with a plant height of 95–105 cm, it has long slender grains and grain yield potential of 4.5–5.0 t ha^{-1}.

Utpala (IET 13422) This is a derivative of the cross Pankaj × Jhingasail. This is photoperiod sensitive and salt tolerant (EC 6.0–8.0 dS m^{-1}). It is semi-tall; grains – long slender, resistant to BLB, sheath rot, sheath blight, moderately resistant to neck blast and rice tungro virus (RTV), and also resistant to white backed plant hopper (WBPH), green leaf hopper (GLH), stem borer (SB), and brown plant hopper (BPH). It is suitable for water regime of 30–40 cm and has yield potential of 3.7–4.8 t ha^{-1}. It is released by the West Bengal State Variety Release Committee (SVRC) in India in 2002. It has been notified in 2003 and recommended for cultivation in West Bengal state under rainfed/irrigated and coastal ecosystem.

Bhutnath (IET 12855) This is a derivative of the cross SR 26 B × Pankaj. Tall indica type, photoperiod sensitive variety with plant height of 112 cm, having tolerance to salinity stress (EC 6.0–8.0 dS m^{-1}); it has grains – long slender, awn absent, milling recovery 70.25%, is moderately resistant to leaf blast, neck blast, sheath blight, RTV, sheath rot, and brown spot. It has heading duration of 110–115 days (maturity 140 days). It is moderately resistant to lodging and shattering and to major insect pests, like stem borer, leaf folder, and brown plant hopper. It has yield potential of 4.5–5.5 t ha^{-1}. It has good milling and cooking qualities with more than 70% milling, 65% head rice recovery and alkali spreading value (ASV) of 5.0 score. It is released by CVRC for coastal rainfed areas of India in 2006.

Amal-Mana (IET 14199/18250) Amal-Mana [CSRC(S) 7-1-4] is a derivative of Pankaj×SR 26B (pedigree method of breeding), recommended for coastal saline areas (salinity tolerance EC_e: 6.0–8.0 dS m^{-1}) with shallow to semi-deep water (15–45 cm) situation. It is tall, erect, moderately resistant to lodging and grain shattering, having medium broad green leaves, long slender grains with good cooking quality. The central sub-committee on crop standards, notification and release of varieties released the rice variety Amal-Mana during 2008–09 for the waterlogged and coastal areas of West Bengal, Odisha and Andhra Pradesh states of India. It is suitable for rainfed/irrigated/coastal saline soils, resistant to stem borer, leaf folder, whorl maggot, case worm and blue beetle, moderately resistant to leaf blight, brown spot and sheath blight (DARE 2009–10). Amal-Mana was notified by the Ministry of Agriculture, Department of Agriculture and Co-operation, Government of India in 2009.

BR23 This is the first salt tolerant rice variety, released in 1998 by Bangladesh Rice Research Institute (BRRI) in Bangladesh. The pedigree is BR716-7-2-1-1 (DA29/BR4). It can tolerate salinity stress of EC 6–8 dS m^{-1} at reproductive stage. It is highly photoperiod sensitive and also moderately tolerant to stagnant flooding. The average plant height is 120 cm, growth duration is 150 days, and yield is 5.5 t ha^{-1}. The grain is long slender type, and it is suitable for late transplanting.

BRRI dhan40 The pedigree of this variety is BR5331-93-2-8-3 (IR4595-4-1-15/BR10), and was released by BRRI in 2003. It is photoperiod sensitive and can withstand salinity stress up to EC 8 dS m^{-1} at reproductive stage. The average plant height is 120 cm, growth duration is 145 days, and yield is 4.5 t ha^{-1}. The grain type is medium bold and suitable for coastal regions.

BRRI dhan41 The pedigree of this variety is BR5828-11-1-4 (BR23/BR1185-2B-16-1) and was released by BRRI in 2003 for the *kharif* season. It is also photoperiod sensitive and can tolerate salinity stress up to EC 8 dS m^{-1} at reproductive stage. The average plant height is 125 cm, growth duration is 148 days, and yield is 4.5 t ha^{-1}. The grain is medium slender type.

BRRI dhan53 The pedigree of this variety is BR5778-156-1-3-HR14 (BR10/BR23//BR847-76-1-1), and was released by BRRI in 2010. This variety was selected through participatory varietal selection (PVS) in different coastal districts of Bangladesh. It is photo-insensitive and has salinity stress tolerance up to EC 8–10 dS m^{-1} both at seedling and reproductive stages, and EC 4–5 dS m^{-1} for the whole life cycle. The average plant height is 105 cm, growth duration is 122 days, and yield is 4.5 t ha^{-1}. The grain is medium slender type, and this variety is suitable for both kharif *kharif* and *rabi* seasons.

BRRI dhan54 The pedigree of this variety is BR5999-82-3-2-HR1 (BR1185-2B-16-1/BR548-128-1-3), and was released by BRRI in 2010. It is moderately photo-period sensitive and can tolerate salinity stress up to EC 8–10 dS m^{-1} at both seedling and reproductive stages, and EC 4–5 dS m^{-1} for the entire season. The average plant height is 115 cm, growth duration is 135 days, and yield is 5.0 t ha^{-1}. The grain is medium slender type. This variety was selected through PVS trials in different coastal districts of Bangladesh. It also tolerates moderate stagnant flooding.

BRRI dhan73 The pedigree of this variety is IR78761-B-SATB1-28-3-24 (BRRI dhan40/NSIC Rc106), and was released by BRRI in 2014. It is photoperiod insensitive and tolerates up to EC 12 dSm^{-1} at seedling stage and EC 8 dS m^{-1} for the entire life cycle. The average plant height is 120 cm, growth duration is 120–125 days, and yield is 4.5–6.1 t ha^{-1}. The grain is medium slender type. This variety was selected through PVS trials in different coastal districts of Bangladesh. It also tolerates moderate stagnant flooding.

Under flash flood situation (salinity tolerance up to EC 4–6 dSm^{-1}) and water depth (up to 40–60 cm) the varieties recommended are Swarna – Sub 1 and CR 1009 – Sub 1 in India.

8.3.1.2 Improved *Boro* Varieties with Salient Characteristics

Annada This variety is cross product from MTU 15/Waikoku, released by CVRC in India in 1987. It matures in 110–120 days with short bold grain and average grain yield of 3.0–3.5 t ha^{-1}.

WGL 20471 This variety locally called *Lal-minikit*, developed in India, can tolerate salinity of EC 6.0–8.0 dSm^{-1} with plant height of 95–105 cm, maturity duration 130 days, and grain yield potential of 5.0–5.5 t ha^{-1} with long slender grains. This variety is highly resistant to gall midge.

Bidhan 2 This variety, developed in India, is also salt tolerant (ECe 6.0 dSm^{-1}), having plant height 105–110 cm, maturity duration 135 days, and grain yield potential of 4.0–5.0 t ha^{-1}.

Lalat Released in 1989 in India, with maturity duration of 125–130 days, and average grain yield 3.5–4.0 tha^{-1}, this variety is resistant to blast, sheath rot, gall midge, brown plant hopper, green leaf hopper, and moderately resistant to blast, sheath blight, brown spot, rice tungro virus, bacterial leaf blight and stem borer.

CST 7-1 (IET 9341) It is a derivative of CSR 1 × IR 24, released by CVRC in India in 1992. This variety is semi-dwarf in stature, salt tolerant (EC 6.0–8.0 dS m^{-1}), and photoperiod insensitive; therefore, can be cultivated both as *aman* and *boro*. It is suitable for medium land situations with plant height 90–95 cm, heading duration of 115–120 days (maturity 145 days), has medium bold grains, and yield potential of 4.5–5.0 t ha^{-1}.

Canning 7 It is a pure line selection from BG-35-2 in India. It is photoperiod insensitive and salt tolerant. Canning 7 and Canning 8 are salt tolerant rice varieties for *boro* season developed in 1989 as secondary selections of BG 35-2 and IR 32307-107-3-2-2, respectively. Canning 7 with flowering duration of 101 days and average grain yield of 4.0 t ha^{-1} is also presently preferred by farmers in this Sundarbans, India due to its salt tolerance, short duration, and flexibility to time of sowing (Sarangi and Maji 2017).

BRRI dhan47 The pedigree of this variety is IR63307-4B-4-3 (IR51511-B-B-34-B/TCCP266-2-49-B-B-3), and was released by BRRI in 2007. It is photo-insensitive and has salinity stress tolerance of EC 12–14 dS m^{-1} both at seedling and reproductive stages, and of EC 6–8 dS m^{-1} for the whole life cycle. The average plant height is 105 cm, growth duration is 145 days, and yield is 6.2 t ha^{-1}. The grain is bold type. This variety was selected through PVS trials conducted in different coastal districts of Bangladesh.

BINA dhan8 The pedigree of this variety is IR66946-3R-149-1-1 (IR29/*Pokkali*), and was released in 2010 by Bangladesh Institute of Nuclear Agriculture (BINA). It is photo-insensitive and can tolerate salinity stress of EC 12 to14 dS m^{-1} both at seedling and reproductive stages, and of EC 6–8 dS m^{-1} for the whole life cycle. The average plant height is 100 cm, growth duration is 145 days during the *boro* season, and yield is 6.0 t ha^{-1} with bold grains.

BRRI dhan55 The pedigree of this variety is IR73678-6-9-B (IR64/*Oryza rufipogon*), and was released in 2011 by BRRI. It is photo-insensitive and can tolerate salinity stress up to EC 8 dS m^{-1} both at seedling and reproductive stages, and up to EC 4–5 dS m^{-1} for the whole life cycle. The average plant height is 100 cm, growth duration is 145 days and yield is 5.0 t ha^{-1}. The grain is long slender type. This variety was selected through PVS with farmers from different coastal districts of Bangladesh. In addition, this variety is moderately tolerant of drought and cold, and can also be grown in partial irrigated condition (*aus*).

BINA dhan10 The pedigree of this variety is IR64197-3B-14-2 (IR42598-B-B-B-B-12/*Nona Bokra*), and was released in 2012 by BINA. It is photo-insensitive and can tolerate salinity stress of EC 12 to14 dS m^{-1} both at seedling and reproductive stages, and of EC 6–8 dS m^{-1} for the whole life cycle. The average plant height is 100 cm, growth duration is 135 days and yield is 5.5 t ha^{-1}. The grain is medium slender type.

BRRI dhan61 The pedigree of this variety is BR7105-4R-2 (IR64419-3B-4-3/BRRI dhan29), and was released in 2013 by BRRI. It is photo-insensitive and can tolerate salinity stress of EC 12–14 dS m^{-1} at both seedling and reproductive stages, and of EC 6–8 dS m^{-1} for the whole life cycle. The average plant height is 96 cm, growth duration is 145 days and yield is 6.3 t ha^{-1}. The grain is medium slender type. This variety was also selected through PVS trials involving farmers from different coastal districts of Bangladesh.

BRRI dhan67 The pedigree of this variety is BR7100-R-6-6 (IR61247-3B-8-2-1/ BRRI dhan36), and was released in 2014 by BRRI. It is photo-insensitive and can tolerate salinity stress of EC 12–14 dS m^{-1} both at seedling and reproductive stages, and of EC 6–8 dS m^{-1} for the whole life cycle. The average plant height is 100 cm, growth duration is 145 days, and yield is 6.3 t ha^{-1}. The grain is medium slender and non-shattering type. This variety was also selected through PVS trials involving farmers from different coastal districts of Bangladesh.

8.3.2 Natural Resource Management

Management of natural resources, like soils and water in coastal region is one of the key important challenges to enhance agricultural production and productivity. In the coastal farming system there are several aspects of soil, crop and water management, which are unique and to be addressed scientifically. The foremost important aspect is the water stress situation which occurs during both wet as well as dry seasons, being excess during the former and scarce in the latter. Again, during dry season, quality of water is affected due to presence of saline water in the upper aquifer. Soil salinity, nutrient deficiency/toxicity, and maintenance of soil health are important components of natural resource management (NRM). Adjustment of cropping pattern, use of stress-tolerant crops and varieties, and related management strategies are key to increasing the profit.

8.3.2.1 Water Productivity as a Criterion for Crop Diversification

Availability of good quality irrigation water is the major constraint for dry season cropping in the coastal areas of eastern India, therefore selection of crops on the basis of water productivity, fitting these crops to appropriate growing period, are essential for efficient use of limited quantity of irrigation water. Scarcity of water in these areas is likely to be more acute under changing climate due to uncertainity in rainfall amount and distribution. Suitable cropping systems for coastal areas were identified in India based on water productivity (WP) to decide on the potential cropping systems for these areas. Highest WP on net return basis was observed in rice-tomato (₹52.2 m^{-3}), rice-maize (₹31.8 m^{-3}), rice-potato (₹28.8 m^{-3}), rice-onion (₹25.2 m^{-3}), rice-sunflower (₹24.6 m^{-3}) and rice-brinjal/chilli (₹24.0 m^{-3}) for the

Table 8.1 Economic water productivity of different cropping systems

Cropping systems	WP on gross return basis (₹.m^{-3})	Cost of cultivation (₹.m^{-3})			WP on net return basis (₹.m^{-3})	BCR
		kharif rice	*rabi* crop	Total		
Rice-sunflower	36	4.2	7.2	11.4	24.6	3.2
Rice-maize	54	4.2	18.0	22.2	31.8	2.4
Rice-horse gram	12	4.2	1.8	6.0	6.0	2.0
Rice-green gram	18	3.0	6.0	9.0	9.0	2.0
Rice-sesame	12	4.2	2.4	6.6	5.4	1.8
Sugarcane	12	–	–	7.2	4.8	1.7
Rice-lathyrus	18	4.2	7.2	11.4	6.6	1.6
Rice-rice	12	3.6	4.8	8.4	2.4	1.4
Rice-tomato	78	3.0	22.8	25.8	52.2	3.0
Rice-brinjal	36	3.0	9.0	12.0	24.0	3.0
Rice-chilli	42	3.6	14.4	18.0	24.0	2.3
Rice-onion	42	3.0	13.8	16.8	25.2	2.5
Rice-potato	66	3.6	33.6	37.2	28.8	1.8
Rice-ladies' finger	18	3.6	6.0	9.6	8.4	1.9
LSD ($p = 0.05$)	6	–	1.2	1.2	6.6	0.5

Source: Sarangi et al. (2017a) (In-house study)

coastal region of India (Sarangi et al. 2017a). The benefit cost ratio (BCR) was highest for rice-sunflower (3.2) followed by rice-brinjal/tomato (3.0), rice-onion (2.5) and rice-maize (2.4). WP on net return basis as well as BCR was lowest for rice-rice (Table 8.1). The crop evapotranspiration (ET_{crop}) computed by modified Penman method revealed that during dry season highest ET_{crop} was observed in case of *boro* rice (604.8 mm). *Boro* rice can be substituted with low water reqiring crops like sunflower, maize, rapeseed, etc.

8.3.2.2 Water Harvesting

In Sundarbans, emphasis should be given in India on surface water storage through harvesting of rainwater. Sen et al. (2012) suggested that in India future strategy should be to minimize dependence on ground water use, and therefore, the source of water for irrigation should be on surface or harvested rainwater use. During wet season the rainfall is generally excess and likely to cause damage to crops due to drainage congestion. After meeting the crop requirement, evaporation and seepage

Table 8.2 Optimal crop allocation for OFR at Nikarighata village under limitations of land, labour and water

Crop	Area allocation (%)							
	OFR full		OFR empty to a SI*		80% labour		OFR empty to a SI + 80% labour	
	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II
Rice	20	40	20	30	20	40	20	35
Wheat	–	–	–	–	–	10	–	–
Chilli	50	50	50	50	35	40	40	40
Cucumber	15	10	–	20	10	–	5	–
Melon	15	10	35	10	15	20	–	–
Net ag. profit in *rabi* (₹)	759	2420	548	2217	662	2071	496	1867
Net ag. profit in *kharif* (₹)	667	2912	667	2912	667	2912	667	2912
Total ag. profit due to OFR (₹)	1425	5332	1215	5129	1329	4983	1163	4779

* SI = Supplemental irrigation
Additional income from horticulture Case I @ ₹ 440 & Case II @ ₹ 0
Additional income from pisciculture Case I @ ₹ 2525 & Case II @ ₹ 12,000
Source: Sen and Ambast (2011)

losses, about 460 mm of rain water remains excess and majority of it lost through surface run-off into sea while there is inadequate water left for irrigation in *rabi* and summer season (Sen et al. 1996). This excess water, if stored in dug-out ponds, will solve not only the problem of flooding, but also will meet water needs for other activities like pisciculture, duckery, crop cultivation during dry season, etc. Farm pond may be created in about 20% land (Bandyopadhyay et al. 2009) and the excavated soil may be used for construction of field *bund*s or embankments. Horticultural crops may be grown on the embankments of the ponds and on field *bund*s throughout the year. This will result in diversification of crop as rest of the field may be utilized for cultivation with harvested water. A simple linear programming model was used to propose an optimal land allocation for *rabi* (winter) cultivation under various limitations of land and water to arrive at contingency plans for maximization of profit (Table 8.2). In normal years of rainfall, it was proposed that rice should be grown in 20% area and 80% area should be cultivated with non-rice crops in case of *bunded* on-farm reservoir (OFR). Whereas, it was 40 and 60%, respectively for *unbunded* OFR. The study also indicates the benefit cost ratio around 2 (excluding income from pisciculture and horticulture) for both *bunded* and *unbunded* OFR, which thus justifies the investment in OFR (Sen and Ambast 2011).

For *rabi* crop cultivation in Sundarbans, proper time of land preparation, sowing and harvesting are most important. Heavy rain and cyclone at the time of harvest often damage the crop. Based on probable weekly water balance a crop calendar was prepared by Ambast et al. (1998). This takes into consideration the suitability of crops for the region and their agronomic management practices. It was suggested to

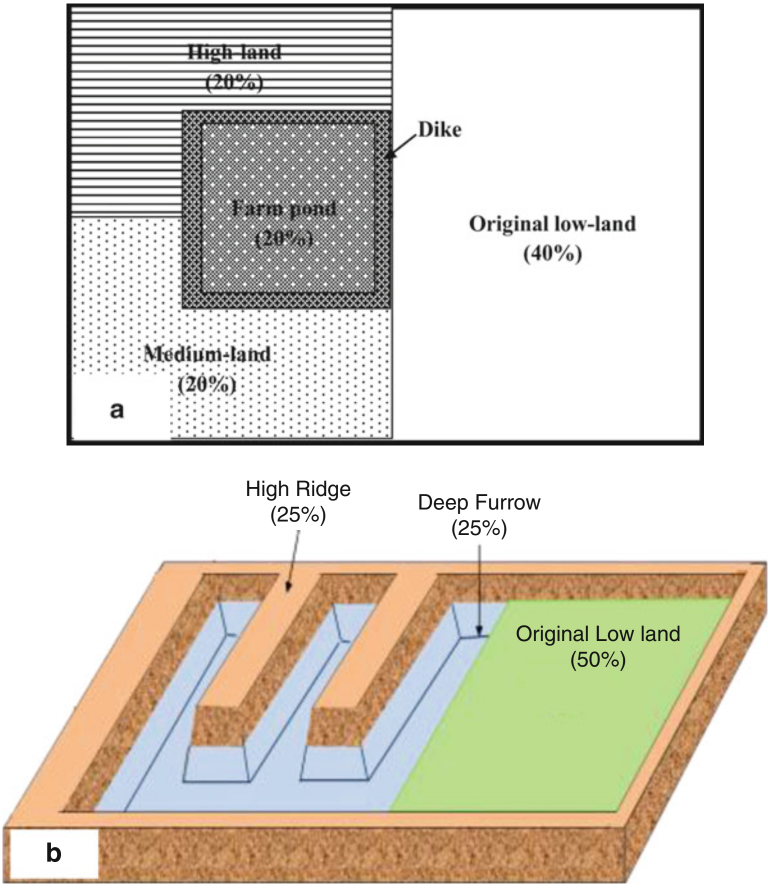

Fig. 8.6 Schematic diagram of (**a**) farm pond and (**b**) ridge-furrow technology developed in India. [Source: (**a**) Bandyopadhyay et al. (2009) (**b**) CSSRI NAIP (2014)]

start land preparation for *rabi* cultivation from 46th to 48th week, followed by sowing in 49th week and harvest the crop before 16th week. This leaves room for a third short duration summer crop (green manure or fodder) after *rabi* harvest.

8.3.2.3 Land Shaping for Crop Diversification and Integrated Farming

Farm pond-based farming is one of the best options for crop diversification and increasing the farmers' income in the Sundarbans region as observed in India (Fig. 8.6). Apart from farm pond (OFR) and related crop diversification, which were explained in the previous section, farmers can also go for other land modifications like furrow and ridge system. In the furrows, rainwater is harvested and ridges remain free from waterlogging during rainy season for vegetable and fruit cultivation. Alternate high ridges (1.5 m top width × 1.0 m height × 3 m bottom width) and deep furrows (3 m top width × 1.5 m bottom width × 1.0 m depth) are recommended for construction in 50% of farm land. The rainwater is harvested in the deep furrows and the harvested rainwater of about 1875 m^3 ha^{-1} is used for initial irrigation during *rabi*. The water stored in furrows is also used for fish cultivation. Due to higher elevation and presence of fresh rainwater in furrows these ridges remain free of waterlogging during *kharif* with less soil salinity build-up in dry seasons. The ridges are used for cultivation of vegetables and other horticultural crops/multi-purpose tree species (MPTs) round the year instead of present practice of mono-cropping with rice in *kharif*.

The coastal lands in the high rainfall areas, as observed in India, usually remain under deep waterlogging due to drainage congestion and lowlying situation where rice is the only crop that can be grown during *kharif* season. In these type of lands, paddy-cum-fish cultivation can be done successfully by digging channels of 1.5 m (width) × 1.5 m (depth) along the periphery of the rice field. The dug-out soil is used for making the *bunds* all around. This system gives scope for cultivation of paddy in the original lowland, fresh water fish in the channel as well as in the paddy field, and vegetables [brinjal (*Solanum melongena*), lady's finger (*Abelmoschus esculentus*), basella (*Basella* sp), french beans (*Phaseolus vulgaris*), broad beans (*Vicia faba*), etc.)] on the boundary *bunds*. Brackish water fish like prawn (*P. monodon*), parsia (*L. parsia*), etc. can be cultured during dry season by using saline water (surface and sub-surface) which are otherwise unsuitable for crop cultivation. The salts accumulated due to brackish water fishery is washed out during the following *kharif* season with initial pre-monsoon showers (drainge should be provided for washing out of the salts), and the cycle follows without damage to soil under lowland situation prone to saline water flooding. The practice is highly remunerative as observed in an in-house study at Canning, India (Table 8.3).

Sorjan (Ridge-Ditch) technology, developed in Bangladesh, is to convert floodprone land into ridges for growing different types of crops and ditches for pisciculture or wetland crops. The height of the ridge is generally 1.8–2.7 m and width 2.5–4.5 m and the width of ditch 0.9–1.8 m (Fig. 8.7). The ridges are used for cultivation of vegetables, fruits and prepartion of nursery beds, where as ditch is used for fishery and duckery.The width of the ridge bed depends on the crops to be grown. For fruit and tree crops, width of ridges is 4–5 m (Shoaib 2013). Shallow Sorjan suitble for cultivation of year-round vegetables, nursery and deeper Sorjan allow rice-fish or rice-duck farming besides vegetables/nursery. This practice is found in some areas of Bangladesh like Fakhirhat Upazila of Bagherhat, Dumurai Upazila of Khulna, Kalapara Upzila of Patuakhai district, and Nasarabad of Pirojpur district (Sattar and Abedin 2012).

8.3.2.4 Integrated Nutrient Management

Long-term soil fertility management trial at Canning Town showed that initially the crops responded to N fertilizers only but not to P and K fertilizers. After few years

Table 8.3 Economic analysis of land shaping techniques (based on operational cost and returns of the year 2012–2013)

Land shaping techniques	Land situation	Crops (*kharif-rabi*)	Operational cost and returns (*kharif* + *rabi*) in (₹/ha)			Benefit cost ratio (Rank)
			Total cost	Total return	Net return	
Control (Traditional system)	Low land (100%)	Rice-fallow	20,487	25,436	4949	1.24 (6)
Farm pond (FP)	Pond (20%), high land (20%), medium land (20%) and original low land (40%)	Fish-fish, vegetable-vegetable, HYV rice-vegetable +sunflower and rice-rice (short duration)	66,123	195,313	85,199	2.95 (1)
Paddy-cum-fish (PCF)	Low land (77%), trenches (11%), high land/dike (12%)	Rice-cotton, Fish-fallow, vegetables-vegetables	68,094	144,851	76,757	2.13 (3)
PCF + Brackish water fish (BWF)	Low land (77%), trenches (11%), high land/dike (12%)	Rice-BWF, Fish-BWF, Vegetable-fallow	216,291	437,255	220,964	2.02 (4)
Deep furrow & high ridge (DF)	Furrows (25%), ridges (25%), lowland (50%)	Fish-fish, vegetables+fruits-vegetables+fruits, rice-cotton	72,424	167,479	95,055	2.31 (2)
Shallow furrow & ridge (SF)	Furrows (20%), ridges (20%), low land (60%)	Fish-rice, vegetables+fruits-vegetables+fruits, rice-cotton	74,265	139,591	65,327	1.88 (5)

Source: Burman et al. (2013)

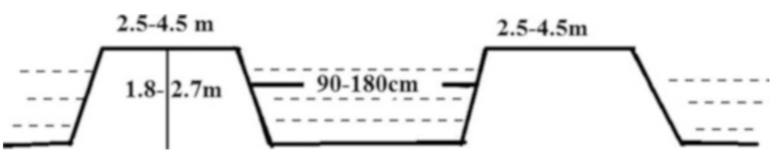

Fig. 8.7 A sketch of Sorjan system of crop cultivation. (Source: Shoaib 2013)

the soils showed gradual decline in the avialable P status when no P fertilizer is applied and in the long run the soil become deficient in P. The decrease of P was more in plots which received N (Table 8.4). This was due to the fact that application

Table 8.4 Effect of N, P and K treatments on grain yield and uptake of nutrients by rice and available nutrients in soil

Treatment	Grain yield of rice (q ha^{-1})			Available nutrients (q ha^{-1})			Cumulative uptake by rice 1980–87 (q ha^{-1})		
	1980	1987	1980–87	N	P	K	N	P	K
$N_0P_0K_0$	23.4	18.4	17.98	2.25	0.16	4.72	3.52	0.42	5.04
$N_{100}P_0K_0$	41.6	35.8	35.28	2.53	0.14	4.70	6.89	0.75	10.23
$N_{100}P_{22}K_0$	43.7	32.1	34.51	2.60	0.29	4.80	7.20	0.86	11.46
$N_{100}P_0K_{42}$	45.3	33.0	33.93	2.48	0.14	4.92	6.75	0.69	10.88
$N_0P_{22}K_0$	27.2	19.8	19.68	2.33	0.34	4.60	3.98	0.47	5.63
$N_0P_0K_{42}$	24.2	15.7	17.86	2.20	0.17	4.90	3.47	0.40	5.36
$N_{100}P_{22}K_{42}$	43.7	31.7	34.88	2.77	0.29	4.70	7.32	0.89	11.64
$N_{100}P_{11}K_{21}$	45.4	34.2	34.94	2.70	0.22	4.65	7.05	0.82	10.75
Initial in 1980	–	–	–	2.34	0.20	4.70	–	–	–
CD (P = 0.05)	5.8	5.2	5.80	0.31	0.02	NS	–	–	–

Note: The subscripts indicate doses of N, P, K in kg ha^{-1}; avilable nutrients after 8 years of cropping
Source: Bandyopadhyay and Maji (1993)

of N increased yield and uptake of nutrients including P. In control, the decrease in available P after the 8th cropping cycle was from 20 kg to 15 kg ha^{-1} with a cumulative uptake of 42 kg P ha^{-1}. Application of higher doses of P fertilizer increases the available P status of soil, particularly when P was applied without N. Application or omission of N fertilizer (urea) did not show any effect on available N content in soil. Regular application of N is essential for higher yield of crops as well as sustainable productivity and maintenance of soil health. Application of P @ 11 kg ha^{-1} for each crop of rice and 5.5 kg ha^{-1} for each crop of maize is necessary for maintaining P fertility status of coastal soils of Sundarbans. Application of K or its omission had no effect either on yield of crops or on available K status of soil (Bandyopadhyay and Maji 1993). However, recent studies at Canning Town showed that for preventing lodging and for disease tolerance in tall indica rice, application of K is essential, similarly when hybrid maize is cultivated the doses of P and K are 34.9 and 33.2 kg ha^{-1} respectively for higher system yield (Sarangi et al. 2017b).

Yield of crops were better when combined sources of nitrogen, viz. inorganic + organic sources of nitrogen were applied to soil instead of inorganic source of nitrogen (urea) alone. Best yield of crops under rice-based cropping system in coastal region of West Bengal was obtained when city compost was used as the organic-N component as the combined sources (organic + inorganic) of nitrogen. Use of leaves of locally available trees as organic component, also produced yield at par with that of city compost. For coastal regions of Andhra Pradesh and Tamil Nadu leaves of locally available Gliricidia plants and that of a leguminous tree (*Derris indica*), respectively in combination with inorganic nitrogen (urea) proved to be the best treatments. Nutrient management studies during dry season rice revealed that the fertility status of soil was improved due to application of organic manures while application of inorganic source of nutrients alone did not show any residual

Table 8.5 Yield of Canning 7 rice variety and soil properties in the second year of study under different nutrient management practices during the dry season at CSSRI Canning Town Research Station

Nutrient management	Grain yield (tha^{-1})	Straw yield (tha^{-1})	BD (g cc^{-1})	OC (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
RDF	3.77	6.22	1.51	0.44	203.3	10.5	394.1
RDF + Azolla	4.41	7.26	1.42	0.53	282.5	12.8	400.4
RDF + FYM	5.02	9.11	1.33	0.61	332.9	18.9	411.5
LSD $_{0.05}$	0.60	0.77	–	–	–	–	–

Source: Sarangi et al. (2014) (In-house study)

improvement in soil available nutrient status. Application of Azolla and FYM produced significant improvement in yield of rice. Application of different organic manures to soil in combination with inorganic fertilizer reduced the soil bulk density and improved the organic carbon status soil (Table 8.5).

Grain yield of dry season rice in coastal area of West Bengal was 24% higher due to combined application of FYM along with chemical fertilizers over application of chemical fertiliser alone (Sarangi et al. 2014). In lowland rice application of fresh water fern *Azolla* add orgnic matter as well as it fixes atmospheric nitrogen due to the presence of BGA (*Anabaena* species) in the lobes of *Azolla* leaves. Green manure is a good on-farm source of N, it fixes atmospheric N, and makes it available to the field crop. Green manuring has been a traditional practice. In the last decade, there has been an increasing interest in green manuring due to increasing concern in soil health, environment and cost of fertilizers. In coastal areas, green manuring with Dhaincha (*Sesbania* sp.) is feasible by sowing the seeds during the month of April to take the advantage of occasional pre-*kharif* rain. This crop is incorporated into the puddled field before transplanting of rice seedlings. Use of green manure, especially *Sesbania rostrata*, which nodulates in roots as well as in stem, in direct-seeded rainfed lowland rice, gives better performance and maintains the nutrients supply. Growing of sunnhemp (*Crotalaria juncea*) as a green manure crop along with rice and incorporating 1 month after germination provides nutrients and conserves soil and water (Sarangi et al. 2007).

The data in Table 8.6 show that coastal soils of Sundarbans are normally well supplied with available Fe, Mn, Zn and Cu, excepting in Mathurapur and Kakdwip blocks where Zn deficiency was observed to the extent of 30 and 15% of soil samples, respectively (Maji and Bandyopadhyay 1991). Most of the soils have high content of active Fe, which sometimes present in toxic concentrations, whereas in some places deficiency of Zn in rice is observed due to it's reduced availability under submerged condition. Due to Zn deficiency, a disease called '*Khaira*' is caused in rice crop. This disease was observed during seedling stage in patches in the nursery and also after 10–15 days of transplanting. To overcome this disease 0.5–1.5 kg Zn ha^{-1} may be applied as a foliar spray (0.5% solution with water). If Zn deficiency is prevalent in the soil, apply 10–25 kg ha^{-1} $ZnSO_4.7H_2O$ to the soil during final land preparation (Sarangi et al. 2017b).

Table 8.6 Range and mean values of DTPA-extractable Fe, Mn, Zn and Cu in soil

Block	No. of soil samples	Fe (ppm)		Mn (ppm)		Zn (ppm)		Cu (ppm)	
		Range	Mean	Range	Mean	Range	Mean	Range	Mean
Canning	14	15.1–370.5	103.0	10.2–144.0	43.5	0.6–13.4	3.8	3.0–8.8	5.6
Basanti	9	64.9–279.6	154.5	14.3–59.3	41.2	1.2–14.3	5.0	3.7–9.6	6.9
Sandeshkhali	9	41.4–297.1	150.4	6.1–51.7	25.8	0.6–4.6	2.8	2.2–9.3	5.2
Kakdwip	6	15.6–70.2	35.7	16.0–75.1	30.7	0.3–1.9	1.2	3.1–5.3	4.0
Mathurapur	9	14.4–129.6	56.3	10.5–44.4	20.5	0.4–2.9	1.4	1.0–5.1	2.8
Overall	47	14.4–370.5	104.4	6.1–144.0	33.6	0.3–14.3	3.0	1.0–9.6	5.0

Source: Maji and Bandyopadhyay (1991)

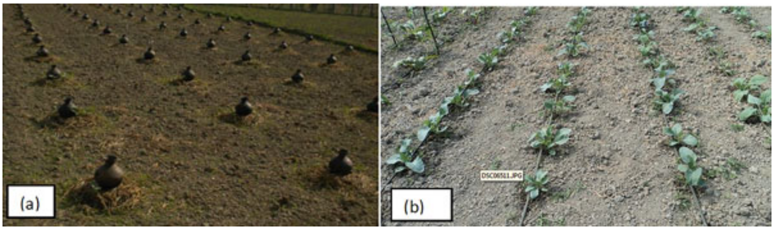

Fig. 8.8 Efficient irrigation methods [(**a**) pitcher and (**b**) drip irrigation] for growing *rabi* crops in Sundarbans. (Source: In-house study at Canning)

8.3.2.5 Introduction of Advanced Irrigation Technologies

Availability of good quality irrigation water is the major constraint for dry season cropping in Sundarbans region. Irrigation efficiencies of surface systems may range between 30 and 60%, conservatively estimated for the rice-oriented cropping system. Sprinkler systems generally achieve efficiencies in the range of 60–85%, and drip systems commonly operate at 85–95% efficiency (Rawitz 2008). Hence, low water requiring crops and water saving irrigation technologies like drip irrigation are essential for efficient use of irrigation water, reducing the effect of salinity, increasing water productivity, reducing the energy use in crop cultivation, and increasing the profit. Control of salinity levels under drip irrigation involves leaching of salts from the root zone by applying irrigation water in excess of the soil water depletion (Hanson and May 2011). Pitcher irrigation is another water-saving practice, which may be followed in some areas of Sundarbans both in India and Bangladesh for growing *rabi* season crops, like watermelon (*Citrullus lanatus*), sweet gourd (*Lagenaria siceraria*), bitter gourd (*Momordica charantia*), cucumber (*Cucumis sativus*), etc. Pitchers are perforated to make hole of about 1-inch diameter at the bottom and 0.5–1 m long jute ribbon inserted in the hole (Fig. 8.8a). The pitchers are then placed in pits at a depth of 5–9 cm and jute ribbon spread at the same depth so that wet jute can keep the soil moist continuously (Shoaib 2013).

The drip system can be efficiently used for cropping with the limited amount of available fresh as well as saline water, hitherto not permissible under conventional irrigation, in the *rabi* season (Fig. 8.8b). For cultivation of vegetable crops like okra/lady's finger, lateral spacing will be 70 cm and plant to plant spacing will be 30 cm.

8.3.2.6 Estimation of Ammonia Volatilization and of Toxic Gas Evolution in Rice Fields and their Management

Coastal soils are extensively used for paddy cultivation during *kharif* under submerged conditions. Nitrogen is the major nutrient required for salt affected soils but its efficiency is poor in salt affected soils. The major forms of losses of nitrogen from soil is through volatilization, which increases with increase in soil salinity and varies with the type of inorganic nitrogen fertilizer used. With increase in soil salinity from

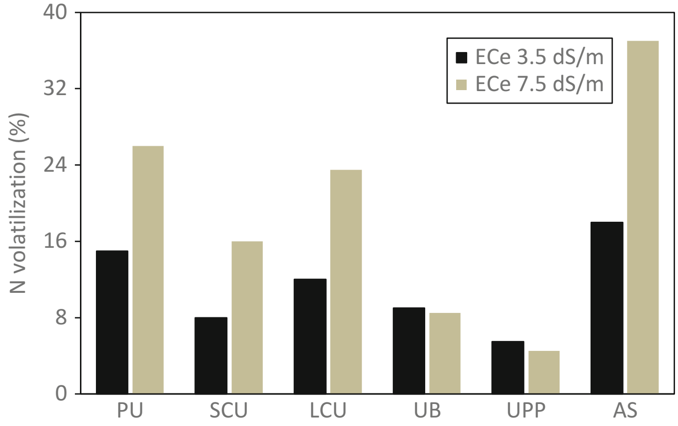

Fig. 8.9 Volatilization losses of N from different fertilizers, West Bengal, India. (Redrawn from Bandyopadhyay and Sen 1985 with permission)

3–4 dSm^{-1} to 7–8 dSm^{-1}, the volatilization loss increased from 17.8% to 37.3% for ammonium sulfate (AS), from 14.6% to 26.1% for prilled urea (PU), from 12.0% to 23.4% for lac-coated urea (LCU), and from 8.4% to 16.3% for sulfur-coated urea (SCU). A field method was developed to estimate volatilization loss in waterlogged rice field (Sen and Bandyopadhyay 1987). A foam pad was fitted in a petridish of same size and rested upside down on iron grills provided at top open end of a both-end-open cylinder (38 cm height, 18 cm dia). The cylinder had perforations (hole size 6 mm) on all sides at 5 cm apart to maintain an identical microclimate inside and outside it. Ammonia N (NH_3-N) volatilized from flood water within the cylinder was trapped in foam pad (soaked with 1 N H_2SO_4) as $(NH_4)_2SO_4$. Volatilization loss from soil can be substantially reduced through placement of N fertilizer at shallow soil depth (5 cm). N at 100 kg ha^{-1} was applied as AS, PU, SCU, LCU, urea briquet (UB) and PU in paper packets (UPP) to puddled, waterlogged fields with ECe 3.5 and 7.5 dSm^{-1} in a pot experiment. Except with UB and UPP, volatilization nearly doubled at 7.5 dSm^{-1} (Fig. 8.9). Volatilization loss from ammoniacal-N fertilizers was found to be more than that from urea (Bandyopadhyay and Sen 1985).

It revealed that a considerable amount of H_2S gas is evolved from rice field of coastal saline soil due to reduction of sulphate salts to sulphides. A portion of sulphides formed in soil is released as H_2S gas in the atmosphere causing environmental pollution. The gas gives strong smell of H_2S in coastal rice fields and may cause low rice yield. The other portion of the H_2S formed reacts with soluble metallic cations in soil forming mostly insoluble metallic sulphides of which iron sulphide is the primary one. The insoluble metallic sulphides form coating on the surface of rice roots and interferes with the nutrient absorption capacity of the roots. Free H_2S has high toxicity to plants and animals. Application of ferrous sulphate to soil reduces the concentration of H_2S in soil solution by precipitating it as FeS. The precipitated sulphides give a dark coloration to the rice soil as commonly

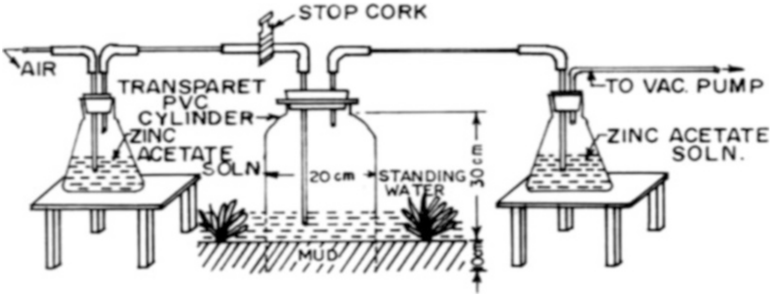

Fig. 8.10 Simple technique for estimation of H_2S gas emission from waterlogged rice fields in Sundarbans. (Source: CSSRI 2011, open access)

encountered in the coastal rice fields. A simple technique has been developed at ICAR-CSSRI, RRS, Canning, India for field measurement of H_2S gas and the insoluble metallic sulphides formed in soil (CSSRI 2011) (Fig. 8.10).

A considerable amount of methane gas is also produced in waterlogged rice fields, causing environmental pollution. Application of prilled urea and green manure significantly enhanced methane emission. Prilled urea or green manure at 60 kg N ha^{-1} effected a 1.5–2-fold increase in methane emission over that in control. Application of green manure in combination with prilled urea further enhanced methane emission significantly over that in treatments with prilled urea and green manure alone. Use of mixture of prilled urea and nitrification inhibitors such as nimin or placement of urea supergranule in flooded rice fields can be considered as suitable options for mitigating methane emission from rice fields without affecting grain yield (Rath et al. 1999).

8.3.2.7 Soil Salinity Assessment at *In-Situ* Soil Moisture

Salinity of a soil is traditionally inferred from measurements of electrical conductivity (EC) in arbitrary soil-water mixture of definite proportions. These measured values either overestimate or underestimate the salinity depending on the *in-situ* soil moisture and thus the soil salinity plants are subjected to. Sen and Bandyopadhyay (1989) suggested method to estimate actual soil-water salinity (ECw) from the conventionally determined salinity values (ECe or EC_2 or EC_5, denoting EC at saturation extract or at 1:2 soil-water extract or at 1:5 extract, respectively, etc.). For estimating the actual soil water salinity, the measured values of electrical conductivity (ECe or EC_1 or EC_2) and the *in-situ* soil moisture values are required (Fig. 8.11).

Five soils having different textural compositions and water retentivities were used to study the relation between soil salinity and soil moisture (Fig. 8.11). Observed parameter EC_w was normalized with respect to EC_i, i.e., EC_w/EC_i and plotted against *in-situ* soil water content (Θ_{in}). Thus, the influence of initial salinity status of soil on the relationship between EC_w and Θ_{in} was eliminated. For each soil, plotted data

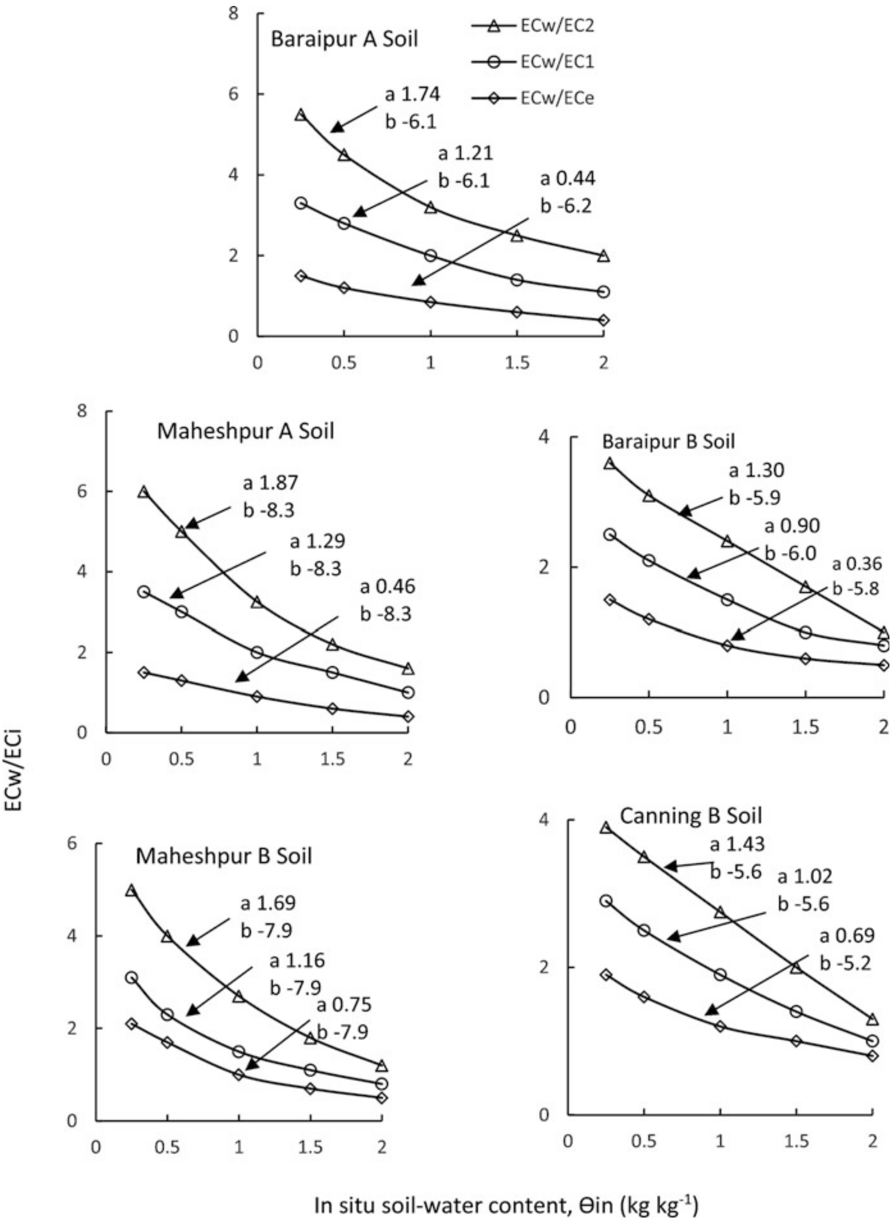

Fig. 8.11 Variation of soil-water salinity with dilution, Silt+clay percent Maheshpur A < Maheshpur B < Baruipur A < Baruipur B < Canning B. [Source: Redrawn from Sen and Bandyopadhyay (1989)]

showed exponential relationship between EC_w/EC_i and Θ_{in}, which was described by equation using least square technique as:

$$EC_i/EC_w = a.e^{-b\Theta_{in}}$$

Thus, ECw can be estimated from the known experimental values of EC_i and Θ_{in}. In the above relationship, 'a' and 'b' are constants (Fig. 8.11). It was found that while both 'a' and 'b' appeared to vary with soil texture and with other basic soil properties, viz., mineralogical, exchange, tortuosity, etc., 'a' alone was dependent on dilution, i.e., $^{a}EC_2$ > $^{a}EC_1$ > $^{a}EC_e$ (Fig. 8.11).

8.3.2.8 Technologies for Increasing Cropping Intensity Practices

During dry season majority of lands remain fallow as farmers get uneconomic yield due to non-availability of suitable technology for salt-affected and irrigation water-stressed soils. Technology has, however, been developed for *rabi* season crops, like maize and rapeseed for their successful establishment (Fig. 8.12). Highest system rice equivalent yield (REY) was obtained in direct sown rice (DSR) followed by raised-bed sown (RBS) maize (Sarangi et al. 2017c); and in rice-rapeseed system the REY was higher in DSR-zero tillage (ZT) sown rapeseed in comparison to other establishment methods. (Sarangi et al. 2017c). Mulching of paddy straw in each case tends to reduce the salinity build-up, and reduce irrigation requirement due to conservation of soil moisture. Increase in yield of maize under RBS was due to less salinity development and higher water-use efficiency.

The mean system REY, net return, and BCR (benefit cost ratio) were 11.66 t ha^{-1}, US$ 1192 ha^{-1} and 2.06, respectively for DSR-RBS maize (Table 8.7) with higher mean irrigation water productivity (79 kg per ha-cm) and energy productivity (461 kg per GJ) of *rabi* maize. Zero tillage helps in early sowing of rapeseed just after harvest of *kharif* rice which helps in its maturity under favourable weather

(a) (b)

Fig. 8.12 (**a**) Raised-bed sowing of maize with paddy straw mulching and (**b**) zero tillage sowing of rapeseed are efficient crop establishment methods for *rabi* crops. (Source: In-house study at Canning, India)

Table 8.7 System rice equivalent yield (REY), net return and benefit cost ratio (BCR) of rice-maize cropping system under different establishment methods in *kharif* and tillage practices in *rabi*

	Rice-maize system REY (t ha^{-1})			Net return (US$ ha^{-1})			BCR		
Treatments	2013–14	2014–15	2015–16	2013–14	2014–15	2015–16	2013–14	2014–15	2015–16
DSR-ZT	10.56	9.65	8.33	1057.38	825.54	574.77	2.05	1.75	1.47
DSR-CT	11.04	10.19	7.71	1174.61	958.00	467.08	2.17	1.87	1.39
DSR-RBS	12.81	12.12	10.04	1466.46	1230.00	878.92	2.41	2.08	1.70
UNPT-ZT	8.74	9.41	7.75	645.69	676.62	316.46	1.58	1.57	1.24
UNPT-CT	10.48	9.72	7.80	963.69	849.08	350.15	1.87	1.71	1.27
UNPT-RBS	11.61	11.65	10.67	1144.77	1053.85	857.08	2.00	1.86	1.62
PT-ZT	8.67	10.15	7.64	490.31	620.62	134.15	1.39	1.45	1.09
PT-CT	11.54	10.69	7.79	1004.62	874.77	225.23	1.80	1.63	1.15
PT-RBS	11.73	11.83	10.11	1027.85	913.38	599.85	1.79	1.64	1.40
CD (P = 0.05)	0.71	1.87	1.35	124.46	319.85	253.69	0.10	0.16	0.19

DSR dry direct seeding; *UNPT* unpuddled transplanting; *PT* puddled transplanting; *ZT* zero tillage; *CT* conventional tillage; *RBS* raised bed sowing; 1US$ = ₹65
Source: Sarangi et al. (2017c) (In-house study)

Table 8.8 System rice equivalent yield (REY), net return and benefit cost ratio (BCR) of rice-rapeseed cropping system under different *kharif* establishment methods and *rabi* tillage practices

Treatments	Rice-rapeseed system REY (t ha^{-1})	Net return (US$ ha^{-1})	BCR
DSR-ZT	7.35	750.77	1.98
DSR-CT	6.79	648.00	1.83
DSR-RBS	6.68	602.15	1.75
UNPT-ZT	7.05	593.23	1.68
UNPT-CT	5.83	342.77	1.38
UNPT-RBS	6.24	423.23	1.47
PT-ZT	7.12	458.00	1.45
PT-CT	6.42	314.46	1.30
PT-RBS	6.42	288.31	1.27
LSD ($p = 0.05$)	0.38	84.46	0.10

DSR dry direct seeding; *UNPT* unpuddled transplanting; *PT* puddled transplanting; *ZT* zero tillage; *CT* conventional tillage; *RBS* raised bed sowing; 1US$ = ₹65
Source: Sarangi et al. (2017c) (In-house study)

conditions. The system involving DSR followed by ZT rapeseed produced higher system REY (7.35 t ha^{-1}), net return (US$751 ha^{-1}) and benefit cost ratio (1.98) (Table 8.8).

8.3.2.9 Fruit/Vegetable Crops/Cultivars Suitable for Increasing Cropping Intensity

After the harvest of *kharif* paddy suitable *rabi*/summer season crops are grown. The suitable crops and their varieties that can be grown in saline soils of Sundarbans are listed in Table 8.9.

Job's tears (*Coix lacryma jobi*) was identified as a suitable fodder for the coastal areas as it is highly salt-tolerant and also tolerant to occasional waterlogging in in India. The biochemical studies revealed that the plant contains stigmasterol, which imparts salt tolerance to this plant. Salt tolerant grasses, such as Para grass [*Brachiaria mutica* (Forsk) Stapf.], Karnal grass [*Leptochloa fusca* (Linn.)] may also be grown on unutilized land which may be used as fodder for cattle in integrated farming system. Physiological studies on sunflower had shown that the plant restricts the flow of sodium in to the leaf tissues by storing excess amount in its stem.

Cotton and Chilli were observed to be quite tolerant to salinity in India. Chilli can be grown salinity up to EC 6.7 dSm^{-1} and cotton up to EC 9.9 dSm^{-1}. Cotton accumulates less amount of Na in the plant organs as compared to chilli. Cultivation of hybrid maize under raised beds with paddy straw mulching was found to be successful and profitable in Sundarbans region in India.

Different varieties of sapota (var. Badami, Cricket ball and Kalaptti) and guava (var. Kashi, L-49 and KG) have been tested under varying levels soil salinity (ECe 2.5, 5.6, 8.6 & 10.6 dSm^{-1}) in India. In general, sapota tends to be more resistant

Table 8.9 Suitable *rabi* season crops and their varieties for Sundarbans region

Crops	Varieties/Cultivars	
	India	Bangladesh
Maize	Grain purpose: GK 1421, Aditya -303, Indo-hybrid	Grain purpose: BHM-5, 9, Pacific 11, Pacific 60, Pacific 984, Pacific-987, Barnali, Khaibhutta, BARI Hybrid Maize- 4, 5, 7, 9 & 11
	Fodder purpose: GBM 84-3, African Tall, GBM 84-1 and GBM 92-1	Fodder purpose: Barnali, Khaibhutta, BARI Hybrid Maize 3
Lathyrus	Nirmal (NP-24), Ratan, Prateek, Mahateora	BARI Khesari 1 & 2
Mungbean	Sona mung, Panna (B-105), Chaiti mung	BM 01, BARI mung 6 & BM 08
Sunflower	PAC 36, Morden, Surjya 51, Siri-333	Hysun 33, Kironi (DS-1)
Sugar beet	Red Ball, Ruby Ball, Ramonskya 06 and Mozzanoply	SB001, SB003, SB006, SB007, SB008 & SB009
Safflower	Bhima, Manjira and some GMU lines	–
Cotton	J.K. 260-2, J.K.276-4-1-2, F-414, MESR-17	CB-12, CB-13, CB-14, Rupali-1, HC-1, HC-2
Barley	Karan 19, Ratna, DL-120	BARI Barley-4, 7 & BHL-15
Sweet potato	Pusa Safed, Samrat, ST-14, CIP-440038, CIP SWA-2 & Sree Bhadra	BARI Misty Alu-6 & 7
Chilli	Tejaswini (Sansani), Diamond, CA 960, Suryamukhi	BARImorich 1, Debgree
Tomato	Pusa Ruby, Siox, Marglobe, Deb	BARI tomato-2, BARI tomato-14, 15, BARI Hybrid tomato-5
Potato	Kufri Pukhraj, Kufri Jyoti	BARI Potato-7, 21 & 29
Onion	Sukh Sagar	BARI Onion-1 (Pata Piaz), BARI Onion-5
Okra	Ankita, Avantika, Rohini, Pusa Sawyani, Pusa Makhamali, Pankaj, American Red, Desi 5 Dhari and Desi 7 Sira	BARIdherosh 1
Knol-Khol	Soldier, Winner	Challenger
Bitter gourd	Samurai, Meghalaya, Nano	Tia F1, KakoliF1, Taj-88
Brinjal	Pusa Purple Long, Pusa Purple Cluster, Makra, Pusa Kranti	BARIbegun-4 (Kazla), BARIbegun-5 (Nayantara)
Indian Spinach (*Poi sag*)	Local, *Basella alba* (white), *Basella rubra* (red), Ladna	Local
Cucumber	Seven star, Hangama	–
Coriander	RCR-41, ACR-1, Local	BARI Dhania 1
Fennel	RF-101, RF-1	–
Black cumin	AN-1, Local	BARI Kalozira 1
Fenugreek (*Methi*)	Local	BARI Methi 1, BARI Methi 2

(Sources: In-house study at Canning, India, BARI (2015), Humphreys et al. (2015), Shoaib (2013)) than guava in terms of growth performance. Fruit weight of sapota var cricket ball and guava var. KG was found higher than other cultivars in both the fruit crops. Root length decreased with corresponding increase in soil salinity. It has been observed that under normal and less saline soil condition the roots move vertically downwards, whereas under higher salinity level they move horizontally.

Spices, medicinal plants, aromatic plants are also feasible in Sundarbans, India under moderate salinity stress with selected varieties. Among the spices [Fennel (*Foeniculum vulgare*), coriander (*Coriandrum sativum*), fenugreek (*Trigonella foenum-graecum*) and black cumin (*Nigella sativa*)], fennel (Var. RF-1) was most tolerant to soil salinity (ECe 3–6 dSm^{-1}). Growing of coriander as leafy vegetable is more profitable than as seed crop. The most suitable varieties for that purpose are: RCR-41 and ACR-1. Aromatic plants, like lemongrass (*Cymbopogon citratus*), palmrosa (*Cymbopogon martinii)*, bhringaraj (*Eclipta prostrata*), *Aloe vera* and mentha (*Mentha piperita*) survived well under the soil salinity (ECe) level of 3–6 dSm^{-1}. The aromatic species to some extent could tolerate waterlogging and could survive waterlogging even up to seven days in the field. Among all these species *Cymbopogon flexuous* and *Aloe vera* produced maximum fresh biomass but dry biomass production was higher in case of *Aloe vera sp*. than *Cymbopogon flexuous* and *Cymbopogon martini*. Among the perennial medicinal plants *Rauwolfia serpentina* L. (Swarpagandha) survived and it completed the life cycle and produced seeds. Other suitable medicinal plants are pudina (*Mentha arvensis*) and tulsi (*Ocimum sanctum*).

8.3.3 Allied Agronomic Technologies

8.3.3.1 Dry Direct-Seeded Rice (DSR) during *Kharif*

The productivity of rice during *kharif* season in the coastal areas are low due to several factors, like cultivation of traditional low-yielding varieties, moderate to high soil salinity, and occasional flooding by heavy rains following transplanting. Medium to deep water submergence is an important abiotic stress factor in the coastal areas, and considering increasing trend of increase in seawater level, along with increasing trend in frequencies and intensities of flooding, as reported due to global warming, the situation is likely to aggravate in future. Prolonged partial flooding with 30–60 cm water depths reduces rice productivity because of high mortality, suppressed tillering, reduced panicle size, and high sterility. Therefore, mechanism to withstand such problem is essential to increase the yield in the coastal areas. Dry direct sowing of paddy during last week of May, besides growing medium (Amal-Mana, SR 26B, Sabita, Patnai 23, Geetanjali) to deep water submergence tolerant varieties [CSRC(D) 7-0-4, CSRC(D) 12-8-12, NC-678], could be a possible strategy to escape or withstand flood situation and increase crop productivity, as observed in India (Sarangi et al. 2017a).

8.3.3.2 Drum-Seeding of Pre-germinated Seeds during Dry Season

Direct wet seeding of rice using a drum-seeder is effective and could enhance yield and net returns for farmers in coastal areas as shown in India. The eight-row drum-seeder is 1.8 m wide, the diameter and length of each drum are 0.18 m and 0.25 m, respectively. Distance between rows is 0.20 m (Devnani 2008). Each drum has a capacity of 2 kg of pre-germinated seeds, however, the drums should not be filled to its capacity, and about one-third should be kept empty for easy flow of seeds through the perforated holes. The seeds are soaked in water for a day and then incubated for another 24 hours for sprouting. To prevent sprouts mixing up with each other, sprout length should not be more than 7–8 mm. The sprouted seeds are air-dried in the shade for about 10–15 minutes before sowing to facilitate proper dropping of seeds. The land is puddled as usual, leveled carefully, and excess water is drained out. The field is not irrigated for 2–3 days after sowing to allow roots to anchor, and then the depth of water is increased gradually as the seedlings grow. Drum seeding of pre-germinated seeds saves about 10–18% variable costs compared with transplanting, mainly because the latter had higher requirements of labour and inputs on account of raising of seedlings in a nursery, uprooting of seedlings, transporting, and transplanting them. Benefit cost ratio was found to be significantly higher under an in-house study in drum-seeding (1.94) in comparison to transplanting (1.27) during *boro* season (Sarangi et al. 2014).

8.3.3.3 *Azolla* in Drum-Seeded Field and Use of Vermicompost as Organic Sources of Nutrients

If, however, the supply of FYM, being the primary organic resource for nutrients, is limited, *Azolla* can be used as a substitute for FYM as found in India. Before the application of *Azolla* into the main field, the basic stock of viable material is maintained in a nursery with a water depth of 3–6 cm. *Azolla* stocks were put into beds @ 1 kg m^{-2}, and allowed to grow for a month. Fresh *Azolla* @ 2 t ha^{-1} is inoculated in the main field after about 4 weeks following drum-sowing. The *Azolla* mat was incorporated into the soil 4 weeks after inoculation. Compared with RDF treatment, the organic carbon increased by 20.4 and 38.6% in *Azolla* and FYM treatments, respectively, observed in an in-house study at Canning, India. The application of organic nutrient sources had also a positive effect on the availability of major nutrients (Sarangi et al. 2014).

The residues and by-products produced from crop cultivation and dairy husbandry can be efficiently utilized after decomposing through suitable earthworm species, such as *Eudrilus eugeniae* and fungal inoculants, viz. *Trichoderma viridae*, observed in India. The choice of earthworms for vermicomposting (Table 8.10) in India is limited to a few, since these worms have not only effect for quick conversion, but also can reproduce faster. Higher mass reduction of vegetable market waste was recorded in the vermicompost processed by *E. eugeniae* (75%), followed by that

Table 8.10 Weight and other physical parameters of the substrate (vegetable market waste) and respective vermicompost of three earthworm species (Mean ± sd; n = 3)

Parameters	0 day	60 days		
		Eudrilus eugeniae	*Eisenia fetida*	*Perionyx excavatus*
Weight (kg)	5.00 ± 0.005	1.25 ± 0.03	1.85 ± 0.04	2.5 ± 0.03
Temperature (°C)	29.8 ± 0.06	24.1 ± 0.04	24.2 ± 0.05	24.4 ± 0.04
Moisture content (%)	55.73 ± 0.08	65.2 ± 0.03	64.72 ± 0.03	64.04 ± 0.01
pH	6.31 ± 0.07	7.12 ± 0.02	7.08 ± 0.01	6.95 ± 0.02
EC (mhos cm^{-1})	495.5 ± 0.04	3354.4 ± 0.02	2716.7 ± 0.07	1983.2 ± 0.06

Source: Pattnaik and Reddy (2010)

of *E. fetida* (63%), and *P. excavates* (50%). The stabilization of substrate due to the vermicomposting process was higher in the vermicompost processed by *E. eugeniae* compared to other two (Pattnaik and Reddy 2010). *E. eugeniae*, brown and red to dark violet worms, originally from Africa, and popularly called the "African night crawler" having excellent growth and high conversion ratio (Sarangi and Lama 2013), and therefore may be used for obtaining quality vermicompost in coastal region.

8.3.3.4 Protected Cultivation of High-Value Crops

Improved technology should be adopted for cultivation of off-season vegetables, flowers, etc. Contrary to conventional agronomical practices, under protected cultivation, there are attempts to moderate weather parameters, avoid extreme weather adversities and other stress related constraints, not conducive to crop growth. The yield and quality are improved, inputs are utilized efficiently and there is assured income for farmers, found in India. Vegetables like tomato (var. GS 600), capsicum (var. Indra, Natasa, Swarna, Orobelly, Bombay), cucumber (var. Hilton, Mini Angel, Satis and Gian); flower crops like rose (var. First Red, Golden Gate, Mercedes), gerbera (Cabana, North star); and spices like sweet pepper (var. Nun 3019, Nun 3020, Indira) can be cultivated with high net income (Table 8.11) in India.

8.3.3.5 Mushroom Cultivation

Paddy straw is abundantly available in coastal areas, and this may be utilized for mushroom cultivation. Paddy straw may be used as substrate for mushroom cultivation to provide additional income to the farm families in India. Paddy straw mushroom (*Volvariella volvacea*) can be cultivated during summer and rainy season (March to October), whereas as Oyster mushroom (*Pleurotus ostreatus*), can be grown during winter (November to February) season (www.agricultureinformation.com/postings/sushanta-naik-low-cost-mushroom-cultivation/) in Sundarbans.

Table 8.11 Economic benefits from protected cultivation of high value crops

Crop	Estimated yield (t ha^{-1})		Increase in yield (%)	Estimated net returns (₹ ha^{-1} $crop^{-1}$)		Increase in net returns (%)
	Open cultivation	Protected cultivation		Under open cultivation	Under protected cultivation	
Tomato (*Lycopersicon esculentum*)	2.0–2.5	15.0–20.0	678	5000–6000	30,000–40,000	536
Capsicum (*Capsicum frutescens*)	1.0–1.5	5.0–6.0	340	4000–5000	40,000–50,000	900
Cucumber (*Cucumis sativus*)	1.5–2.0	10.0–12.0	678	3000–4000	50,000–60,000	1471

Source: Sarangi et al. (2016a) (In-house study)

8.4 Conclusions

There is a great potentiality for cropping system intensification in the Sundarbans by growing low water requiring field crops, vegetable and fruits in *rabi*/summer season which are commercially viable and having good market demand. Diversification of agriculture through agroforestry may be an important proponent for resource utilization, enhancing farm income and livelihood security of farmers in these traditionally mono-cropped coastal areas. Appropriate integrated farming system models using pisciculture and animal husbandry on mono-cropped land is important for increasing productivity of land, water, labour and to reduce the risk factor. Integration of duckery/poultry in the low land rice fields may be promoted for higher income. Upon cropping system intensification and mechanization, energy requirement for agriculture will grow rapidly for round the year cultivation. To meet the demand for future energy requirement as well as to reduce the dependence on conventional (non-renewable) energy resources, there is a need to explore the alternative (un-conventional or renewable) energy sources like solar, biological or natural resources. Exploring bio-fuel from potential crops (e.g. sugar beet, jatropha, etc.) suitable in coastal region needs to be carried out. Agriculture in Sundarbans region is likely to be one of the worst sufferers due to changing climatic conditions. Therefore, there is a need for development of stress tolerant crop varieties and management practices for adaptation to climate change and sea level rise due to global warming. Irrigation water is the most crucial factor for intensive agriculture in Sundarbans, therefore crop diversification to low water requiring crops vis-a-vis efficient irrigation management for dry season rice is the pressing need for sustainable farming. Advanced research methodologies to increase water productivity through the use of crop models like APSIM/ORYZA, etc. can help in optimizing the water use, reduce the pressure on the ground water and address salinity development under the imminent changing climate scenarios.

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Fishing boat and a tiger (Courtesy Anil Mistry)

Chapter 9
Aquaculture and Fisheries in the Sundarbans and Adjacent Areas in Bangladesh: Resources, Productivity, Challenges and Opportunities

Kazi Ahmed Kabir, S. B. Saha, and Michael Phillips

Abstract Estuarine aquatic systems and braided rivers in and adjacent to the Sundarbans and the vast area of the Ganges tidal floodplain next to the core forest area in Bangladesh holds rice aquatic faunal diversity and provides plenty of opportunities to grow fish, shrimps and crabs. Currently these systems provide direct employment opportunity for 1.2 million people and indirect or seasonal livelihood for more than 10 million people across the southwest coast. Hilsa is the largest fishery in this region and shrimp brings the highest cash and export earnings. Proper implementation of fisheries regulation is critical to ensure conservation of the rich fish diversity of this region as well as to continue to support livelihood of millions of people living on fisheries. While aquaculture is the major contributor to national fish production, agricultural GDP and export earning, it requires planned advancement from the current state to continue to grow in harmony with environment. Integration with rice and other crops, and with mangrove wherever possible can bring long-term sustainability of these systems. Change in the river flow due to siltation and reduced upstream flow, climate change, sea level rise, outbreak of disease in fish and crustaceans are major challenges for future growth and sustainability of both aquaculture and fisheries in this region. Collaborative and multi-disciplinary research should be undertaken to address these challenges. In addition, there should be mechanism to bring research outputs into use and make impact on sustainability.

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9.1 Introduction

The Sundarbans is the largest productive mangrove forest in the world. It is located in an active delta in the lower Ganges Delta in Bangladesh and India. In this chapter, we will describe about the Bangladesh domain. It is mainly an estuarine ecosystem, dominated by dense forest, specialized in the braided river system, and expanded to adjacent floodplains, which make it not only a forest resource but also a diverse landscape for aquaculture and fisheries. It occupies the land of southern Khulna and southwestern Barisal districts.

The core Sundarbans protect area consists of 7620 km^2 of which 4143 km^2 are land; 1874km^2 rivers, streams and canals; and 1603km^2 marine zone (Hoq 2007). In addition to this core Sundarbans, its adjacent floodplains constitute 300,000 ha under aquaculture (Keus et al. 2017), which in most locations shift from brackishwater to freshwater due to the effect of monsoon (Kabir et al. 2015).

9.1.1 Agro-ecology, Cropping System and Farm Size

9.1.1.1 Agro-ecology

The floodplains adjacent to Sundarbans belong to Ganges tidal floodplain occupying 17,066km^2 located at the southwest end of the country. The greater part of this region has smooth relief having large areas of salinity. Riverbanks generally stand about a metre or less above the level of adjoining basins. Non-calcareous grey floodplain soil is the major component of general soil types. Acid sulphate soil also occupies a significant part of the area, where it is extremely acidic during the dry season. Most of the top soils are acidic and sub-soils are neutral to mildly alkaline while, soils of the core Sundarbans area are saline or alkaline in nature. General fertility level is high, with medium to high organic matter content (Banglapedia 2014).

Surface water in the rivers is saline in most of the western parts towards the southern direction while freshwater flows in the western part. This also depends on the specific river connectivity with upstream rivers and its flow rate. Ground water is gradually less saline in the northern part and the level of salinity is lower than that in the surface water (Sohel et al. 2014). This diverse soil and water conditions allow this region to host rice aquatic biodiversity supporting more fisheries from the open waters and aquaculture options in the inland floodplains. However, siltation in the riverbed is now changing and affecting cropping system including aquaculture and fisheries.

9.1.1.2 Cropping System

Seasonal variation of water salinity in the west and east of the Ganges tidal floodplain takes place (Sohel and Ullah 2012). This influences the cropping practices and production period (Table 9.1). While shrimp farming in the southwest coastal areas (greater Khulna region) is mostly practised in rotation with paddy cultivation, the southeast areas often have rice field with fish in the flooded areas or as pond-based fish culture (Azad et al. 2009). Most of Satkhira used to grow shrimp throughout the year due to the presence of moderate to high water salinity (Alam 2002), which now is becoming more diversified carp-based polyculture in the wet season. Commercial polyculture or alternate culture of shrimp with brackish water and euryhaline finfish species (e.g. Mullet and Tilapia) and crab (*Scylla olivacea*) are carried out in small scale (Azad et al. 2009).

The freshwater prawn (*Macrobrachium rosenbergii*) aquaculture, which is widely adopted in Bagerhat and Khulna districts, has spread to south and central coastal zones namely, Jessore, Patuakhali, and the greater Noakhali districts (Abedin et al. 2000). The freshwater prawn farming is mostly practised in an integrated manner with filter-feeding carps, paddy on the shallower part, while vegetables are grown on the dike of the pond. The integrated prawn-rice-fish-vegetables cycle begins in May/June with stocking of prawn and fish fingerlings, followed by planting of *boro* rice in January (Williums and Khan 2001; Azad et al. 2005).

9.1.1.3 Farm Size and Distribution of Farming

There has been large change in the farm size of shrimp or fish or integrated farming practice in the coastal areas during last 40 years. This change was driven firstly by shift of farming from rice-based crop to shrimp-oriented systems, and further evolvement of integrated farming with polyculture of fish, and secondly by the pattern of ownership of farm, which also has been changed from larger farms on leased land to more individually owned small farms.

Current farm size for shrimp-dominated areas are 2.5–4 ha, and farm size throughout the region varies according to farming practice and ownership pattern. This region is especially dominated by shrimp cultivation and the size of the individual shrimp farms is highly variable. The largest farms are around 11–37 ha, usually under outside lessee. The average farm size has been reducing gradually over the years to an average of 8–10 ha with farmers surrendering leases, and small holders dividing large ponds into smaller *ghers* (see Fig. 9.1; Hoq et al. 1997; Siriwardena 1997; Caritas 1997; BCAS 2001; FFP 2001; Alam and Phillips 2004).

Table 9.1 Annual management practices of various aquaculture practices at different salinity zones. (Faruque et al. 2017)

Salinity Level	Farming activities	Winter – Dry season		Summer – Rainy season							Winter – Dry season		
		J	F	M	A	M	J	J	A	S	O	N	D
Low	Rice cultivation (transplanting-harvesting)	T	T	T	H	H	H				SP	SP	SP
	Dike repairing and bottom soil removal				R	R							
	Prawn rearing and harvesting		H	H		S	S	S		H	H	H	H
	Shrimp rearing and harvesting	Not practised											
	Fish rearing and harvesting	H	H					S	S	S	S	H	H
	Mud crab rearing and harvesting	Not practised											
	Vegetables and fruits	H	H		T			TH	TH	TH	T		H
Medium	Rice cultivation (transplanting-harvesting)	T	T		H	H							
	Dike repairing and bottom soil removal				R	R							
	Prawn rearing and harvesting	H	H			SN	SN	SN		H	H	H	H
	Shrimp rearing and harvesting			SN	SN		SH	SH	SH	H	H		
	Fish rearing and harvesting	H	H					S	S	S		H	H
	Mud crab rearing and harvesting	Not practised											
	Vegetables and fruits				P	P		H	H	H	H		
High	Rice cultivation (transplanting-harvesting)	Not practised											
	Dike repairing and bottom soil removal	R	R										
	Prawn rearing and harvesting	Not practised											
			S	S	SH	SH	SH	SH	SH	SH	H	H	H

(continued)

Table 9.1 (continued)

Salinity Level	Farming activities	Winter – Dry season		Summer – Rainy season							Winter – Dry season		
		J	F	M	A	M	J	J	A	S	O	N	D
	Shrimp rearing and harvesting												
	Fish rearing and harvesting				S	S	S	SH	SH	SH	H	H	H
	Mud crab rearing and harvesting												
	Vegetables and fruits	Not practised											

Notes: *T* Transplanting, *H* Harvesting, *SP* Seedling preparation in seedbed, *R* Repairing, *S* Stocking, *P* Planting, *SN* Stocking and nursing, *H* Harvesting, *SH* Stocking and harvesting

Fig. 9.1 Harvesting of shrimp from an extensive *gher*. (Courtesy authors)

The shape of the farms is also highly variable from rectangular to irregular. It is interesting that the coastal aquaculture farm size is gradually becoming smaller, as most of the farms are operated by individuals. The individual farms (land is owned and operated by one person) are generally smaller in size with an average of 2.28 ha, whereas groups of farmers (land is owned by a number of persons and operated jointly) tend to own a larger farming area, averaging 4.59 ha (DOF 2017a).

9.2 Present Status of Production and Economy

9.2.1 Commercially Important Fish and Crustaceans

The Sundarbans is rich in biodiversity. The aquatic biodiversity is comprised of 53 species of pelagic fish, 124 species of demersal fish, 24 species of shrimp, 7 species of crab, 2 species of gastropods, 6 species of pelecypods, 8 species of locust lobster, and 3 species of turtles (Hoq 2008). Of which most important fin fish species are *Tenualosa ilisha* (Illish or Hilsa shad) and crustaceans are *Panaeus monodon* (Tiger shrimp), *Macrobrachium rosenbergii* (Giant freshwater prawn), and *Scylla olivacea* (Mud crab) (Hoq 2008). There are several other important species including *Johnius argenteus* (Silver Jew fish), *Pomadasys hasta* (White grunter), *Lates calcarifer* (Asian Sea bass), *Pangasius pangasius* (Fatty catfish), *Oreochromis niloticus* (Tilapia), *Chelon subviridis* (Green back mullet), *Mugil cephalus* (grey mullet), *Mystus gulio* (Long whiskers catfish), *Labeo rohita* (Rohu), *Catla catla* (Catla), *Cyprinus carpio* (Common carp), *Barbonymus gonionotus* (Silver barb).

9.2.2 Sectoral Contribution to Economy

Aquaculture and fisheries contribute 3.65% to national GDP, and 23.84% to national agricultural income. It provides 60% of animal protein consumed at the country (BER 2016). Export of shrimp and frozen food constituted a major share in national export earning amounting to US$580 million in 2015. Almost 100% of this export earning comes from the production of shrimp and crabs produced in the brackishwater and freshwater areas of the Sundarbans. Out of 2.2 million metric ton aquaculture product, lower Ganges delta (i.e. Sundarbans and adjacent area) produces approximately 0.5 million metric ton fin fish and 0.25 million metric ton shrimp, and crabs accounting ~25% of national aquaculture production (DOF 2017a). Direct contribution of fisheries to national fish catch is much lower when compared with aquaculture production from both freshwater and brackishwater domain. The Sundarbans itself and adjacent estuaries as well as the inland canals make harvest of 30,000 metric ton which is 3% of national fish catch from open waters (DOF 2017a). The indirect contribution of this fisheries resource is enormous by providing the largest natural nursing ground, an essential habitat for crab and bivalves, and for most of the commercially important fish including hilsa and seabass, and a rich population of freshwater and brackishwater shrimp and mullet. This has significant role in aquaculture and fisheries yield within the Sundarbans domain and beyond. If we extend our area domain a bit to east – the lower Meghna basin – adjacent to eastern part of the Sundarbans, only catch of hilsa is more than

40,000 metric ton. Area-wise, it is the second largest catch of hilsa after Chittagong region. Economic and aesthetic value of this hilsa is enormous and has strong influence over the fish market and supply system in the country. It provides employment to more than a million people through direct engagement in aquaculture or fisheries and associated value chain. Out of this, major share of employment belongs to brackishwater aquaculture sector (Keus et al. 2017). Every year ~200,000 people completely or partially depend on fishing within the canal systems of the Sundarbans mangrove at the estuary, and in the adjacent inland canals and rivers. Besides, there are more than ten million people in this region that indirectly or at a particular season depend on aquaculture and fisheries.

One of the major fishing grounds in the Bay of Bengal as well as in Bangladesh is Swatch of no ground which lies next to the Sundarbans and has been declared as marine protected area since 2014 for an area of 1,73,800 ha fishing ground (FD 2017). Fish harvested in this fishing ground constitutes around 15% of total artisanal marine catch constituting 75,000 metric ton per year. Based on the catch, second largest fish drying industry in the country developed in Dublar Char, a part of the west Sundarbans. This is a seasonal industry and provides employment for thousands of people during the dry season.

9.3 Fisheries in the Sundarbans

Fisheries in the Sundarbans are historically important livelihood for the local inhabitants. It has now been expanded from subsistence artisanal fishing to commercial fisheries. In general, the fisheries resources are categorized into four different groups, i.e.

1. Fisheries in the rivers and estuaries within the protected mangrove forest areas
2. Marine fisheries in swatch of no ground near south Sundarbans national park
3. Fisheries in the eastern riverine estuaries
4. Fisheries in the inland rivers, canals and *beels* (floodplains)

Different local methods of fish catch are shown in Figs. 9.2, 9.3 and 9.4. The common fish catch and their conservation status are presented in Table 9.2. Fish catch varies between habitat, location, season, and the type of gears (Table 9.3) and traps (Table 9.4) used. Though using push net and collection of shrimp and prawn PL are often blamed for deterioration of coastal fisheries diversity, the indiscriminate fishing practice for food fish is also equally responsible. Often it leaves no room for the fish that enters into the canals due to the diurnal tidal effect to escape and return to the estuary. However, practice of using gears and traps (Table 9.4) are gradually reducing with disappearance of *beels* and siltation in the rivers and canals.

Fig. 9.2 Fishing in the estuarine rives by small boats. (Courtesy authors)

Fig. 9.3 Operation of lift net (dharma jal). (Courtesy authors)

9.3.1 Fisheries Conservation and Management Activities

Fisheries conservation and management activities are still limited and thus confront with multi-dimensional challenges like livelihood dependency to environmental changes. Fisheries within the protected Sundarbans are governed by the regulations of forest department (Table 9.5). Set of new regulations have been proposed by FAO (United Nations Food and Agricultural Organization) and ADB (Asian Development Bank) through the projects related to the Sundarbans. Fishing in the extended

Fig. 9.4 Use of nets and fishing traps in canals blocking the whole waterways at small interval. (Courtesy authors)

marine, estuaries and rivers are governed by the marine fisheries ordinance, 1983 (DOF 2017b) and East Bengal Protection and Conservation of Fish Act, 1950 (DOF 2017c).

However, recent scientific evidences to update those management practices are limited. Major intervention for fisheries conservation in this region includes fishing ban period for hilsa in the estuaries and rivers, formation for fish sanctuaries (Fig. 9.5) and its co-management, gear selectivity, and restricted permits for fishing boats based on maximum sustainable yield. In recent years fishing ban periods are strictly monitored and the fishermen receive subsidy for this particular period from the government.

Future sustainability of fisheries and management of fish and aquatic biodiversity depends largely on building scientific basis, developing management practice based on it, and strict implementation of the regulations.

9.4 Aquaculture in the Southwestern Bangladesh

Like other parts of Bangladesh, aquaculture is gradually becoming major contributor to fish and crustacean production in Sundarbans region. The agro-ecosystem surrounding the eco-region is providing 300,000 ha aquaculture farms under many different habitats (Table 9.6). Expansion of aquaculture took place mainly in the tidal floodplains and in the *beels* dictated mainly by the demand of shrimp in the international market.

Table 9.2 Common fishes available in the Sundarbans region. (Rahman et al. 2016a)

Order	Family	Scientific name	Common English name	Local name	Conservation status	
					Bangladesh	Global
Beloniformes	Belonidae	*Xenentodon cancila* (Hamilton 1822)	Freshwater garfish	Kakila	NA	LC
	Hemiramphidae	*Dermogenys pusilla* (Kuhl and van Hasselt 1823)	Wrestling halfbeak	Ekthota	EN	LC
		Tenualosa ilisha (Hamilton 1822)	Hilsa shad	Ilish	NA	NA
Clupeiformes	Clupeidae	*Tenualosa toil* (Valenciennes and Cuvier 1847)	Toli shad	Chandanailish	NA	NA
		Corica soborna (Hamilton 1822)	Ganges river sprat	Kachki	NO	LC
		Gudusia chapra (Hamilton 1822)	Indian river shad	Chapila	NO	LC
	Engraulidae	*Setipinna phasa* (Hamilton 1822)	Gangetic hairfin anchovy	Phaisa	NO	LC
		Thryssa purava (Hamilton 1822)	Oblique-jaw thryssa	Ramchos	NO	NA
Cypriniformes	Cobitidae	*Lepidocephalichthys guntea* (Hamilton 1822)	Guntea loach	Gutum	NO	LC
	Cyprinidae	*Puntius sophore* (Hamilton 1822)	Spot fin swamp barb	Jatpunti	NO	LC
		Puntius ticto (Hamilton 1822)	Ticto barb	Tit punti	VU	LC
		Salmostoma bacaila (Hamilton 1822)	Large razorbelly minnow	Chela	NO	LC
		Esomus danricus (Hamilton 1822)	Flying barb	Darkina	NO	LC
		Labeo bata (Hamilton 1822)	Bata	Bata	EN	LC
		Labeo rohita (Hamilton 1822)	Rohu	Rui	NA	LC
		Gibelion catla (Hamilton 1822)	Catla	Catla	NO	LC
		Devario devario (Hamilton 1822)	Sind danio	Baspata	NO	LC
		Puntius chola (Hamilton 1822)	Swamp barb	Chalapunti	NO	LC
		Rohtee cotio (Hamilton 1822)	Cotio	Dhela	EN	LC
			Indian carplet	Mola	NO	LC

		Amblypharyngodon microlepis (Bleeker 1853)				
Cyprinodonti-formes	Aplocheilidae	*Aplocheilus panchax* (Hamilton 1822)	Blue panchax	Kanpona	NA	LC
Osteoglossi- formes	Notopteridae	*Chitala chitala* (Hamilton 1822)	Clown knife fish	Chitol	EN	NT
Perciformes	Ambassidae	*Chanda nama* (Hamilton 1822)	Elongate glassy perchlet	Lambachanda	VU	LC
		Chanda ranga (Hamilton 1822)	Indian glassy fish	Lal chanda	VU	LC
	Anabantidae	*Anabas testudineus* (Bloch 1792)	Climbing perch	Koi	NO	DD
	Channidae	*Channa punctatus* (Bloch 1793)	Spotted snakehead	Taki	NO	LC
		Channa marulius (Hamilton 1822)	Giant snakehead	Gozar	EN	LC
		Channa orientalis (Bloch and Schneider 1801)	Asiatic snakehead	Cheng	VU	NA
		Channa striatus (Bloch 1793)	Striped snaked	Shol	NO	LC
	Eleotridae	*Eleotris fusca* (Forster 1801)	Dusky sleeper	Kuldi	NA	LC
	Gobiidae	*Glossogobius giuris* (Hamilton 1822)	Tank goby	Bele	NO	LC
		Brachygobius nunus (Hamilton 1822)	Bumblebee goby	Nunabailla	NO	NA
		Pseudapocryptes elongatus (Cuvier 1816)	Lanceolate goby	Cheua	NA	LC
		Odontamblyopus rubicundus (Hamilton 1822)	Rubicusduseelgoby	Lal cheua	NO	NA
		Taenioides cirratus (Blyth 1860)	Whiskered Eel Goby	Dogri	NO	DD
	Latidae	*Lates calcarifer* (Bloch 1790)	Asian Sea bass	Koral	NA	NA
	Nandidae	*Nandus nandus* (Hamilton 1822)	Mottled Nandus	Vheda	VU	LC
	Osphronemidae	*Trichogaster fasciata* (Bloch and Schneider 1801)	Banded gourami	Khailsa	NO	LC
	Polynemidae	*Polynemus paradiseus* (Linnaeus 1758)	Paradise threadfin	Tapasi	NO	NA
	Sciaenidae	*Otolithoides pama* (Hamilton 1822)	Pama croaker	Lal Poa	NA	NA
	Sillaginidae	*Sillaginopsis panijus* (Hamilton 1822)	Flathead sillago	Tulardandi	NA	NA

(continued)

Table 9.2 (continued)

Order	Family	Scientific name	Common English name	Local name	Conservation status	
					Bangladesh	Global
Pleuronecti-formes	Cynoglossidae	*Cynoglossus cynoglossus*(Hamilton 1822)	Bengal tongue sole	Kukurjeeb	NO	NA
Siluriformes	Bagridae	*Mystus vittatus* (Bloch 1794)	Striped River catfish	Rani Tengra	NO	LC
		Sperata aor (Hamilton 1822)	Long-whiskered catfish	Ayr	VU	LC
		Mystus tengara (Hamilton 1822)	Tengra catfish	Kalobujuri	NO	LC
		Rita rita (Hamilton 1822)	Rita	Rita	CR	LC
	Heteropneustidae	*Heteropneustes fossilis* (Bloch 1794)	Stinging catfish	Shing	NO	LC
	Pangasiidae	*Pangasius pangasius* (Hamilton 1822)	Yellowtail catfish	Pangas	CR	LC
	Siluridae	*Ompok pabda* (Hamilton 1822)	Pabdah catfish	Madhu Pabda	EN	NT
		Wallago attu (Bloch and Schneider 1801)	Freshwater shark	Boal	NO	NT
	Schilbeidae	*Silonia silondia* (Hamilton 1822)	Silond catfish	Silon Tengra	EN	LC
		Clupisoma garua (Hamilton 1822)	Garuabachcha	Garua	CR	LC
		Ailia coila (Hamilton 1822)	Gangetic ailia	Kajuli	VU	NT
Synbranchiformes	Mastacembelidae	*Mastacembelus armatus* (Lacepède 1800)	Zig-zag eel	Shal Baim	EN	LC
		Macrognathus aculeatus (Bloch 1786)	Lesser spiny eel	Tara baim	VU	NA
	Synbranchidae	*Monopterus cuchia* (Hamilton 1822)	Swamp eel	Cuchia	VU	LC
Tetraodonti- formes	Teraodontidae	*Tetraodon fluviatilis* (Hamilton 1822)	Green puffer fish	Potka	NO	LC

LC Least Concern, *NT* near Threatened, *DD* Data Deficient, *NO* Not threatened, *CR* Critically Endangered, *EN* Endangered, *VU* Vulnerable, *NA* Not Assessed

Table 9.3 Fishing gear (nets), operation, expenditure and targeted catch. (Rahman et al. 2016a; Siddique et al. 2013; Rahman et al. 2016b)

Gear type	Local name	Mesh size	Shape	Fishermen need	Target species for catch (Local names)	ACC/ Haul/ Day/ gear (kg)
Gill net	Poajal	3.0–6.0	RS	4–5	Hilsa, Poa, Bata, Ramchos	5
	Shahin jal	4.0–7.0	RS	–	Hilsa, Koral, Boal, Ayr, Loitta	30
	Current jal	0.2–0.4	RS	1–2	Pangus, Hilsa, Chapila, Indian major carps	4.5
	Fashjal	4.5–15.0		1–2	Pangas, Poa, Hilsa, Bata, Aire	–
	Chandijal/ Ilishjal	4.0–4.5	RS	10–15	Hilsa, Poa	20
	Koraljal	10.2–15.2	RS	–	Koral, Pangus, Ayr	8
	Koi jal	1.2–5.1	RS		Koi, Magur, Shing, Shol	8
	Puntijal	2.2–3.5	RS	1–2	Punti, Bele, Gulsa, Bata, Koi, Pangas, Poa	–
	Bata jal	2.5–5.0	RS	2–3	Bata, Chewa, Poa	–
Seine net	Jagatberjal/ Shattingjal	0.5–2.0	RS	4–15	Juvenile Pangas, Poa, Juvenile Hilsa	7.5
	Gosijal/ Khotijal	0.2–1.0	RS	1–10	Small fishes, Hilsa	–
Fixed purse net	Behundijal	0.5–2.0	CS	2	Bata, Kuchia, Koral, Koi, Chewa, Chiring, Bashpata, Poa	6.5
	Badhajal	1.0	RS	1	Small fish	2.5
	Goriajal	0.2–2.5	RS	1	Small fish	4.5
	Chorjal	0.5	FS	1	–	5
Cast net	Jhakijal	0.5–1.0	CS	1	Bata, Chela, Taposhi, Prawn, Baim, Koi, Koral, Kuchia	2
Lift net	Dharma jal	0.5–1.5	SS	1	Bele, Taki, Shoal, Punti, Koi, Gulsha, Baim	3
Push net	Moiajal	0.5–1.0	RS	2	Fry, Larvae and Fingerling of various species	2
	Thelajal	0.5–1.0	TS	1	Shrimp larvae, Gulsha, Punti, Tengra, Mola, Chela	1.5
Dip net	Kharajal	0.5–2.0	FS	1	Ketchki, Bele, Shoal, Taki, Punti, Koi, Pangus, Poa, Tengra and Prawn	1

Table 9.4 Commonly used traps, hocks and wounding gears to catch fish in this region. (Siddique et al. 2013)

Gear type	Local name	Size	Shape	Common catch
Fishing traps	Vair	1.0x0.5x0.8 cubic meter	Long box like trap with a door extending from its base to its apex which is made of split bamboo	*Cyprinus carpio, Labeo rohita, Catlac atla, Wallagonia attu, Channa punctatus, Channa striatus*, *Channa marulius* and *Mastacembelus armetus*
	Pangus chai	3x2x2 cubic meter	Rectangular with 2–3 doors and made by bamboo splits. Bait is used in this trap	*Pangasius Pangasius*
	Kholsun	0.7x1.0x0.3 cubic meter	Rectangular box shaped fish trap made of split bamboo, tied with jute rope or cane and consisted of two doors from its apex for fish opening	*Mastacembelus armetus, Anabas testudineus, Puntius spp., Mystus vittatus, Corica soborna, Amblypharyngodon mola, Chanda nama, Colisa fasciatus and small prawn*
	Bitte		Bitte is a basket shaped fishing trap, made of split bamboo with two or three entrances and an opening on the trap for collecting fish	*Mastacembelus armetus*, *Anabas testudineus*, Punti (*Puntius* spp.), Tengra (*Mystus vittatus*), small prawn etc.
	BanarGhop		It is used as a barricade or trap for fish, made of split bamboo.	*Labeo rohita, Catla catla, Mystus vittatus* and prawn
	Icha chai		It is a triangular or cylindrical shaped trap made of bamboo splits and threads	*Mastacembelus armetus* and prawn
Hooks and lines	*Barshi*		It is a very simple barbed hook tied with one end of a line and the other end with a bamboo stick	*Labeo calbasu, Anabas testudineus, Heteropneustes fossilis, Puntius spp., Rita rita, Mystus vittatus* and some carp species
	Borsha		A gear where a narrow small portion of dried bamboo reed is used as float from which a small about half meter long line is hanged with barbed baited hook	*Anabas testudineus, Channa punctatus, Puntius spp., Mystus vittatus* and some other small fish
	Daun		A long line measuring from 46 to 450 m, which	*Rita rita*, *Mastacembelus*

(continued)

Table 9.4 (continued)

Gear type	Local name	Size	Shape	Common catch
			is set into shallow water with bamboo pools 4–6 cm above water. A small line of 0.45–1 m with barbed hooks is lowered into water with bait.	*armetus*,*Polynemus paradiseus*, *Channa striatus*, *Channa punctatus*, *Channa marulius*
	MaittaDaun		A baited long line which may contain even up to 4–5 thousand hooks with 10 cm interval in flowing water with heavy current. A boat is needed to operate this lines	*Wallago attu, Sperata aor, Anabas testudineus, Channa punctatus, Puntius spp., Labeo calbasu, Heteropneustes fossilis, Rita rita*
Wounding gears	Juti	Spear shape	5–10 bamboo splits attached to the shaft by cords measuring 2–3 m in length	*Wallago attu*, *Channa striatus*, *Channa punctatus*
	Konch	Spear shape	10 pieces of bamboo splits are firmly fixed in a bunch. The pointed ends of the bamboo splits are covered with sharp and pointed iron caps to increase the efficiency	*Labeo rohita*, *Catla catla*, *Channa striatus*, *Channa marulius*
	Teta	Spear shape	Long bamboo handle with several iron hooks and iron rod at the base	*Wallago attu, Channa striatus, Channa punctatus, Glossogobius giuris*

9.4.1 Types of Habitat

Aquaculture development in this region was unplanned and expanded based on habitat suitability (Azad et al. 2009). Largely it was conversion of low-lying rice fields into shrimp farms (locally known as *Ghers*) and was further extended into the *beels* (Table 9.6). Besides these two vast aquaculture landscape, ponds, which are highly prevalent in coastal areas (Belton and Azad 2012), provide plenty of opportunities for both subsistence and commercial aquaculture, and is considered as an important source of fin fish production (Pant et al. 2014; Jahan et al. 2010).

Table 9.5 Existing and proposed fisheries management and conservation rules in The Sundarbans Reserve Forest (SRF) *Khals'*,branches of rivers i.e., canals. (Hoq 2007)

Legislation	Summary of regulations	Implementing agencies
Indian Forest Act, 1878	Empower the Forest Department to manage the inshore and offshore fisheries in the Sundarbans and near shore 20 km marine waters	Forest Department
Hunting and Fishing Rules, 1959	A fishing permit is required to fish in reserved or protected forests	Forest Department
	Royalty may be levied on fish caught in tidal waters of reserved and protected forests	
	It is illegal to use poison, explosives or fixed engine fishing gears, or to dam or bale water in reserve and protected forests	
Major Fisheries Regulations for SRF	*Khal Closure Regulation (1989):* closes 18 *khals* permanently for fishing to ensure natural fish breeding	Forest Department
	*Collection & Export of Live Crab Regulation (1995):*closes the entire SRF for crab fishing from December to February to ensure crab breeding	
	Closed Season Regulation (2000): closes fishing in the entire SRF for the five species (*P. pangasius, P. canius, L. calcarifer,*	
	M. rosenbergii, S. serrate) during 1st May to 30th June to ensure natural breeding	
Wildlife Sanctuary Regulations, 1999	Fishing is permanently prohibited in the three wildlife sanctuary of SRF	Forest Department
Other Regulations for Fisheries in SRF	It is illegal to place nets across a *khal and thereby completely block it*	Forest Department
	It is illegal to sting a rope transversely across a *khal*	
Proposed regulations	Introduction of closed season	Some of the FAO proposal have been implemented by Forest Department
Proposed by FAO through its project (BGD/84/056) in 1994	Introduction of protected zones i.e. fish sanctuaries	
	Introduction of minimum size limit of two species –30 cm for *L. calcarifer* and 10 cm for *J. argentatus*	
	Restriction on number of gillnets	

(continued)

Table 9.5 (continued)

Legislation	Summary of regulations	Implementing agencies
	Maintenance of exploitation rates for commercial species at current levels except *P. monodon* fry.	
	Coordination of regulatory powers of Forest Department and Department of Fisheries for life- cycle management of migratory fish stocks i. e *T. ilisha* and *L. calcarifer*	
Proposed by World Bank through its project in 1998	Closure of small *khals* (Less than 30 m wide) for 12 months within 5 km radius of Forest Stations in SRF, in alternating years	Some of the regulations have been implemented and implementation of others are questionable
	Permanent closure for wildlife sanctuaries and any other protected areas	
	Maintenance of records of permits issues and catch for individual fisherman	
	Maintenance of annual harvest limit for various species, initially *T. ilisha*, all catfishes and mud crab	
	Issuance of catch quota to individual fisherman based on a share of the total allowable catch (TAC)	
	Restriction of shrimp fry catch to boundary rivers only	
	Release of small fishes back to the water caught in shrimp fry collection nets	
	Prohibition on harvesting of brood crabs or female crabs with egg	
	Maintenance of minimum harvesting weight of 200 g for male and 120 g for female crabs	
	Enforcement of National Fish Act to maintain minimum harvesting size limits and closed seasons	
	Penalties are specified for fishing without a permit, fishing in restricted areas, using poison, explosives or banned materials, catching undersized fish during prohibited months or continuing fishing after having reached the individual allocated quota	

Fig. 9.5 Co-management of breeding grounds in the large river estuaries. (Courtesy authors)

Table 9.6 Major aquaculture habitats in the south-west coastal zone. (Jahan et al. 2015)

Homestead pond	A pond, usually small, constructed close to the homestead and used for a range of domestic purposes, such as drinking water, bathing and washing clothes
Gher	A rice field in southern Bangladesh modified by deepening it to provide sufficient water to hold fish and/or crustaceans and raised dikes to prevent their escape. Often, though not always, it is integrated with rice cultivation, either concurrently or in consecutive seasons
Commercial pond	A pond excavated with the intention of year-round production of fish primarily destined for sale. It is usually, but not always, on land formerly used for rice cultivation
Beel	A large, naturally occurring depression holding water for all or part of the year, made suitable for fish culture by enclosing it with high dikes to retain water and prevent flooding. Typically, *beels* are formed by inundation of low-lying lands during flooding, where some water gets trapped even after floodwaters recede from the floodplain. *Beels* may also be caused by rain filling up in low-lying areas, especially during the monsoon season
Rice-fish plot	A rice field in northern Bangladesh modified by deepening it to provide sufficient water to hold fish with raised dikes to prevent their escape. Rice cultivation is practised concurrently with fish production or in consecutive seasons

9.4.2 Levels of Intensification

Traditionally aquaculture has been practised extensively relying largely on wild seeds and fertilization. From this traditional extensive system the advancement was more on integration with other crops (Ahmed et al. 2014; Bunting et al. 2017), diversification by adopting polyculture to increase fish production from an unit area and adapting with the annual seasonal change (Ahmed 2013a; Ahmed and Flaherty 2013; Faruque et al. 2017). Unlike other South and Southeast Asian

Table 9.7 Types of aquaculture systems based on productivity level and management. (Jahan et al. 2015)

Extensive	Depends mainly on the natural productivity of the water body for fish growth
	Minimal or occasional use of low-quality supplemental feeds such as farm by-products, including rice bran, rice products and mustard oil cake
	Irregular use of fertilizer, particularly organic fertilizer (e.g. cow dung)
	Low level of control over stock management
	Low stocking density (under 15,000 fingerlingsha^{-1})
	Low level of fish productivity (under 3 t ha^{-1})
Semi-intensive	Fish nutrition derived from both natural feeds produced in the pond (phytoplankton and zooplankton) and external inputs of supplemental feed such as homemade feed and commercially produced pelleted feed
	Control of stock management
	Intermediate level of stocking density (15,000–35,000 fingerlings per ha)
	Regular use of fertilizers, particularly inorganic fertilizers (urea, triple superphosphate and di-ammonium phosphate)
	Occasional replacement of pond water
	Moderate to high level of productivity (4–20 tha^{-1})
Intensive	All fish nutrition derived from external feed inputs, most commonly in the form of formulated pelleted diets
	Control of stock management
	High stocking density (above 35,000 fingerlings per ha)
	Regular pond monitoring
	Frequent replacement of pond water
	High level of productivity (above 20 t/ha^{-1})

countries where the change was towards more intensification and driven by commercialization, in Bangladesh this advancement, described above, was unique and considered more sustainable (Bunting et al. 2017).

Current level of intensification of coastal aquaculture can be broadly categorized by extensive, semi-intensive, and intensive, which vary in terms of management practices and yield (Table 9.7).

9.4.3 Common Production Technologies

Within the broader spectrum of habitats there are 15 major aquaculture technologies practised at different levels of intensification (Table 9.8). However, in terms of area occupancy, more than 70% of the land is under shrimp-based farming practice (Keus et al. 2017). Often this farming is integrated and rotational depending on annual rainfall and salinity in the tidal rivers (Ahmed and Diana 2015; Bunting et al. 2017; Ahmed 2013a; Faruque et al. 2017; Karim et al. 2014).

Table 9.8 Major aquaculture production technologies practised in the south-west coastal Bangladesh. (Jahan et al. 2015)

Technology	Productivity
Fish polyculture (homestead)	Extensive
Fish polyculture with small indigenous species SIS (homestead)	Extensive
Pangus culture (pond)	Intensive
Carp culture (pond)	Intensive
Tilapia culture (pond)	Intensive
Koi culture (pond)	Intensive
Carp and prawn culture (pond)	Semi-intensive
Fish polyculture (*gher*)	Semi-intensive
Shrimp culture (*gher*)	Extensive
Shrimp monoculture (pond)	Intensive
Shrimp culture and rice farming (*gher*)	Extensive
Shrimp and prawn culture and rice farming (*gher*)	Extensive
Prawn culture and rice farming (*gher*)	Semi-intensive
Rice and fish (*beel*, commercial)	Semi-intensive

Table 9.9 Productivity from different salinity zones. (Faruque et al. 2017)

	Aquatic agricultural system Yield (kg ha^{-1} year^{-1})											
Crop	Low salinity				Intermediate salinity				High salinity			
Prawn	323	±	25	a	232	±	14	b	0	±	0	
Shrimp	0	±	0	a	171	±	11	a	295	±	33	b
Prawn + Shrimp	323	±	25	a	404	±	18	b	295	±	33	a
Fish	284	±	23	a	269	±	24	a	128	±	41	b
Dike crops	4027	±	464	a	1837	±	503	b	0	±	0	
Rice	4986	±	385	a	3133	±	26	a	0	±	0	
Total	9620	±	673	a	5642	±	564	b	422	±	55	c

9.4.4 Fish, Crustaceans and Integrated Crops Produced from Different Farming Systems Distributed in Different Salinity Zones

The integrated and diversified coastal aquaculture has different spectrum by salinity, while production and crop composition vary accordingly (Table 9.9). The average production indicates the very level of productivity, lower diversification and no integration, coupled with a trend of reducing rice and dike crop productivity with increasing salinity. This also indicates that the increase in total national production from coastal aquaculture should be due to horizontal expansion rather than intensification of the system.

9.5 Mangrove Loss due to Expansion of Shrimp and Coastal Aquaculture in Bangladesh

Like other southeast Asian countries, mangrove destruction due to expansion under shrimp and coastal aquaculture took place in Bangladesh also. This was a planned intervention misguided by international development programmes driven by the market demand largely between 1977 and 1988 (Hossain et al. 2001). This loss was mostly confined in the southeastern part of Bangladesh (Table 9.10), but didn't affect much on the core Sundarbans lying at the lower Ganges delta (Ahmed et al. 2017).

9.5.1 Impact on Environment

Environmental impacts have increasingly become a matter of concern for both government and public with the fast expansion of coastal aquaculture dominated by shrimp farming (Paul and Vogl 2011). Horizontal growth of shrimp farming is often unregulated, uncontrolled, and uncoordinated (Deb 1998; Metcalfe 2003; Samarakoon 2004; Alam et al. 2005). Mangrove destruction was not prominent in the Sundarbans region, although massive destruction took place in the Chakaria Sundarbans, located in the south-eastern part of Bangladesh (Hossain et al. 2001). At the beginning of this growth of shrimp farming it was widely dependent on wild shrimp post-larvae (PL), which is considered as one of the major reasons for loss of coastal aquatic biodiversity and reduced fish catch (Hoq 2007; Islam et al. 2004).

Major concerns in the Sundarbans were the trapping of salt within the farms for the entire season in order to continue with shrimp production (Azad et al. 2009) and encroachment to public waterbodies, canals and smaller rivers (Paul and Vogl 2011),

Table 9.10 Loss of mangrove forests to shrimp farms in coastal Bangladesh

Mangrove forest	Location	Area lost (ha)	Reference
Chakaria Sundarbans	South-Eastern Bangladesh	8500	Hossain et al. (2001), Shahid and Islam (2002)
Mangrove forest along the Naf River		667 or 1800[a]	Shahid and Islam (2002), Hossain and Hossain (2001)
Mangrove forest on Maiskhali Island		290	Shahid and Islam (2002)
Mangrove forest on Jaliardwip Island		133	Shahid and Islam (2002)
Mangrove forest on Matabar Island		104	Shahid and Islam (2002)
Total		~10,000	Ahmed et al. (2017)

Data compiled by Ahmed et al. (2017)
[a]This figure included mangroves in off-shore islands

which were further facilitated by reduced upstream flow to influence salinity intrusion (Sohel and Ullah 2012). Changes, especially in terms of the salinity regime, impact integration opportunities especially with rice and dike crops (Faruque et al. 2017). Besides modification of *beels* (floodplains) landscape was changed either by natural siltation and then converted to rice field, or encroachment by human for shrimp *ghers* has altered the ecosystem (Paul and Vogl 2011; Dasgupta et al. 2017; Sohel and Ullah 2012). Embankments were made to foster green revolution – rice production and prevention of flooding in the croplands, while human habitation has greatly impacted the river based irrigation and drainage systems (Ahmed 2013b). Outbreak of disease and pollution due to poor farm management creates negative impact on environment (Azad et al. 2009; Wahab et al. 2003) as well as challenges to sustainability of growth of aquaculture (Paul and Vogl 2011).

9.5.2 Socio-Economic Consequence

Expansion of aquaculture had both positive and negative impacts on the society. The significant improvement of people's economy in this area followed by higher consumption of fish has benefited positively (Ahmed 2013b; Islam et al. 2005; Karim et al. 2014; Faruque et al. 2017). Thousands of job opportunities were created and industrial advancement, especially in the areas of shrimp seed production and post-harvest processing, have raised the economy of both rural and urban areas of south-west Bangladesh (Keus et al. 2017; Ahmed 2013b; Ahmed and Flaherty 2013; Bunting et al. 2017). However, this advancement also brought negative consequence, especially on possession of land and allowing independence to farmers to choose their own cropping pattern (Paul and Vogl 2011; Paul and Vogl 2013; Afroz and Alam 2013). Involvement of school going children in the PL collection appeared as a big social problem as number of drop off from school in this region increased during 1990s (Afroz and Alam 2013). However, this has been greatly reduced by advancement of hatchery- produced PL and their marketing at grassroots levels (Keus et al. 2017). Economic loss due to shrimp disease and loss of employment were also noticed in many places especially during 1990s (Paul and Vogl 2011). Subsequent shifting of the aquaculture system due to shrimp disease from shrimp to fish-based system has developed new value-chain and creating opportunities for integrated farming again as this doesn't require retaining saline water in the aquaculture *ghers* (Kabir et al. 2015; Ahmed and Flaherty 2013; Ahmed et al. 2014).

9.5.3 Land Use Conflicts

Land use conflict appeared as the major social problem as a consequence to expansion of shrimp farming (Paul and Vogl 2011; Azad et al. 2009). Richer people from the city tried to take over poor people's land (Islam 2006). So the poorer group wanted to stay focused on rice. However, this has been well addressed in last decade by the government and establishing "*jami jar gher tar*" ("the *gher* belongs to the land owner") rule facilitated by developing technologies to grow shrimp, prawn, fish and crops together in small pieces of land (Ahmed et al. 2014). However, this conflict still exists in areas of medium to low salinity zone where rice and other crop farmings still compete with aquaculture – especially shrimp (Maniruzzaman 2012).

9.6 Recent Advances in Aquaculture Technologies

9.6.1 Advances in Fish and Crustaceans Seed Production and Breeding Technology

One of the major challenges for improving coastal aquaculture was to get quality seed for both carp and shrimp. This has come long way and is contributing to the process of growth and diversification through collaborative research and development activities of Bangladesh Fisheries Research Institute (BFRI), Department of Fisheries (DOF), Government of Bangladesh, WorldFish and Private Sector Hatcheries (Keus et al. 2017; Karim et al. 2016).

Commercial breeding of Indian major carps, *i.e.* rohu, catla and mrigal, and tilapia are widespread across the region. In addition, seeds of common carp, silver carp, big head carp and black carp are produced in Jessore region adjacent to the lower Ganges delta providing necessary seed for sustaining aquaculture diversification in this area. *Mystus gulio*, a popular brackishwater catfish, seed is also produced commercially. Seeds of climbing perch (*Anabas testudineus*), pangus (*Pangasius pangasius*), singh (*Heteropneustes fossilis*), magur (*Clarias batrachus*) and chital (*Chitala chitala*) come from Mymensingh region. Seabass, mud crab and mullet seeds are still collected from wild sources, leaving the opportunity to develop commercial breeding and seed production to further diversify the aquaculture production, and increase profitability in the mixed brackish-freshwater systems. Collection of wild black tiger shrimp seed, which was often blamed for destruction of coastal aquatic biodiversity, has almost stopped. Shrimp PL demand is widely supplied by the hatcheries now-a-days. After the emergence of White Spot Disease (WSD), the testing facility for the pathogen was in place to ensure disease free seed supply to the farmers. This has been advanced further by the introduction of domesticated specific pathogen free (SPF) shrimp PL since 2014. Giant freshwater prawn seed production technologies were also popular in this region. However, since 2012, hatcheries in Khulna district region are facing unknown disease outbreak at a larval stage and the seed supply is currently a limiting factor for growth of freshwater prawn. Recent initiatives to produce genetically improved rohu, catla and silver carp are expected to help in boosting up freshwater fish production from the *ghers* and beyond (Keus et al. 2017).

9.6.2 Feed Management Technologies

In 2000s when culture systems started to improve by adopting better management practices, access to both fish and shrimp feed remained as one of the major challenges. This has been addressed in the last decade mostly by the industry and facilitated by development projects of the Government of Bangladesh (GOB) and NGOs. Now, approximately two million metric ton of fish and shrimp feed is produced in the country of which 15–20% is supplied to this region (Mamun-Ur-Rashid et al. 2013). The feed industry has evolved from hand-made and homemade feed to semi-automatic sinking feed to finally extruded floating pellets. Presently, 112 commercial fish feed companies are producing feed and distributing throughout the country including the Sundarbans region. There are approximately 1000 semi-automatic feed mills serving from large individual farms to small scale farmers in remote areas throughout the country, of which more than 100 are located in this region.

Recent initiative was to develop feed for pond systems to increase efficiency of feed use, ensuring longer-term sustainability by reducing the use of fishmeal, and environmental impact of the same. This is still at pilot phase but has potential to create impact throughout the tropics for intensification of pond-based aquaculture in a more sustainable way.

9.6.3 Advances in Bio-security, Disease Prevention, Diagnosis, and Treatment

Bio-security at hatchery and nursery level is well maintained. However, with the exception of semi-intensive shrimp farms, this is poorly maintained at farm level (Belton and Azad 2012). Consciousness and facilitation for disease prevention, diagnosis, and treatment are, however, limited. Recently, several programmes have been launched jointly by DOF, BFRI and WorldFish to facilitate this at farmers' level.

9.6.4 Advances in Sustainable Intensification and Integration of the Farming System

Farming systems are still largely extensive and have room to improve for increasing fish production for both local and international market. CGIAR Challenge Program for Water and Food conducted research in high saline areas for developing low cost technology in order to diversify the production system and integrate aquaculture with agriculture. Research result demonstrates potential to increase shrimp production ~two folds higher and fish production ~five fold higher by following rotational polyculture (Table 9.11). This research also demonstrates that the income from fish produced in rotational polyculture can make up the loss due to disease during shrimp cultivation and also provides nutritious food for household consumption (Kabir et al. 2015).

There is large potential for integration with rice and dike cropping during monsoon. However, this largely depends on the start and extent of monsoon rain, irrigation and drainage infrastructure, and farm design (Kabir et al. 2016). There was no significant effect on fish production due to inclusion of rice in the system (Fig. 9.6). Both local and high yielding varieties (HYV) of rice can be integrated in the *gher* system, and fertilization for rice is not essential when grown in a fish pond (Fig 9.7). The apparent equal yield of rice from both local and HYV rice varieties was more likely for the higher tolerance of local varieties to water stagnation and salinity change compared to HYV varieties. Due to challenged water management the HYVs can't reach it's optimum yield potential. Similarly, the rice fields inundated under water and integrated with fed fish system received required nutrient from the feed and waste of the fish. Thus, addition of fertilizer doesn't make any change in the yield. However, the limitation of the experiment was both the treatments were run is the same pond and thus the result might have some bias as well.

The government has adopted policy and organized programmes together with development partners to use these technologies for sustainable intensification. However, some major challenges still limit this expansion – namely poor water infrastructure, limited access to electricity, increasing disease risk with intensification of the production system, and lack of investment capital.

9.6.5 Adaptability with Environmental Changes and Reducing Impact

Proper management can ensure a sustainable growth and benefit of shrimp cultivation. Protection and restoration of aquatic environment from pollution due to shrimp cultivation is the most essential theme of environmental management. Hossain et al. (2013), in a significant publication, however stated that shrimp farming in Bangladesh coastal areas has been associated with a number of environmental and societal impacts which hinder sustainable development in this blooming sector and identified management of various factors being the keys to mitigate the adverse effects. One of the ways of reducing environmental impact is to reduce nutrient input to the system. However, reducing nutrient input has consequence with production potential. We need to find a balance between production target and environmental management. The application of nutritious pond concept for low input intensification can be a potential option for sustainable intensification and reducing environmental impact.

Table 9.11 Fish and shrimp production from traditional *gher* farming and two proposed low input improved practice for high saline coastal areas. (Source: In-house study)

Culture pattern	Cycle 1 (Mar–May)		Cycle 2 (Jun–Aug)		Cycle 3 (Sep–Nov)		Total annual yield	
	Shrimp (kgha^{-1}. cycle^{-1})	Tilapia (kgha^{-1}. cycle^{-1})	Shrimp (kgha^{-1}. cycle^{-1})	Tilapia (kg.ha^{-1}. cycle^{-1})	Local cat fish[a] (kg.ha^{-1}. cycle^{-1})	Tilapia/Rohu (kg.ha^{-1}. cycle^{-1})	Shrimp (kg.ha^{-1}. year^{-1})	Fish (kg.ha^{-1}. year^{-1})
Farmer's practice[b]							390	659
Monoculture	566		292			3308	857	3308
Polyculture	374	1744	193	778	558	480	567	3560

[a]*Heteropneustes fossilis* and *Clarias batrachus*
[b]multiple stocking & harvesting – not split by cycle

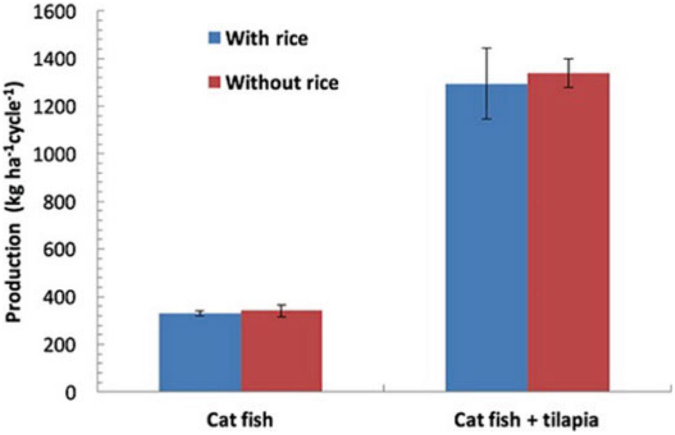

Fig. 9.6 Fish production with and without rice at monoculture and polyculture treatments. (Kabir et al. 2016)

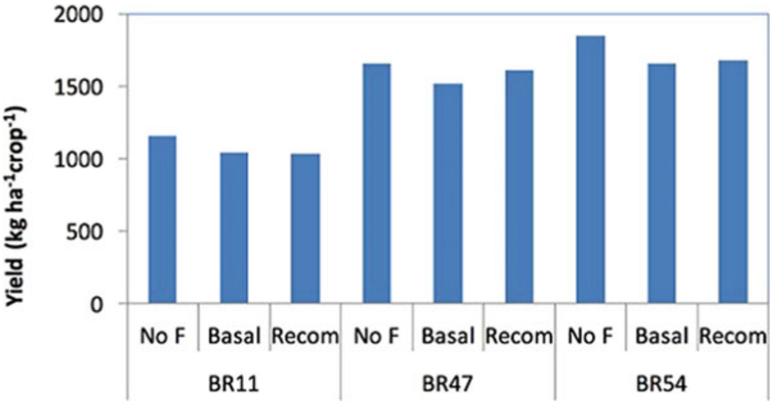

Fig. 9.7 Performance of rice varietal yield under different fertilization scheme

9.7 Challenges and Opportunities

Challenges and opportunities are diverse over varied landscape and habitats. Major common challenges to sustain and grow aquaculture in this region include climate change and environmental uncertainties; shrimp and fish disease; land use conflict, land fragmentation and its consequence on farming practice; and industrialization.

Application of research output at higher scale requires policy revision and multi-stakeholder integrated approach. Often this coordinated approach is lacking in Bangladesh and stands as a bottleneck to address the existing and upcoming challenges and to the best use of opportunities for maximizing economic and environmental benefits.

Careful steps should be taken to restore some of the losses made in the past due to unplanned or misleading growth and development activities. While scaling a technology ecological, social and economic factors should be considered in immediate, short term and longer-term perspective.

9.8 Conclusions

The Sundarbans is a unique and important aquatic resource for both fisheries and aquaculture. Its functional importance as a nursery ground for many fin fish and shell fish species have cross-boundary importance. Vast aquaculture habitats which are partly used at this moment can be of greater importance in the coming days in terms of food and nutrition security, export income and employment. However, a plan is required considering overlapping interest of fisheries and aquaculture with strong scientific base. Strengthening and activation of multi-stakeholder coastal zone management is essential for conservation and management of fisheries; enhancement of aquatic and wetland biodiversity; and sustainable intensification of aquaculture, along with developing means to monitor and mitigate the environmental and societal impacts. Finding ways to grow aquaculture and fishery in harmony in a mangrove ecosystem is of vital importance.

This vast fertile area thus provides great opportunity to improve fish and shrimp production and improving the livelihoods of the people in this region. Land zoning for different products, landscape-based integrated approach for saving fisheries, and technological advancement for sustainable and resilient aquaculture vis-a-vis their environmental and societal impacts can be the future directions for growth and improvement of fisheries and aquaculture.

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Traditional net fishing in deep forest area (Courtesy D. Burman)

Chapter 10
Freshwater Aquaculture in Sundarbans India

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Abstract Aquaculture is an important economic activity and a flourishing sector in India with varied resources and vast potentials, growing at the pace of 4.5% annually, contributing to national income, employment generation and foreign exchange. Sundarbans, the world's largest delta is a globally recognised ecologically sensitive area of West Bengal. This deltaic region, besides its role in estuarine ecological balance contributes to economic and livelihood development through resource utilisation and fish production. This region is rich in biodiversity and harbours both fresh and brackish water fish species. Therefore, apart from brackish water aquaculture, freshwater sector contributes parallel economy and livelihood security of the peoples living in close vicinity in the eco-region. But fish productivity in the range of 1000–1200 kg ha^{-1} $year^{-1}$ in this region is much lower at present in comparison to national average of 2840 kg ha^{-1} $year^{-1}$ mainly due to the non-scientific culture, poor quality fish seed, and overall lack of knowledge. The unutilised freshwater resources of this eco-region provide huge scope for development of freshwater aquaculture with proper management in spite of its remoteness, lack of communication with mainland, and extreme natural disasters like cyclone and flood the region encounters with. In this chapter, the present status and constraints of freshwater aquaculture of Sundarbans with recommended practices has been described focussing on quality fish seed production, scientific freshwater aquaculture practices, integrated fish farming, and the resultant gender upliftment through training and demonstration.

Keywords Sundarbans freshwater aquaculture · Livelihood · Integrated fish farming · Composite fish culture · Quality fish seed · Gender upliftment

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10.1 Introduction

India offers a huge potential for aquaculture development and globally the country now takes the second position, after China, with only 6% share in global aquaculture production (FAO 2016). Annual fisheries and aquaculture production of India increased from 0.75 mt in 1950–51 to 10.79 mt in 2015–2016. Specifically freshwater aquaculture of the country experienced over a tenfold growth in the past three decades, 0.37 mt in 1980 to 4.39 mt in 2014 (Kumar 2016; FAO 2016).

Among the different states of the country, West Bengal plays a key role in aquaculture production and it is just behind the state of Andhra Pradesh in case of food fish production. From the point of view of West Bengal, this state has 0.816 million ha inland sector and 19,639 sq. km marine sector with 158 km coastline (Handbook of Fisheries Statistics 2014–2015, Govt. of West Bengal) where about 3.2 million fisher population are involved. The Indian Sundarbans is situated in southern part of this state covering about 0.6 million ha out of which 0.4 million ha is under forest. Because of its geographical location, this estuarine mangrove area is rich in fish biodiversity and the local livelihood is mainly depending upon collection of fish, crab and shrimp from river. But this area has a huge scope of freshwater aquaculture as many sweet water ponds and canals are unutilised till now as recent freshwater aquaculture technologies have not reached in most of the places mainly due to its remoteness, lack of communication with mainland, and extreme natural disaster like cyclone and flood by the rivers frequently encountered with. In recent years, Sundarbans is facing various problems due to global warming, encroachment of forest by the human, over-exploitation of natural resources, and rapid reduction of wild animals in the forest area. Initiation of different activities through government and non-government level for saving this world heritage through sustainable use of natural resource, and introduction of modern technological inventions, along with skilled development of the island dwellers offers tremendous opportunities for future improvement in freshwater aquaculture productivity. Scope and provision for such improvement vis-a-vis problems existing in this eco-region has been discussed in this chapter.

10.2 Freshwater Aquaculture in Sundarbans: Status, Problems and Recent Developments

10.2.1 Geographical Location and Ecology

The Sundarbans is ecologically situated in southern part of the Gangetic delta between the Hooghly river (a course of the Ganges) in India on the west and the river Meghna (a course of the Brahmaputra) in the Bangladesh on the east and is bounded by the Ganges-Padma and the Padma-Meghna on the north and by the Bay of Bengal on the South. The tract covers about 435 km in length and includes an area of 72,727 sq. km having parts of 2 districts (24-Parganas North and South) of West Bengal of India and from the districts of Khulna and Bakhergunj in Bangladesh. The Indian Sundarbans delta is bounded by the Ichamati-Raimangal River in the east, by the Hooghly River in the west, by the Bay of Bengal in the south, and the Dampier-Hodges line, drawn in 1829–1830, in the north. It is a very remote area consisting of 102 Islands, out of which 54 are inhabited and rest of the Islands support mangrove forest.

The Indian Sundarbans alone boasts of 69 plant species, of which 30 are true mangroves, 20 are mangrove associates, and 12 belong to the black *mangal*. Only 40 species of mangroves are known in the entire world. The ecological richness extends to the waters. Mangroves and their roots play a role in purifying and enriching the waters and acting as nurseries to a large number of fish, shrimp and crab species. It has been said that "Sundarbans mangrove forest form the largest nursery for fish and shell fishes and are responsible for the coastal fishery of the whole of eastern India" (Chacraverti 2014). The intertidal zone in this region, with its mudflats, are known to host a wide variety of invertebrates, provide feeding ground for juvenile fishes, and play an indispensable role in the local food web (Mondal 2003).

10.2.2 Production Status

A lion share in aquaculture production of India is contributed by West Bengal. Majority of people of the state eat fish resulting in the requirement of approximately 1.6–1.7 mt fish per annum. Year-wise production and demand of fish in the state of West Bengal are shown in Table 10.1. During 2014–15, the state has produced 1.617 mt fish, of which 1.438 mt was from the inland and only 0.179 mt from the marine sector (Handbook of Fisheries Statistics 2014–15, Govt. of West Bengal). The state contributes approximately 21–23% of inland fish production of the country, with major share from two districts- North and South 24 Parganas, and part of these districts fall in Indian Sundarbans. Sundarbans is recognised as a UNESCO World Heritage Site. Fishery is treated as the backbone of Sundarbans economy. A large population of this eco-region is dependent on culture and capture fishery. Apart from coastal and brackish water aquaculture, freshwater aquaculture is increasing day-by-

Table 10.1 Year wise demand and production (in 0.1 million tonnes) of fish in West Bengal

Year	Demand	Production	Deficit or Surplus
2010–11	15.85	14.43	(−) 1.42
2011–12	16.06	14.72	(−) 1.34
2012–13	16.29	14.90	(−) 1.39
2013–14	16.51	15.80	(−) 0.71
2014–15	16.72	16.17	(−) 0.55

Source: Handbook of Fisheries Statistics 2014–15, Govt. of West Bengal, India

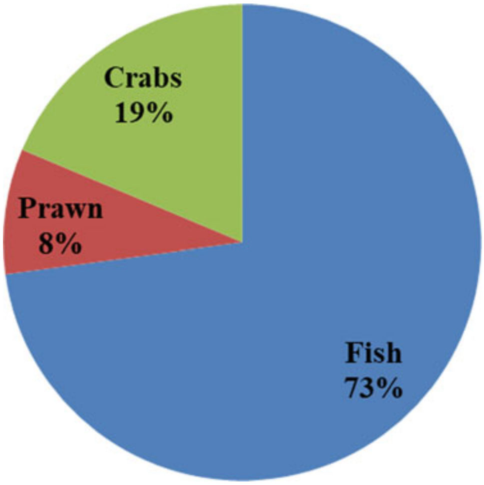

Fig. 10.1 Species diversity in the Sundarbans delta

day and contributes parallel economy and livelihood security in Sundarbans eco-region. This deltaic region harbours around 172 species of fishes, 20 species of prawn, and 44 species of crabs (Fig. 10.1) (Mahapatra et al. 2014).

10.2.3 Salient Biochemical Properties and Nutrient Profiling of Important Fish Species

Fish is the cheapest source of animal proteins and availability. Fishes are rich in polyunsaturated fatty acids (PUFAs), at the same time, it is a healthy food owing to its rich contents of proteins, oils, vitamins and minerals (Table 10.2).

Nutrient profiling of fishes shows that fishes are superior nutrients and number of health benefits are believed to be associated with regular fish consumption. Since Sundarbans is primarily brackish water area with river and *bheries* along with small freshwater ponds in almost every household, consumption of fish is high in comparison to other places of West Bengal. So, from the nutritional point of view, it is very important to develop the fisheries resources in a sustainable way for food security in the future.

10.2.4 A Household Activity

Sundarbans acts as the nursery ground for nearly 90% of the aquatic species of eastern coast of India. The availability of both important commercial and non-commercial species of the continental shelf in India and neighbouring countries very much depends on the services of Sundarbans ecosystem. The Sundarbans delta

Table 10.2 Nutrient composition of some important fishes found in Sundarbans. (Mohanty et al. 2011)

	Proximate composition			Minerals (mg/100 g)						
Fish species	Crude protein (%)	Crude fat (%)	Ash (%)	Ca	P	Na	K	Fe	Mn	Zn
Anabas testudineus	16.97	6.98	5.33	248.4	161.2	236.2	180.3	2.8	0.7	1.1
Clarias batrachus	16.26	5.24	2.22	222.4	129.4	201.5	262.1	2.2	0.2	0.7
Amblypharingodon mola	18.46	4.10	1.64	853.0	–	–	630.0	5.7	4.2	3.2
Channa striata	20.50	4.07	1.45	82.2	198.3	44.7	153.8	1.9	–	–
Channa punctata	19.84	3.15	1.00	766.0	535.0	–	–	1.8	–	1.5
Systomus sarana	20.84	3.15	1.17	30.2	268.2	34.4	121.3	2.6	–	–
Oreochromis niloticus	20.47	0.58	0.90	585.2	235.0	–	–	–	–	–

provides suitable ambience for nursery and breeding ground for fishes. Generally, estuary receives abundant supply of nutrients from land drainage and large quantities of organic detritus from mangrove forest which is an important source of energy for a wide variety of estuarine consumers. Further, many commercial estuarine fishes grow to maturity here and make up a large part of the near-shore fishery of the northern Bay of Bengal. Other fishes and prawns that spend most of their lives in freshwater descend annually to the estuary for spawning. Therefore, many marine and freshwater prawn and fish require this environment to complete their lifecycle. Aquaculture in Sundarbans is based upon both inland and marine fisheries resources. A proper linkage between the two culture systems can change the whole outlook of aquaculture and food security in this eco-region.

Freshwater aquaculture practice in Sundarbans area is mainly non-scientific culture of indigenous fishes like rohu *Labeo rohita*, catla *Catla catla*, mrigal *Cirrhinus mrigala*, bata *Labeo bata*, silver barb/java barb *Barbonymus gonionotus*, tilapia and exotic fish like common carp *Cyprinus carpio*, silver carp *Hypophthalmichthys molitrix*, bighead carp *Aristichthys nobilis*, pangas *Pangasianodon hypophthalmus*, pacu *Piaractus brachypomus*, etc. This farming normally undergoes in the small ponds adjacent to the household and the size ranges from 0.02 to 0.1 ha. The freshwater fish production is very low and it ranges annually from 1000 to 1200 kg ha^{-1}. These fishes are cultured mainly for domestic consumption. The ponds are generally 2–3 m in depth and filled up with rainwater during the monsoon season. Farmers generally stock fish seed (fry and fingerling) from the local vendors. These seeds mainly come from Rajendrapur Fish Seed Market, Naihati, North 24 Parganas, West Bengal and local people stock this seed indiscriminately in their pond mainly during the period of April–August depending upon the rainfall and water availability. In many cases a small quantity of freshwater prawn (*Macrobrachium rosenbergii*) collected from river/creeks are also stocked during the rainy season. Usually in traditional farming system, fish grow on the natural productivity and provision of supplementary feed is not available. Scientific management of these household ponds is a very rare view. Mass mortality during fish stocking is a very common phenomenon in this remote area due to poor quality seeds supplied by the local vendors. Harvesting of fishes starts just after 3–4 months of stoking for household consumption purpose.

Families in this area excavate a portion of their low-lying paddy field/own backward to get earth to raise the land and construct dwelling houses. Therefore, almost every household possesses these excavated areas for use as ponds and filled with monsoon fed water. These ponds (small water body) are used for freshwater aquaculture. Water of these ponds is also used for household purposes like washing of utensils, bathing and even for drinking purpose. Fish produced in these ponds are mostly used for domestic consumption and excess quantity is sold in local market. Freshwater aquaculture is also carried out in large ponds (either owned by individuals or few families), land-shaping ponds (mainly excavated for agricultural irrigation purpose) and low-lying inundated paddy fields. Cultivable aquaculture species in Sundarbans are shown in Table 10.3.

Table 10.3 Cultivable aquaculture species of Sundarbans

Common name	Local name	Scientific name
Freshwater finfishes		
Catla	Catla	*Catla catla*
Rohu	Rui	*Labeo rohita*
Mrigal	Mrigal	*Cirrhinus mrigala*
Bata	Bata	*Labeo bata*
Calbasu	Kalbos	*Labeo calbasu*
Olive barb	Saral punti	*Systomus sarana*
Mola carplet	Mourala	*Amblypharyngodon mola*
Silver barb/ java barb	Java punti	*Barbonymus gonionotus*
Grass carp	Ghesorui	*Ctenopharyngodon idella*
Common carp	American rui	*Cyprinus carpio*
Silver carp	Silver carp	*Hypophthalmichthys molitrix*
Bighead carp	Bighead	*Aristichthys nobilis*
Striped catfish	Pangas	*Pangasianodon hypophthalmus*
Clown knifefish	Chitol	*Chitala chitala*
Nile tilapia	Nilontica	*Oreochromis niloticus*
Mozambique tilapia	Tilapia	*Oreochromis mossambicus*
Magur	Magur	*Clarias magur*
Stinging catfish	Singhi	*Heteropneustes fossilis*
Climbing perch	Koi	*Anabas testudineus*
Giant murrel	Shal	*Channa marulius*
Striped murrel	Shol	*Channa striata*
Spotted murrel	Lata	*Channa punctata*
Bronze featherback	Pholui	*Notopterus notopterus*
Asian striped dwarf catfish	Tangra	*Mystus vittatus*
Gangetic mystus	Pata/patitangra	*Mystus cavasius*
Giant river catfish	Guizza/ Seenghala	*Sperata seenghala*
Long whiskered catfish	Aar/ Ayre	*Sperata aor*
Wallago/Helicopter catfish	Boal	*Wallago attu*
Butter catfish	Pabda	*Ompok bimaculatus*
Freshwater shellfishes		
Giant freshwater prawn	Golda chingri	*Macrobrachium rosenbergii*
Indian freshwater prawn	Sada chingri	*Macrobrachium malcomsonii*
Ganges river prawn	Chapra chingri	*Macrobrachium choprai*
Brackish water finfishes		
Long whiskers catfish	Nona tengra	*Mystus gulio*
Barramundi/ Asian seabass	Bhetki	*Lates calcarifer*
Goldspot mullet	Parse	*Liza parsia / Chelan parsia*
Tade gray mullet	Tade	*L. tade / Planiliza tade / Chelan planiceps*
Brackish water shellfishes		
Whiteleg shrimp	Vanamei	*Litopenaeus vannamei*
Tiger shrimp	Bagda chingri	*Penaeus monodon*

10.2.5 Problems Encountered

10.2.5.1 Climate-Induced Storms

Geographically, Sundarbans is vulnerable to cyclonic effect as situated in tropical zone. Shallow depth of Bay of Bengal as compared to Arabian sea, facilitates to form low pressure which, in turn, akin to develop cyclonic storms moving towards the Sundarbans due to South-North polar movement. As a result, severe storms affected the Sundarbans till date at every 2–3-year interval. In 2009, one such cyclonic storm called “Aila” virtually washed out entire Sundarbans region. This storm resulted severe loss of indigenous freshwater fish biodiversity, freshwater pond became saline, as a result of which majority of fishes died and the rest were washed away.

10.2.5.2 Lack of Skilled Knowledge

Various islands of Sundarbans which are not connected with the mainland are facing serious problems due to technical knowledge gap of recent scientific aquaculture activities. Unmanaged pond devoid of little or no application of fertilizer, manure, lime has made this area a bottom line of the aquaculture activities. Poor knowledge of stocking density of fish, stocking size, and ratio, has made poor utilization of available resources in this productive area. In most of the places there is no concept about the nursery and rearing pond which considered as most profitable part of aquaculture.

10.2.5.3 Nature of Soils

Soils are principally Alfisols (older alluvial soil) and Ardisols (coastal saline soil) (Mondal 2003). The salinity has resulted in the predominance of halophytic vegetation, especially mangroves.

Presence of acid sulphate soil in different regions of Sundarbans at different depths is a problem in this area. In many cases it has been seen that when this layer is exposed during excavation of ponds the water becomes acidic as sulphuric acid is formed, and the water pH becomes 5–6 or less resulting in the slow growth or even mass mortality of fishes, and this continues up to next 3–5 years to stabilize.

10.2.5.4 Fish Seed Availability and Marketability

Poor knowledge associated with poor quality fish seed has made the problem more acute in this region. Though quality fish seed is now a major problem in India, seed sellers are creating the situation vulnerable to the farmers by providing poor quality fish seed and taking advantage of absence of any hatchery in this island region.

Fig. 10.2 Aluminium *hundi*

Generally, some local people are engaged with the business of fish seed selling in this region. Vendors are going to a fish market called "Naihati Fish Seed Market" at North 24-Parganas district of West Bengal which is a fish seed production hub of India. After purchasing the fish seed from the market during night time, they carry the fish seed through aluminium *hundi* (generally 2 hundies hanging from a bamboo rod on the shoulder of the vendor) and reached different islands in next morning after a journey of 5–8 h with simple hand splashing in the container (Fig. 10.2). These seeds, when purchased and released in ponds, in most cases, do not survive due to prolonged transportation. As a consequence, repeated fish seed stockings, as a method, in a season have been adopted by the farmers of Sundarbans as there is no alternative option. Another aspect is that, seed quality is unknown to farmers as they do not have any option to judge the brood stock or identify the hatchery from where the fishes come. Beside this, fry mortality is commonly caused by the congestion and/or lack of proper food (Ray 1993). This situation has made the freshwater aquaculture activity in this deltaic island less productive and less cost-effective.

10.2.5.5 Anthropogenic Pressure

Native species like *Ompok pabda*, *O. bimaculatus*, *Wallago attu*, *Channa striatus*, *C. marulius*, *C. punctatus*, *Systomus sarana*, *Clarias amagur*, *Glossogobius* sp., *Amblypharyngodon mola*, *Colisa fasciata*, *Chitala chitala*, *Notopterus notopterus*, *Macrognathus pancalus*, *Anabas testudineus*, *Nandus nandus*, etc. are fishes which are reducing drastically in this region due to frequent intrusion of salt water over the years into the island and continuous anthropogenic pressure due to over-exploitation under increasing demand. Low production in freshwater aquaculture is also another reason for the dependence upon this naturally occurring fish species in this region.

10.2.5.6 Disease Outbreak

Fish diseases in the freshwater of Sundarbans have not been studied extensively. Due to the slight salinity existing in freshwater of Sundarbans, the incidence of fish diseases was rare in the past (Chand et al. 2012). But due to climate change events like cyclone, coastal flooding, erratic monsoon, storm surge, land erosion, temperature rise, sea level rise, extended summer, and saline water flooding due to breaching of pond embankments, mass mortality of fish, imparting extreme stress and several disease outbreaks, take place. Disease and growth retardation of fish are hence categorised as extreme risk in Sundarbans. Bacterial diseases like Epizootic ulcerative syndrome (EUS, Fig. 10.3), fin and tail rot, dropsy, parasitic diseases like Argulosis, Lernaeasis, Myxoboliasis (Fig. 10.4) and fluke infestations (Dactylogyrosis and Gyrodatylosis) are common problems in finfish, whereas, white spot, soft shell syndrome, blackening of gill and fungal infection are common in prawns and crabs, which render the farming at risk (Ray 1993). During the onset

Fig. 10.3 Ulcerative syndrome in *Labeo bata*

Fig. 10.4 Myxoboliasis in *Labeo rohita* collected from Sundarbans

of winter and after the rainy season the incidence of disease are reported to be more. The reason may be due to loss of appetite and poor immunity in winter and influx of pathogen, pesticide and chemicals from the agricultural fields in the post-rain period run off (Bly et al. 1997). Apart from climate change, accumulation of decaying organic matter in the pond bottom, over-stocking, absence of balanced feed are often main causes of disease in freshwater fish of Sundarbans.

10.3 Recent Aquaculture Developments in Sundarbans*:* An Initiative in Bali Island

10.3.1 Quality Fish Seed Production

Fish seeds are generally not available locally in good quality and quantity in the eco-region. This is the primary requirement for fish culture, and thus seed production was possible after the development of induced breeding technology of Indian major carps in 1957. There was no carp hatchery for fish seed production in Sundarbans deltaic island. In the year 2013, ICAR-CIFA took an initiative for installation of Fiber Reinforced Plastic (FRP) carp hatchery at the campus of Bali Nature and Wildlife Conservation Society in Bali Island. It was composed of 3 units: breeding/ spawning pool, egg/spawn collection tank, and spawning pool. The spawning pool is cylindro-vertical in shape having 2.15 m diameter, 0.9 m height, 1:22 bottom slope, and can hold 3409 litre water though operational capacity is 2950 litre with the system of water circulation and shower facility. During operation, water supply comes from an overhead tank placed at a height of 2 m from the hatchery floor for providing water circulation inside the pool through 5 numbers of 15 mm diameter rigid PVC elbows caring nipples fitted in the same direction at the floor. There is one single point 25 mm diameter water inlet also fitted at the side wall of the pool bottom. For regulation of water flow, all the water inlet pipes are interconnected and fitted with individual full-way valves. At the top of the pool one shower is provided for better aeration. Egg/spawn collection tanks have rectangular size of $1 \times 0.5 \times 0.5$ m and have water holding capacity of 250 litres. During operation the water level in the tank is maintained at a height of 0.45 m (water volume 225 litres) by fixing a drain pipe of 63 mm at a distance of 38.7 cm from the base. Cotton inner *hapa* having tank size is used inside the collection tank to collect egg/spawn from the breeding and hatching pool. Another part, i.e. hatching/incubation pool is of 1.4 m in diameter and 0.98 m in height having 1400 litre total volume and 1200 litre net egg incubation volume. It has 2 chambers: inner chamber (0.4 m diameter and 90 cm height covered with nylon bolting cloth of 0.25 mm mesh to filter excess water into the drain), six numbers of 15 mm diameter duck-mouth for water supply fitted at the bottom of the hatchery at 45^0 angle. There are two drainage outputs: at the centre and the base of the outer chamber of the pool. The flow rate in the pool during operation

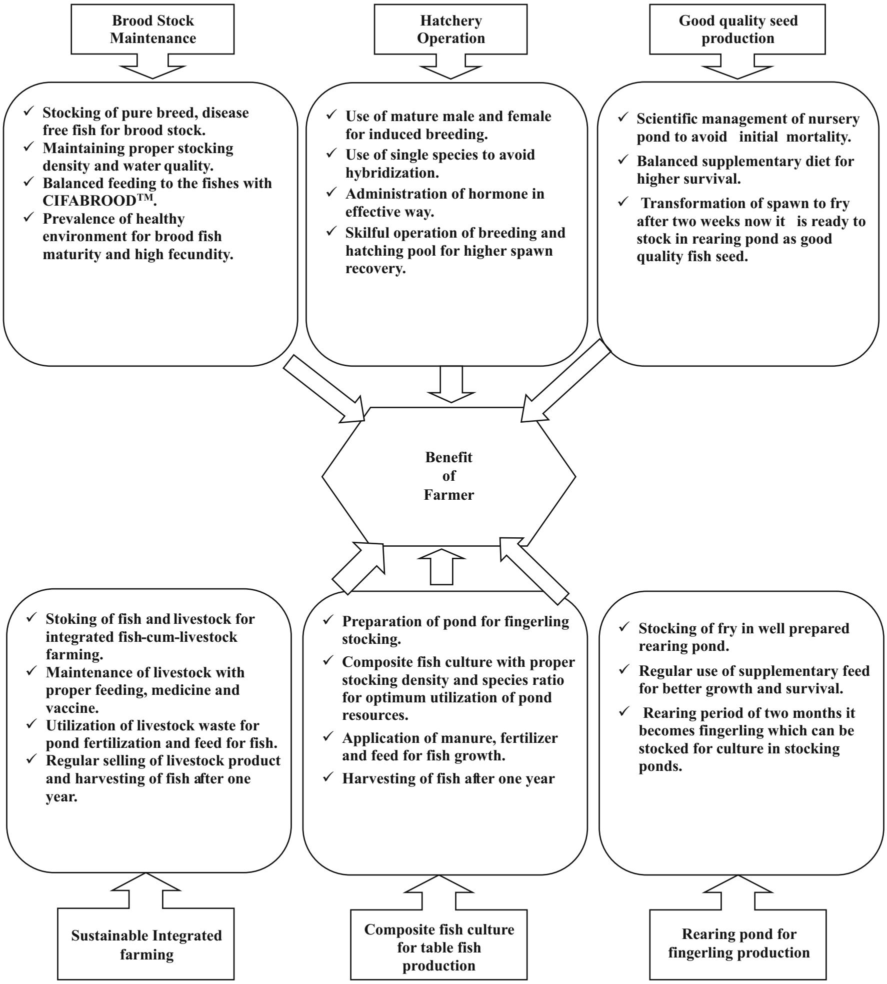

Fig. 10.5 FRP carp hatchery at Bali island: different functions and uses

is maintained at 0.3–0.4 l s^{-1} (Chakrabarti et al. 2016). Different functions and uses of FRP carp hatchery operation at Bali island are shown in Fig. 10.5.

In the year of 2013, FRP hatchery came into operation, location of which is shown in Fig. 10.6, where induced breeding of rohu (*L. rohita*) was undertaken and about 0.45 million spawn were produced from which around 0.1 million fingerlings were also produced. Breeding activity is shown in Fig. 10.7. In later phases, induced breeding of Indian major carps like catla and mrigal and medium carp like bata were also demonstrated and in 5 years (2013–2017) total 3.8 million spawn were produced (Fig. 10.8). Fish seeds produced in the hatchery were supplied to different parts of Bali Island of Sundarbans for grow-out culture. Later, 2015 onwards, the Department of Forest, Govt. of West Bengal has also started demonstration in

Fig. 10.6 Location of FRP carp hatchery at Bali Island. (Courtesy: Google Map 2017)

Fig. 10.7 Breeding activity using FRP hatchery at Bali Island

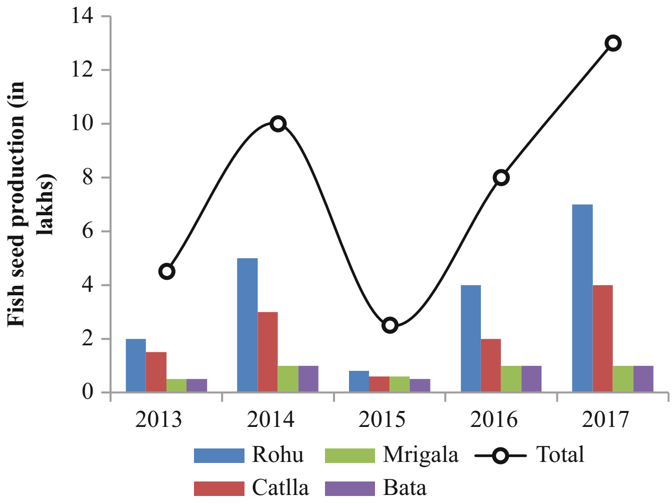

Fig. 10.8 Year-wise fish seed production at Bali Island

different islands like Pakhiralaya, Sajnekhali, Goasaba, etc. Under the guidance of ICAR-CIFA, presently fry and fingerling production of major and minor carps in Chunakhali, Basanti Block is in progress and many farmers also adopting the technolgies for aquaculture development of different remote islands of Sundarbans.

10.3.2 Grow-Out Fish Culture

Fish culture in Sundarbans region is mainly based on small backyard pond 0.02–0.10 ha size for household consumption. Three Indian major carps, namely rohu, catla and mrigal, contribute bulk of the production in this area, whereas the exotic carps such as silver carp, common carp, and grass carp, bighead carp form the second important group. Several other medium and minor carps are also cultured because of their region- specific demand like bata (*L. bata*), Java barb (*B. gonionotus*), calbasu (*L. calbasu*), etc. In recent years some people have started farming of pacu (*Piaractus brachypomus*) and pangas (*Pangasianodon hypophthalmus*) along with the other fishes. Few farmers also have started culture of monosex tilapia, *O. niloticus* (popular as Nilontica) both in monoculture and polyculture. Additionally, Punti *(Puntius* sp.*), C. magur, H. fossilis, A. testudineus, C. marulius, C. striata, C. punctata, Chitala chitala, N. notopterus* and *A. mola* are also the components of aquaculture which are produced naturally in this area but the continuous decrease of these species is a major concern. *Lates calcerifer, Liza parsia, Mystus gulio, Liza tade* are very common among brackish water fishes, and *M. rosenbergii,* the freshwater giant prawn is cultured in almost all ponds along with the freshwater finfishes.

10.3.3 Composite Fish Culture

Composite fish culture practice in Sundarbans is mainly non-scientific culture with very low production of below 1000 kg $ha^{-1}y^{-1}$ except in some places where farmers are trained through ICAR-CIFA and in some demonstrated ponds, where fish production has reached more than 4000 kg $ha^{-1}y^{-1}$ (Chakrabarti et al. 2016). The average depth of ponds in most of the areas varies from 2.5 to 4 meter and ponds are mainly fed with rainwater but without any inlet-outlet facility. The stocking density and species combination also vary widely. In a gross view the stocking density ranges from 20,000 to 30,000 numbers per ha though the culture practice is devoid of any supplementary fish feed or present in very negligible amount. Stocking of three Indian major carps in combination with other species followed in the region are (i) IMCs- rohu, catla, mrigal and exotic carps- silver carp, grass carp, common carp, (ii) IMCs, medium & minor carps- *L. bata*, *B. gonionotus*, *L. calbasu*, (iii) IMCs & other exotic sp.- *P. brachypomus*, *P. hypophthalmus*, *O. niloticus*, (iv) IMCs, exotic carps, *B. gonionotus*, *O. niloticus*, (v) brackish water fishes- *Lates calcarifer*, *Liza parsia*, *Mugil cephalus*, *Etroplus suratensis*, and (vi) IMCs & brackish water fishes- *Lates calcarifer*, *Liza parsia*, *Mugil cephalus*. With all this fish species combination *M. rosenbergii* are stocked in various stocking densities starting from 500 to 20,000 per ha. In case of *M. rosenbergii* it is seen that 2 types of culture practice are followed. Initially, post-larvae of 15–30 day-old are caught from the river and creeks, managed in a very small nursery pond (25–50 m^2) up to 2–3 months, and then they are released into culture pond. Fish seed of brackish water fishes are collected from river by the local people and released into the pond for further culture.

In the Sundarbans area, farmers do not practise nursery rearing separately and use the grow-out ponds for growing spawn/fry size fish to table size. Such type of culture (culturing all stages of fish – fry, fingerlings, juveniles and sub-adults) in the same pond probably is a unique characteristic of West Bengal polyculture. So, fish mortality is very common to all the parts after stocking of fish. During the last week of May (just before onset of monsoon), up to the month of October fish stocking occurs in various phases depending upon the availability of seed, and the year-round calendar on freshwater fish culture is shown in Fig. 10.9. Generally, it is noticed that, almost all farmers stock their seeds 2–4 times in a season depending upon availability of water in ponds, fish mortality and desired fish species, though the size varies from fry to advanced fingerlings. But, in maximum cases, no pre-stocking management is followed though the pond naturally dries-up during the summer season or maintains very little amount of water in it.

Pond management in Sundarbans area is totally a negligible phenomenon throughout the year as in most of the cases application of organic manure, use of chemical fertilizer and liming is not done. Occasional use of limestone ($CaCO_3$) 2–3

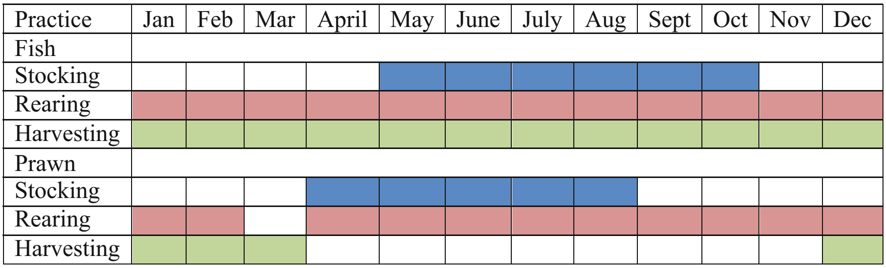

Fig. 10.9 Calendar of freshwater fish culture activity of Sundarbans

times in a year without calculating the area and water availability in the pond is a very common practice. During the last few years because of the involvement of ICAR-CIFA and other institutions in different places of Sundarbans region, fish pond management for scientific aquaculture practice came into existence through demonstration of composite fish culture and training to the farmers in village and block level. In Bali Island under Gosaba block, demonstration of 13 units of composite fish culture covering total area of 1.3 ha revealed total fish production of 5.966 tonnes during the year 2013–2014 (Chakrabarti et al. 2017).

10.3.4 Integrated Fish Farming

The integration of fish farming with agriculture and animal husbandry is very popular in Sundarbans areas and it is considered as sustainable farming system, which delivers greater efficiency in utilization of resources, minimizes risk by diversifying crop, and provides food security and additional income generation for marginal and small-scale farming people of the region.

The most popular integrated fish farming in Sundarbans area is paddy-cum-fish culture and livestock-cum-fish culture. In paddy-fish integration, paddy fields retain water for 3–6 months in a year. The culture of selected species of fish in field which remains waterlogged even after the harvest of paddy crop (Fig. 10.10) provides an opportunity to grow fish and provide off-season occupation for farmer with additional income. In many cases, digging of peripheral trenches and sometime within the paddy field, construction of dykes, sowing of improved varieties of rice like Ratna, Masuri, IR-30, CR-1080, IR-24 and other indigenous variety along with release of selected fish like rohu, common carp and mrigal are generally used. Fish seeds are stocked in paddy- cum-fish culture field during the month of June–July and harvested during the month of November–December. During this period of time the fishes become 200–300 g in size and used for consumption or sometimes released into the pond for further development in culture pond. In some areas of Sundarbans land shaping is becoming an effective model for paddy-cum-fish culture. Trenches of about 3 m width × 1.5 m depth is dug around the field with a ditch of

Fig. 10.10 A view of paddy-cum-fish culture

6 m × 6 m × 3 m (depth) at corner. The excavated soil is used for making pond dykes 3 m width and 1.5 m height to protect the fishes from the paddy field (Dagar et al. 2016). This dyke is used for the production of vegetable/fruit. Due to creation of different land situations and round the year crop cultivation, organic C, available N, P and K, and biological activities in surface soil are improved under this culture practice following land shaping.

As a part of the practice, application of livestock excreta as manure in cropped fields is common but in case of aquaculture it is usually ignored in most of the traditional cases for the lack of knowledge. Removal of sediments from old ponds and application of the same in the aquaculture ponds can be treated as organic fertilizer application and thereby minimising the cost of external fertilizer application. Apart from the nutrient management practice, farmers should be trained on farming of high yielding varieties of poultry bird and duck for both meat and egg purposes for higher output and income. Awareness about the vaccination, disease diagnosis and medicine application of the livestock would help them to prevent mass mortality throughout the year. Proper integrated farming will not only help them in effective nutrient management and economic development but also help to reach one step ahead towards the sustainable development in this ecologically constrained site.

During the year 2013–2014, ICAR-CIFA has demonstrated 38 units of duck-cum-fish integrated farming; a typical duck house on fish pond in the same island is shown in Fig. 10.11. In Bali Island, a total production of 13.947 tonnes fish, 77,037 eggs and 1415 kg duck meat from 2.96 ha water area was produced with mean net return of Rs.36,739 per unit. For a typical tribal family of average 5 members, the demonstration offered 67% alternative livelihood through fish-duck farming technology (Chakrabarti et al. 2017). The mean cost-benefit ratio reduced to 1.86, given in Table 10.4. This is due to addition of netting charge and contingency money for

Fig. 10.11 Duck house on fish pond as a part of integrated farming at Adibasipara, Bali, Sundarbans

calculation of true economics which were not accounted in the paper authored by Chakrabarti et al. 2017 as this part was managed by the beneficiary farmer.

A typical comparison of economics under composite fish culture and integrated duck-cum-fish farming from 0.1 ha area demonstrated in Bali Island is shown in Table 10.4.

10.4 Social Implication: Gender Upliftment through Aquaculture

In Sundarbans, a major part of rural population is inhabited by Scheduled Caste (SC) and Scheduled Tribe (ST) communities, considered to be lower in the hierarchy of social structure, a mere superstition. Like other parts of India, the SC/ST population of this delta are also associated with lot of social and economical problems with poor literacy and high drop-out rates at schools. Hence, large number of the population is incapable to move beyond the primary sector and has complete dependence on nature and natural resources. Presence of brackish water rivers, mudflats, saltpans and poor soils coupled with severe cyclonic storm make the lands barren for a time. All these reduce agricultural production and explain why population increase results in great poverty. It is a fact that the young man and woman are migrating from these islands to different parts of India to act as agriculture labour or non-agricultural work like civil construction and allied activities. The rest are here for fishing mainly from rivers and creeks. Sundarbans is one place where the term "fisherman" can often mislead. Here a substantial proportion of

Table 10.4 Economics of composite fish culture and Integrated duck-cum-fish farming in Bali Island (unit water area = 0.1 ha)

Item	Composite fish culture	Integrated duck-cum fish farming
Expenditure (in Indian Rupees)		
Seed	2800	2800
Fish feed @`18 kg^{-1}	7500	7500
Net and hundi	2500	2500
Lime	350	350
Duckling 30 numbers @`25 duckling^{-1}	0	750
Duck feed @`25 kg^{-1}	0	2000
Shade	0	5200
Tray	0	400
Transportation cost		
Fish seed and feed	650	650
Duckling and duck feed	0	500
Netting charge	750	1000
Contingency money	750	1200
Total expenditure	**15,300**	**24,850**
Income (in Indian Rupees)		
Selling of fish 400 kg @`110.00 kg^{-1}	49,500	49,500
Eggs 2600 nos. @`5.00 piece^{-1}	0	13,000
Meat 50 kg @`170.00 kg^{-1}	0	8500
Gross income	**49,500**	**71,000**
Net return (in Indian Rupees)	**34,200**	**46,150**
B/C ratio	**2.24**	**1.86**

fishers are women and they are engaged in professional fishing. Moreover, quite often the woman is a boat-fisher in her own right. Women go to the forest in the core (protected) area also. There also they might go as an all-woman team of two or three. It is, however, not usual for a woman to stay the night in the deep forest. However, occasionally fishing team using *khalpata jal* (channel stake nets) in the deep forest might include married couples. Such a team might stay a night or two in the forest (Chacraverti 2014). Generally, net like *galsha* (floating gillnet, also known as current net and anchored gillnet), *behundi* (bagnet), *berjaal* (Drag Shore Seine), *chawrpata* (Shore stake nets), *khyapla* or *khyaola* (throw net) are used depending on the place of river, fish size, fish type, etc. Lacking a boat or net, women in the Sundarbans often simply get down in the local creeks with a *hundi,* and catch fish with their hands, or with a small bag net, or get into the local river. Women with different fishing nets are shown in Fig. 10.12. The cheapest, yet profitable, low-investment fishing is catching *bagda* (black tiger prawn, *Penaeus monodon*) seeds in the rivers (Chacraverti 2014). That is why thousands of women risk their lives and health, wading chest deep in the Sundarbans waters, and earn their

Fig. 10.12 Women with different types of fishing net

livelihood. Not only women, but men, old and young, try, if nothing else, to supplement their income by stepping into the river for *bagda* seeds.

However, the numbers of fisher women have dwindled in the last few years as, on the one hand, the catch has declined and, on the other, the hatcheries have conquered the market. In this scenario, intervention of Indian Council of Agricultural Research (ICAR) has shown a new horizon when ICAR-CIFA started intervention at Bali Island through involving the local women in aquaculture and integrated farming. Through continuous training to the local men and women about freshwater aquaculture, pond management and integrated aquaculture, and demonstration of technologies (Fig. 10.13), the people have started to utilize their small pond and integrated farming have made them successful towards the sustainability. Still, there are so many places where aquaculture technologies should be spread which will help the islanders self-dependent in terms of food security.

10.5 Conclusions

The Sundarbans mangrove forest is highly diverse and a productive ecological community in the world. It provides a wide range of important ecosystem services including food and water supply for millions of its inhabitants, protection against severe natural calamities, acting as a giant long term carbon sink, habitat of many animal and plant species, and supporting the livelihood of human settlement over the period of time. During the last two-and-a-half centuries, the Sundarbans mangrove

Fig. 10.13 Local people with harvested fish from pond and ICAR-CIFA officials

ecosystem has been affected by human impact, climate change, and consequently, the extreme weather events. Anthropogenic activities in the inhabited part of Sundarbans have a greater incremental impact on mangrove forests, salinity increase, and land loss (Ghosh et al. 2015). It is found that direct anthropogenic pressure on this strictly protected forest comes from the extraction of goods and enlarging arable land (Das Gupta and Shaw 2013).

However, this situation was not created in a single day or in particular one season. Excessive dependence on natural resource like river fish, honey, fuel wood, timber from forest, and above all poaching of wild animals, has resulted in irreversible impact on the entire mangrove area of Sundarbans region. This is why it is important to reconfigure developmental plans by including local requirements and approach the problem through a multi-scalar and polycentric manner, instead of looking at conservation and climate change adaptation separately. Here agriculture can play a vital role though most people have insufficient land, and even equitable land distribution will not help since the total amount of arable land available is not sufficient for supporting the bulk of the population. Hence, the issue of alternative employment for those directly dependent on natural produce needs to be addressed on a war-footing.

During the last 5 years ICAR-CIFA is trying to find out the loopholes or trying to mitigate the problems through aquaculture rather than river fishing. In Sundarbans, this is essential for interdisciplinary collaboration between natural and social scientists to develop policies addressing conservation and climate change adaptation. ICAR-CIFA has initiated to form a blueprint through its initiative by adopting local SC/ST people, NGOs, and Co-operative Societies for development of alternative livelihood options through sustainable aquaculture, integrated farming, incorporation of improved breed of duck and poultry, along with human resource development activity, through training in village and at block level. Other national institutes of ICAR have also become very much concerned and their initiative is making this heritage back to its original glory giving indication through reduced poaching, increase in aquaculture production in different pockets of islands, and participation of women in aquaculture activity. The West Bengal government recently announced a number of developmental measures for the Sundarbans including ecotourism infrastructure (Danda 2007) and also promoting ICAR-CIFA-developed technologies in different part of Sundarbans area. Multiplication of the initiatives in different islands through different government agencies, NGOs, private level, small and marginal investors, etc. can improve the situation, whereas authorities should take lead role to examine and oversee the progress to ensure sustainability in future course.

Rainwater harvesting to get freshwater for multipurpose use like fish farming and integrating with livestock and crop production, land shaping, reclamation and re-excavation of sweet water sources including step-cutting or terracing on inward-slopes of the ponds, linkage between the fisheries output and effective marketing/processing, and moreover development of alternative climate adaptive livelihood options for the fish farmers, which will match to their skill and capacity, should be developed. The risky job of river fishing and crab collection has formed widow village and still it is continuing in form of tiger and crocodile attack in the deep forest area due to human-wild conflict in core forest area. Awareness among the farmers through continuous training, technology demonstration and development of alternative climate adaptive livelihood options for the fish farmers will help in meeting the food security and sustainable development of Sundarbans aquaculture.

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Coastal fishing boats (Courtesy Ratul Saha)

Chapter 11
Brackishwater Aquaculture: Opportunities and Challenges for Meeting Livelihood Demand in Indian Sundarbans

T. K. Ghoshal, Debasis De, G. Biswas, Prem Kumar, and K. K. Vijayan

Abstract Brackishwater farming in India has been a traditional practice for centuries and confined mainly to the *bheries* (manmade impoundments in coastal wetlands) in Sundarbans, West Bengal, India. Scientific brackishwater aquaculture started in India with tiger shrimp (*Penaeus monodon*) farming initiated during early 1990s. With the introduction of Pacific white shrimp (*Penaeus vannamei*) during 2009, Indian aquaculture industry has grown rapidly. In addition, certain marine/ brackishwater fish such as, seabass, mullets, milkfish and pearlspot have shown a lot of promise. Successful domestication of indigenous Indian white shrimp (*Penaeus indicus*) and experimental farming using hatchery–produced seed by ICAR–Central Institute of Brackishwater Aquaculture (CIBA) showed encouraging results. Besides domestic consumption, fishery products exported from the state were 1.05 million tons of value Indian rupee (INR) 33,4420 million during 2015–16. Indian Sundarbans located in the south–east end of West Bengal offers congenial environment for growth of variety of fishes and shrimps. Frozen shrimp and live crab are the main export items from brackishwater aquaculture in Sundarbans. As the economic benefit is greater, there is a tendency of Sundarbans dwellers to shift from fishing to aquaculture for better livelihood. There is vast scope for sustainable development of brackishwater aquaculture in Sundarbans to meet the livelihood demand utilizing the unused and underused areas and adopting advanced farming practices. Challenges faced by Sundarbans aquafarmers need to be tackled by appropriate management tools like social mobilization of aqua producers, technology assessment and refinement, participatory planning, and capacity building of key stakeholders.

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Keywords Sundarbans · Brackishwater aquaculture · Technology development · Biosecurity measures · Species diversification · Sustainable development · Livelihood · Opportunities · Challenges

11.1 Introduction

The greatest challenge India faces is to ensure food security of the largely undernourished protein-starved population, especially in the context of declining land resources available for agriculture and animal husbandry. Hence fisheries, mainly aquaculture sector, would have to emerge as the savior to meet increased food demand. Carp in freshwater and shrimps in brackishwater form the major areas of activity in Indian aquaculture. Brackishwater farming in India is an age-old traditional system confined mainly to the *bheries* (manmade impoundments in coastal wetlands) of West Bengal, similar to *gheris* in Odisha, *pokkali* (salt resistant deep water paddy) fields in Kerala, *kharlands* in Karnataka and Maharashtra, and *khazans* in Goa coasts (Alagarswami 1981). These systems have been sustaining production of 500–750 kg ha^{-1} year^{-1} with shrimp contributing 20–25% without additional input, except that of trapping the naturally bred juvenile fish and shrimp seed during tidal influx (FAO 2014).

Scientific farm management in brackishwater sector in India initiated during early 1990s concentrated around the giant tiger shrimp (*Penaeus monodon*), which witnessed a phenomenal increase during 1990–1994, and the bust came in 1995–1996 with the outbreak of viral disease. Later, with the advent of bio-secured closed culture technology (Panigrahi et al. 2009) using better management practices, semi-intensive shrimp farming started to regain its lost glory during early years of last decade. Apart from the giant tiger shrimp, certain marine/ brackishwater fishes such as seabass, mullets, milkfish, catfish and pearlspot have shown a lot of promise for commercial aquaculture. Since 2009, the culture of exotic white-leg shrimp, *Penaeus vannamei*, has attracted the farmers' attention because of its fast growth, low incidence of native diseases, availability of Specific Pathogen Free (SPF) domesticated strains, and culture feasibility in wide salinity range. Recently, ICAR-Central Institute of Brackishwater Aquaculture (CIBA) has been successful in domestication of indigenous Indian white shrimp, *Penaeus indicus*, and experimental farming using hatchery-produced seed showed promising result. Seabass farming was popularized by ICAR-CIBA through culture demonstration of seabass in different coastal states of India. India produced 4.88 million tons of aquatic animals through aquaculture during 2014, ranking second in the world only after China, while total fisheries production was 9.6 million tons (FAO 2016).

Indian Sundarbans located in the lower Gangetic region of the sub-continent at the apex of Bay of Bengal (within latitude 21°13′ N–22°40′ N and longitude 88°03′ E–89°07′ E), covering little less than half of the total Sundarbans, offers a congenial environment in terms of salinity and other hydrological parameters for the growth and culture of variety of fishes. This region is intersected by a complex network of tidal waterways, mudflats, and small islands of salt-tolerant mangrove forests, and presents an excellent example of ongoing ecological processes, which is vulnerable to environmental alterations. In this coastal region, there are a large number of poor marine fishermen who primarily depend on the Hooghly-Matla estuarine complex and the adjacent sea for their livelihood. As the economic benefit is greater than that in traditional fishing, there is a tendency to shift from fishing to aquaculture. In tune with the Indian trend, aquafarmers of Indian Sundarbans has adopted scientific brackishwater farming with remarkable success which has become an important tool for increasing livelihood security in such a vulnerable eco-region. There is vast scope for sustainable development of brackishwater aquaculture in Sundarbans to meet the livelihood demand utilizing the unused and underused areas and adopting advanced farming practices. Challenges faced by Sundarbans aquafarmers need to be tackled by appropriate management tools like social mobilization of aqua producers, technology assessment and refinement, participatory planning, and capacity building of key stakeholders, which are being discussed in this article.

11.2 Area, Production and Productivity

In India, about 13% of 1.24 million ha potential brackishwater resource is under use at present. Farmed tiger shrimp production recorded over fivefold increase from 28,000 tons in 1988–89 to 144,347 tons utilizing 149,632 ha in 2006–2007 (MPEDA 2017), and was operating at around 100,000 tons tiger shrimp till introduction of white leg shrimp during 2009. Afterwards, a shift towards white leg shrimp from tiger shrimp was observed over recent years (Fig. 11.1). In this process,

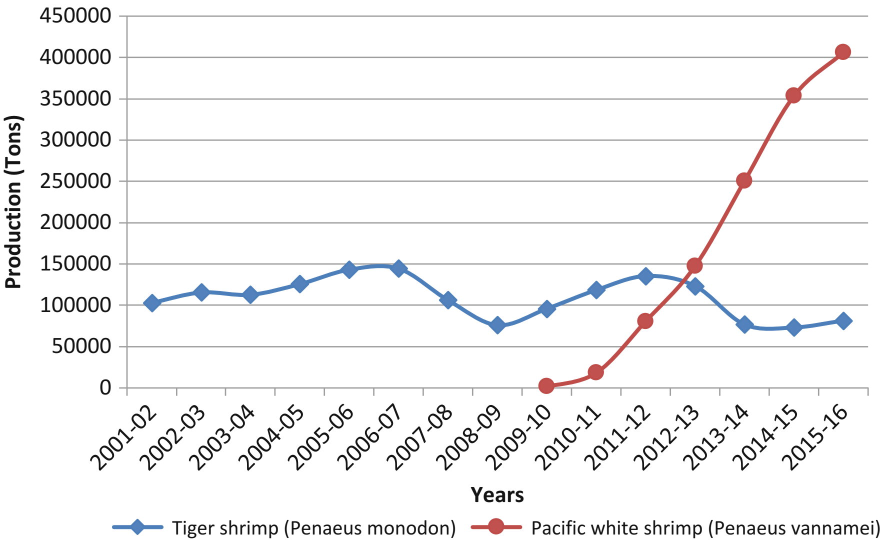

Fig. 11.1 Shrimp production trends in India over last 15 years. (Source: MPEDA 2017)

tiger shrimp production was reduced to 81,450 tons utilizing 68,846 ha with productivity of 1.18 tons ha^{-1} $year^{-1}$, while production of white leg shrimp reached all-time high of 406,018 tons utilizing area of 59,116 ha with productivity of 6.87 tons ha^{-1} $year^{-1}$ during 2015–2016 (MPEDA 2017).

Total fish production in West Bengal during 2015–2016 was 1.67 million tons of which 0.12 million ton was contributed by shrimp (DoFWB 2016). West Bengal being the largest producer of tiger shrimp among Indian maritime states produced 61,998 tons of tiger shrimp utilizing 50,593 ha during 2015–2016, and majority of this was produced in Indian Sundarbans covering two maritime districts (South and North 24 Parganas) occupying most of the 0.21 million ha potential brackishwater areas in the state. The age-old traditional farming methods of shrimp and finfish with some modification still exist because of their simplicity and cheapness. A part of these are being gradually replaced by modern improved culture practices.

Brackishwater farmers of West Bengal started adopting white leg shrimp farming late compared to other Indian maritime states. First, white leg shrimp farming demonstration in West Bengal was carried out by ICAR-CIBA, Kakdwip Research Centre, Kakdwip during 2012, and farmers started to adopt its farming since 2013 replacing tiger shrimp. White leg shrimp production in West Bengal during 2015–16 was 6776 tons utilizing 1387 ha area with productivity of 4.88 tons ha^{-1} $year^{-1}$. A comparative trend of tiger shrimp and white leg shrimp production in West Bengal is presented in Fig. 11.2.

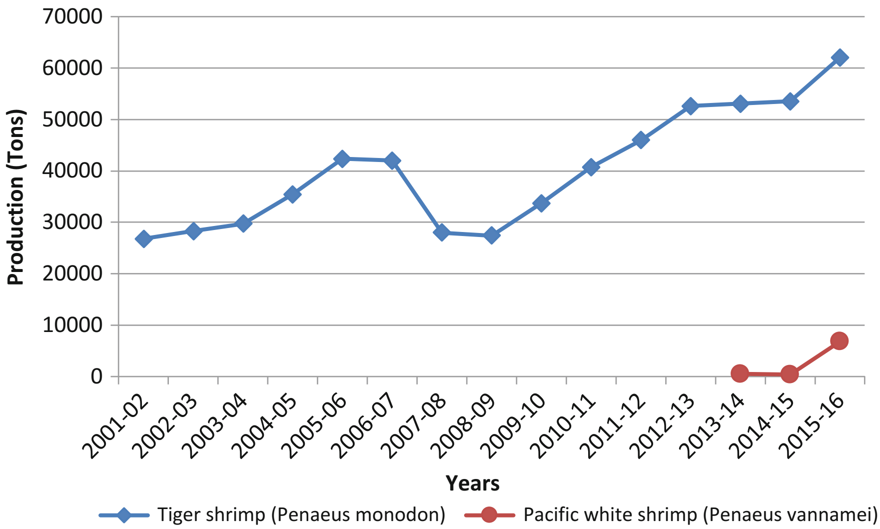

Fig. 11.2 Shrimp production trends in West Bengal over last 15 years. (Source: MPEDA 2017)

11.3 Contribution of the Sector to the Indian Economy

India has shown continuous and sustained increments in fish production since independence. Constituting about 6.3% of the global fish production, the sector contributes 1.1% of the GDP and 5.15% of the agricultural GDP of India. The total fish production of 10.07 million metric tons during 2015–2016 had nearly 65% contribution from the inland sector of which major share came from culture fisheries (NFDB 2017). There are 429 Fish Farmers Development Agencies (FFDAs) and 39 Brackishwater Fish Farmers Development Agencies (BFDAs) in India for promoting freshwater and coastal aquaculture. The annual carp seed production is to the tune of 25 billion and that of shrimp about 12 billion, with increasing diversification in the recent past. Fish and fish products have presently emerged as the largest group in agricultural exports of India with 1.05 million tons in term of quantity and INR 33,4420 million in value during 2015–16. This accounts for around 10% of the total exports of the country and nearly 20% of the agricultural exports. More than 50 different types of fish and shellfish products are exported to 75 countries around the world (NFDB 2017).

Fisheries sector of West Bengal contributed 2.35% of Net State Domestic Products (NSDP) during 2014–15 which is much higher than contribution of the sector in Indian GDP indicating its importance to the state's economy (DoFWB 2016). Besides domestic consumption, fishery products exported from the state was 91,263 tons of value Rs. 34,390 million during 2015–16. Frozen shrimp and live crab are the main export items from brackishwater aquaculture in Sundarbans.

11.4 Advances in Brackishwater Aquaculture Technologies

There are five different brackishwater aquaculture practices mentioned in the literature, ranging from traditional to super-intensive (Shiva and Karir 1997; Primavera 1998; Rosenberry 1999). Most common practices followed in Sundarbans are traditional, extensive, semi-intensive, and intensive. These are divided according to stocking densities and the extent of management, i.e. level of inputs (Table 11.1), which turns out into different economic outcomes (Table 11.2).

Traditional systems are often characterised by polyculture of shrimp and fish or by rotation with rice. In this method, low-lying areas near the banks of saline water rivers and creeks are encircled by peripheral dyke, and tidal water is allowed to enter into the impoundment along with natural seeds of various species of shrimps, crabs and fishes. Water is retained with periodical exchanges during lunar cycles and the animals are allowed to grow utilizing natural food. After 3–4 months, partial harvesting starts using tidal inflow during lunar cycles and continues up to 10–-11 months. Productivity in this system ranged between 500–750 kg ha^{-1} year^{-1} of which about 30% is constituted by prawns/ shrimps and 70% by other brackishwater fishes.

Table 11.1 Farming practices based on level of management, stocking density and production

Parameters	Traditional	Extensive	Semi-intensive	Intensive
Pond size (ha)	0.1–50	1–10	0.2–2	0.1–1
Stocking	Natural	Natural + artificial	Artificial	Artificial
Stocking density (seed m^{-2})	Unregulated	2–6	6–20	20–50
Seed source	Wild	Wild + Hatchery	Hatchery	Hatchery
Annual production (t ha^{-1} yr^{-1})	< 0.6	0.6–1.5	2–6	7–15
Feed source	Natural	Natural	Natural + Formulated	Formulated
Fertilizers	No	Yes	Yes	Yes
Water exchange	Tidal	Tidal+ pumping	Pumping	Pumping
Aeration	No	No	Yes	Yes
Diversity of crops	Polyculture	Monoculture, polyculture rarely	Monoculture	Monoculture
Disease problems	Rare	Rare	Moderate to frequent	Frequent
Employment (persons ha^{-1})	1–2	2–3	3–4	4–5

Source: In-house data

Table 11.2 Comparative economics of different brackishwater farming practices for 1 ha water area. Amounts are in INR (100 INR = 1.56 US $)

Particulars	Traditional	Extensive	Semi-intensive	Intensive
Lease rent	30,000	30,000	45,000	45,000
Earth work	20,000	30,000	40,000	50,000
Water filling	–	10,000	20,000	20,000
Bleaching powder	–	–	12,000	12,000
Lime	8000	20,000	40,000	40,000
Organic fertilizers	8000	18,000	26,000	26,000
Probiotics	–	–	65,000	120,000
Seed	40,000	75,000	120,000	300,000
Feed	–	100,000	540,000	1,040,000
Fuel	–	30,000	160,000	280,000
Manpower	120,000	200,000	280,000	360,000
Harvest and marketing	10,000	15,000	20,000	25,000
Total expenditure	236,000	528,000	1,368,000	2,318,000
Gross return	390,000	810,000	1,800,000	2,880,000
Net return	154,000	282,000	432,000	562,000
Benefit cost ratio	1.65	1.53	1.32	1.24

Source: In-house data

The extensive farming is commonly known as improved traditional farming, which relies on the tides to provide most of the food for the shrimp and as a means of water exchange. Feed for shrimp is naturally occurring, and in some cases fertilizers or manure is added to promote algal growth. Low stocking densities result in modest yields. This system involves construction of peripheral canals/ ponds of size ranging from 1 to 5 ha. Shrimp seed at the rate of 15,000–20,000 per ha are stocked. The average yield is 1500–1700 kg ha^{-1}, including finfishes. Supplementary feeding is not generally practised; however, some farmers use oilcakes and rice bran as supplementary feed.

Semi-intensive cultivation involves stocking densities beyond those that the natural environment can sustain without additional inputs. Consequently, these systems depend on reliable shrimp post larvae (PL) supply and greater management intervention compared to extensive ponds. With stocking rates of 6–20 shrimp PL per m^2, fertilizers are applied to augment natural food in the ponds. Supplementary feeding is done using formulated feeds preferably in pelletized form. Maximum annual yields range from 2 to 6 tons per hectare. The risk of crop failure increases with increasing farming intensity, which is mainly due to the impact on water quality exerted by the high stocking densities and supplementary feeding. The higher the culture intensity, the higher the capital required, and higher the risks involved. Thus, the increased capital inputs required for semi-intensive culture often preclude its adoption by small-scale producers. Most of the tiger shrimp monoculture is carried out in this system.

Intensive grow-out systems utilize ample supplies of clean sea/ estuarine water, adequate infrastructure, and well-developed hatchery and feed industries. Intensive shrimp farming introduces small enclosures (down to 0.1 ha), high stocking densities (20–50 hatchery-produced shrimps per m^2), around-the-clock management, very high inputs of formulated feeds, and aeration. Yields range from 7 to 15 tons ha^{-1} $year^{-1}$ with high risk of crop failure due to diseases. Most of the *P. vannamei* farming is conducted in this method using specific pathogen free (SPF) seeds under strict biosecurity protocol.

11.4.1 Scientific Shrimp Farming Practices Followed in Indian Sundarbans

11.4.1.1 Site Selection

The site is selected only after thorough analysis of information on topography, ecosystem, meteorological, socioeconomic conditions, and economic viability. Coastal sites with gentle slopes towards the sea are selected requiring less financial inputs. Clay loam or silty clay loam soil is preferred (CIBA 2004). Site should be easily accessible with availability of basic needs and not within coastal regulation zone (CRZ) following Coastal Aquaculture Authority of India (CAA) guidelines.

Fig. 11.3 A typical shrimp farm design in Sundarbans. (Courtesy: Authors)

11.4.1.2 Farm Design and Construction

Proper designing and construction of farms are essential for efficient management and for promoting environmental protection. A typical shrimp farm is shown in Fig. 11.3. The height of peripheral dyke is built in accordance with highest flood level. Height of the pond dyke should be at least 2 m with side slope of 1:1 for clayey soil and 3:1 for sandy soil (CIBA 2004). Rectangular or square ponds are appropriate. A reservoir pond is required to act as settlement pond. Effluent treatment pond (ETP) becomes an essential part of a semi-intensive farm.

11.4.1.3 Pond Preparation

Good pond preparation is the key to reduce disease risks and improving shrimp production. Presence of black soil in pond bottom is checked in wet condition. Black soil may be removed either using mud pumps in wet condition or manual labor after drying. Optimum average soil pH should be 6.5–7.5. Lower soil pH may be corrected applying lime. Soon after pH correction, ponds are filled with optimum quality water up to a depth of 120–150 cm after screening through 60–80 mesh net. Water is retained for 3 days with aeration for 1–3 h daily. Aerators are positioned properly to achieve maximum water circulation. Every 500 kg production beyond 2000 kg ha^{-1} requires minimum 1 KW aeration power (Boyd 1998). Pond is disinfected by applying bleaching powder @ 60 ppm (20 ppm chlorine) during late evening. After 5 days, dolomite @ 100–200 kg ha^{-1} and organic juice @ 200 litre ha^{-1} on the following day are applied to stimulate plankton bloom. This schedule is repeated three times at a gap of 3 days. Organic juice is prepared by mixing 60 kg paddy flour, 20 kg molasses and 3 kg yeast in 200 L freshwater ha^{-1}, and incubated for 48 h in air tight condition (Panigrahi et al. 2009). When the color

Fig. 11.4 A typical view of the biosecured shrimp pond in Sundarbans. (Courtesy: Authors)

of the water is green, fluctuation between morning (6:00 AM) and late afternoon (3:00 PM) pH is below 0.5 and other parameters in optimum range, the pond is ready for stocking.

11.4.1.4 Biosecurity Measures

Biosecurity measures are of immense importance in shrimp farming to protect the stock from diseases. Farm should be protected with bird and crab fencing (CIBA 2010a). A typical biosecured shrimp pond is shown in Fig. 11.4. Proper hand and foot wash in potassium permanganate solution is mandatory before entering the farm. Every pond should have separate implements. Water depth more than 120 cm in the pond reduces stress and risks of diseases. Farming in closed ponds i.e., '0 exchange' restricts entry of pathogen and carriers of diseases. All implements are washed in chlorinated water before first use. Proper understanding of the personals on biosecurity measures is most important.

11.4.1.5 Stocking

Selection of good quality PL for stocking is an important criterion. Good quality seeds are characterized by uniform size, intact appendages, healthy appearance and active movement. Further, seeds which tested negative for monodon baculo virus (MBV) and white spot syndrome virus (WSSV) are stocked. Stocking is done during early morning or late evening after proper acclimatization to pond water condition. Recommended stocking density is up to 30 number per m^2 for specific pathogen free (SPF) *P. monodon* (CAA 2012) and up to 60 numbers per m^2 for *P. vannamei* (CAA 2009).

11.4.1.6 Feeding Management

Feed accounts for about 60% of total operational expenditure. Both over-feeding and under-feeding may result in crop loss. Feed should contain appropriate nutrients for the particular species and should be of appropriate crumble or pellet size as per size of shrimp. Feed should be stored in dry and aerated place. Daily ration is divided into meals and applied as per Tables 11.3 and 11.4. Daily ration is calculated as per Tables 11.5 and 11.6. Blind feeding is practised up to 50 days and feed requirement afterwards is calculated based on estimated biomass through sampling and using the formula (Chanratchakool et al. 1994):

$$Daily\ ration\ (kg) = \frac{Mean\ body\ weight\ (g) \times Stocking\ no \times Assumed\ survival\ (\%) \times Feeding\ rate\ (as\%of\ biomass)}{10000 \times 1000}$$

For example, daily feed requirement for 100,000 tiger shrimp of 5 g average body weight with assumed survival of 90% using Table 11.5 would be:

Table 11.3 Distribution of daily ration in meals in Tiger shrimp and Indian white shrimp farming

	Percentage of daily ration in meals				
	6 AM	11 AM	2 PM	6 PM	10 PM
1st month	40	–	–	60	–
2nd month	40	–	–	30	30
3rd month	20	20	–	30	30
4th and 5th months	15	15	10	25	35

Source: In-house data

Table 11.4 Distribution of daily ration in meals for *P. vannamei* farming

	Percentage of daily ration in meals				
	6 AM	9 AM	12 PM	3 PM	6 PM
1st month	40	–	–	60	–
2nd month	40	–	–	30	30
3rd month	20	20	–	30	30
4th and 5th months	15	15	10	25	35

Source: In-house data

Table 11.5 Feeding schedule for Tiger shrimp and Indian white shrimp

For first 50 days				50 days onwards		
Age in days	Feed increment (g) / day	Feed (kg)/ day / 100000 PL15	Crumble/pellet size	Mean body weight (g)	Feeding rate (as % of body weight)	Feed in each check tray (g/kg)
1	–	2.0	Fine crumble	5–10	5.5–4.7	24–28
2–10	400	2.4–6.0	Fine & coarse crumble	10–15	4.7–4.0	28–30
11–20	500	6.5–11.0	Fine & coarse crumble	15–20	4.0–3.6	30–33
21–30	600	11.6–17.0	Coarse crumble	20–25	3.6–3.0	33–36
31–50	500	17.5–27.0	Coarse crumble & pellet	25–35	3.0–2.3	36–41

Source: In-house data

Table 11.6 Feeding schedule of *Penaeus vannamei* farming

For first 50 days				50 days onwards		
Age in days	Feed increment (g) / day	Feed (kg)/ day / 100000 PL15	Crumble/pellet size	Mean body weight (g)	Feeding rate (as % of body weight)	Feed in each check tray (g/kg)
1	–	2.0	Fine crumble	5–10	5.5–4.5	2–3
2–10	400	2.4–5.6	Fine crumble	10–15	4.5–4.0	3–4
11–20	500	5.6–10.1	Fine & coarse crumble	15–20	4.0–3.5	4–5
20–30	600	10.1–15.5	Coarse crumble	20–25	3.0–2.5	5–6
31–50	700	15.5–28.8	Coarse crumble & pellet	25–30	2.5–2.0	6–7

Source: In-house data

$$\frac{5 \times 100000 \times 90 \times 5.5}{10000 \times 1000} = 24.75 \text{ kg}$$

Six check trays (80 × 80 × 10 cm) per ha are placed on the pond floor just beyond the dyke slopes and a small part of the calculated meal is placed in trays during feeding. Check trays are monitored after 2 h of feed application. If some feed is left in trays, feed is reduced by 10–20%; when feed is fully consumed within 2 h, increment of 10–20% in the next meal is done. Quantity of feed in check trays varies with pond size and can be calculated from recommended 'feed in each check tray (g kg^{1})' provided in Tables 11.5 and 11.6 for respective species using the formula:

$$Quantity\ of\ feed\ in\ each\ check\ tray\ (g) = \frac{1600 \times Feed\ in\ each\ check\ tray\ (g/Kg) \times Quantity\ of\ meal\ (Kg)}{Area\ of\ pond}$$

For example, feed quantity in each check tray for each kg of meal for tiger shrimp of 5 g average body weight (Table 11.5) in different pond sizes would be:

$$Check\ tray\ feed\ quantity\ for\ each\ kg\ of\ meal\ in\ 1000\ sq\ m\ pond$$
$$= \frac{1600 \times 24 \times 1}{1000} = 38.4\ g$$
$$Check\ tray\ feed\ quantity\ for\ each\ kg\ of\ meal\ in\ 2000\ sq\ m\ pond$$
$$= \frac{1600 \times 24 \times 1}{2000} = 19.2\ g$$

11.4.1.7 Water Quality Management

Maintaining optimum water quality (Table 11.7) is very important to minimize stress and disease risks, and to finally achieve better shrimp production. Liming is most important in water and soil quality management. Water pH should range from 7.5 to 8.5 with diurnal fluctuation less than 0.5. Dissolved oxygen (DO) should not be

Table 11.7 Normal, optimum and critical ranges of water quality parameters in shrimp farming

Physico-chemical parameters	Shrimp farm pond water		
	Normal	Optimum	Critical
Temperature (°C)	18–32	28–32	<14
pH	7.0–9.0	7.5–8.5	<6 (Daily fluctuation more than 0.5)
Salinity (ppt)	10–35	15–25	<5 and > 40 (Daily fluctuation <5)
Transparency (cm)	25–40	30–40	<20 and > 60
Dissolved oxygen (ppm)	3.0–9.0	4.0–7.0	< 4
Total ammonia nitrogen (ppm)	<4	<3.7	–
Free ammonia (ppm)	<0.1	<0.1	>0.1
Nitrate-N (ppm)	0.25	<0.25	>1.5
Nitrate-N (ppm)	–	0.2–0.5	–
Dissolved-P (ppm)	0.008–0.20	0.10–0.20	–
Hydrogen sulphide (ppm)	<0.003	Nil	>0.003

Source: In-house data

Table 11.8 Mineral concentration (mg/L) in seawater and factors for each ppt of salinity in pond water

	Sodium	Potassium	Magnesium	Calcium	Chloride	Sulphate
Sea water (35 ppt)	10,500	380	1350	400	19,000	2700
Factor[a]	304.5	10.7	39.1	11.6	551	7.40

[a]Factor is multiplied with water salinity value to get mineral concentration required
Source: In-house data

allowed to drop below 4 ppm at any time (CIBA 2010b). Aeration is done before each feeding. Organic juice is applied fortnightly to maintain C: N ratio in the pond. Commercially available probiotics are also used.

Mineral supplementation is required for *P. vannamei* at low salinity and in areas with mineral deficiency in soil. Mineral concentrations at a particular salinity should be equivalent to that of seawater diluted to that salinity (CIBA 2016). Mineral concentrations of seawater and factors for 1 ppt salinity are presented in Table 11.8.

For example, concentration of calcium at 4 ppt should be 46.4 (4×11.6) mg/ L.

Mineral requirement is calculated by using the following formula:

$$Mineral\ salt\ requirement\ \left(g/m^3\right) = \frac{Concentration\ of\ mineral\ in\ water\ (mg/L)}{Percentage\ of\ the\ mineral\ in\ salt} \times 0.1$$

11.4.2 *Diversified Aquaculture Practices Recommended for Sundarbans*

In recent years, successful farming demonstrations of finfishes have paved the way for commercial farming expansion in brackishwater sector in West Bengal. Asian seabass, grey mullet and pearlspot are presently under farming in the state. Milkfish farming has been initiated recently with remarkable success.

11.4.2.1 Asian Seabass

Cannibalism being one of the most serious problems, Asian Seabass (*Lates calcarifer*) farming is done in two phases viz., nursery and grow-out. Nursery pond size ranges from 500 to 2000 m^2 with water depth of 50–80 cm. A well-prepared pond is important as predators and competitors can endanger the stocked fry. Fry ranging from 1 to 2.5 cm are stocked @ 20–50 individuals m^{-2}. Fry are fed with chopped and grounded (4–6 mm^3) trash fish at 100% of biomass initially and gradually reduced to 10% at the end in two equal meals during 9:00 AM and 5:00 PM. The nursing period lasts for about 30–45 days until fingerling stage (5–10 cm) is reached. Hapa, a net cage (mesh size 1.5–2 mm) having dimension of 2 × 1 × 1 m, is used for nursery rearing of seabass fry in pond, where 200–300 fry are stocked in series of hapas and fed with finely chopped trash fish in same way as in ponds. Fry in hapa rearing system can be fed with marine fish larval diet at three times a day (Biswas et al. 2010). Fishes are graded in different size groups at 5–7 day intervals and restocked in thoroughly cleaned and sundried hapas. Better survival is achieved in hapa nursery rearing than in pond. For production of fingerlings, hapa is an ideal system for nursery rearing of seabass (Kumar et al. 2016). As cannibalism and differential growth are major problems in seabass nursery, supplementation of 0.5% of L-tryptophan in larval diet reduces cannibalism and improves survival of seabass fry (Kumar et al. 2017a).

The grow-out phase lasts for about 8–12 months. There are two culture systems employed in pond grow-out of seabass:

(i) The supplementary feeding system is followed in places with adequate supply of fresh trash fish at low-cost. Fingerlings are stocked @ 10,000–20,000 ha^{-1}. Chopped trash fish is fed twice daily in the morning at 8:00 AM and afternoon at 5:00 PM at 10% of biomass initially and gradually reduced to 5% at the end. A very recent development on improving the dietary intake of seabass is the introduction of moist feed. A production of 2–3 tons per ha can be achieved in 8–12 months.
(ii) Forage fish feeding system shows great promise. Abundant natural food is produced and selected tilapia brood stocks are released in the pond at the rate of 5000–10,000 ha^{-1}. Sex ratio of male to female is 1:3. Tilapia is reared in pond for 1–2 months or until tilapia fry appear in sufficient number. Seabass juveniles (8–10 cm in size) from nursery are stocked at the rate of 10,000–20,000 per ha. Fertilization is continued to maintain tilapia seed production. Seabass production of 2–3 tons ha^{-1} and tilapia production of 1–2 tons ha^{-1} is achieved in 8–12 months (Biswas et al. 2011a).

11.4.2.2 Grey Mullet

Full-scale commercial production of grey mullet (*Mugil cephalus*) is a new area of aquaculture diversification in India. This is done in two phases, namely nursery rearing and grow-out culture. After collection from natural sources, fry are transported in oxygen packs at a density of 240 fry L^{-1} for long distance (Kumar et al. 2012). After acclimatization, fry are stocked in well-prepared earthen nurseries at high densities (up to 25 m^{-2}), where they depend mainly on natural food in fertilized ponds (Biswas et al. 2012). Moreover, periphyton-based seed rearing is a better option compared to complete feed-based system (Biswas et al. 2017). Rice or wheat bran is sometimes used as an additional source of food. Fry are kept in the nursery ponds for 4–6 months (from January–February till June–July) until they are about 20–30 g in weight. The fingerlings are then caught, either by draining the nursery ponds into catch ponds or by netting. Grey mullets are usually grown in monoculture or polyculture ponds. Prior to stocking, ponds are prepared by drying, ploughing, and manuring with 2.5–5.0 tons cowdung per ha. Ponds are then filled to a depth of 25–30 cm and kept at that level for 7–10 days to build up a suitable level of natural feed. The water level is then increased to 1.5–1.75 m and fingerlings are stocked @ 1–2 m^{-2}. Extruded feed is supplied to semi-intensive ponds at 5% of biomass initially and gradually reduced to 1% at the end. The growing season is normally about 7–8 months. A production of 2.3–3.7 tons ha^{-1} can be achieved. In polyculture, they are usually stocked with tilapia, milkfish and pearlspot in brackishwater, and with common carp and silver carp in freshwater. In this case, feeding and fertilization programmes are usually targeting the other cultured species, and the mullet feed on the natural feed, detritus, and feed leftovers. Acclimatized to the appropriate salinity, and stocked as 10–15 g individuals at 0.6–0.7 m^{-2}, a harvest of 4.3–5.6 tons ha^{-1} $crop^{-1}$ can be obtained.

11.4.2.3 Pearlspot

Pearlspot (*Etroplus suratensis*), also known as 'green chromide', is cultured in the state of Kerala in traditional manner in the Pokkali fields. Farming of this species is practised in West Bengal in a small scale. This fish is highly adapted to captive farming due to its ability to feed on a variety of natural foods. Pearlspot can spawn many times during a prolonged breeding season. Environment simulation, rather than hormonal manipulation, is employed for inducing captive breeding of pearlspot. Captive breeding is carried out either in ponds, tank and cage systems provided with artificial substrates and breeding pits. Appropriate water levels and moderate water flow trigger captive breeding in tank system. Around 400–2000 eggs are laid per brood and over 90% survival is generally obtained. Tank based breeding is also possible for captive seed production (Biswas et al. 2014). Nursery rearing is done in small earthen ponds and tank system (Biswas et al. 2013). Ponds are sun-dried and limed before letting in water. Water is taken through fine mesh filters to avoid entry of predators. Organic fertilizer is applied @ 500–1000 kg ha^{-1} to boost up plankton bloom. After achievement of sufficient plankton bloom fry of 1–1.5 cm size are stocked @ 5–10 no. m^{-2}. Fishes are fed with mixture of rice bran and mustard oil cake (3:1) in fine powder form at 20% of biomass initially and gradually reduced to 5% at the end. After 2 months, fishes attain a length of 5–10 cm depending on availability of natural food in the nursery ponds. Most of them are harvested to be sold as ornamental fish. Grow-out monoculture is done in similar way with 2–5 no. m^{-2} and feeding is done at 5% of biomass initially and gradually reduced to 2% at the end for 6–8 months. Fishes attain an average body weight of about 100 g in this practice.

11.4.2.4 Milkfish

Milkfish (*Chanos chanos*) is a highly potential candidate species for brackishwater aquaculture because of its fast growth, efficient use of natural food, disease resistance, and readiness to accept variety of supplementary feeds. It constitutes important seafood in Southeast Asia and some Pacific Islands. It is called ‘bangus’ in the Philippines, where it is the national fish. In India, extensive seed availability is observed in south-east and south-west coast during April–June and October–December. Seeds are collected from those areas and reared in saline impoundments. Recently, success in captive breeding has been achieved by ICAR-CIBA. Nursery rearing is carried out in small earthen ponds. Fry are stocked @ 10–25 m^{-2} and fed with 1:1 mixture of oil cake and rice bran as supplementary feeding at 20% of biomass initially and gradually reduced to 6% at the end. Fishes attain 10–30 g in 2–3 months nursery rearing. Pond grow-out is mainly done depending on natural food with low production ranging between 1 and 2 tons ha^{-1} $year^{-1}$ (Biswas et al. 2011b). Recent culture trials in Sundarbans by Kakdwip Research Centre (KRC) of ICAR-CIBA at stocking density of 1 fish m^{-2} and feeding with formulated floating pellet feed (crude protein: 24%, crude fat: 4%) @ 2–6% of fish biomass in non-aerated periphyton supported brackishwater pond, and has achieved production of more than 4 tons ha^{-1} in 8 months. Fishes grew to 400–500 g during 8 months rearing period registering over 90% survival. This fish is a good candidate species for polyculture with shrimp as it has stronger mucosal immune properties compared to that of mullet and seabass (Kumar et al. 2017b) and may help in disease prevention.

11.5 Opportunities, Challenges and Conflicts

11.5.1 Opportunities

There are different opportunities to improve brackishwater aquaculture production. Among short-term strategies, improving traditional system of farming, development and dissemination of low-cost farm-made feed, control of diseases, and improved production through good aquaculture practices like, biofloc and periphyton based system, are the best options available. Long-term strategies like, development of organic farming, genetic improvement of shrimp stock through selective breeding, improved and intensive culture methods, adoption of cage farming of fishes, and overcoming the constrains through participatory fisheries management, public-private partnership, refinement of indigenous technical knowledge, can be taken up (Mehta 2009).

Domestic markets for fish and fish products not only provide an entirely new opportunity for growth but also can act as a buffer in case of gluts in the international markets. Institutional agencies have an onerous task on hand for enabling the domestic markets for fish to establish itself.

11.5.1.1 Improvement in Traditional Farming

Polyculture is potentially more sustainable than monoculture is, due to the reutilization of waste products of one species by another. Shrimp polyculture represents an important alternative to solving and/or minimizing some of the problems (i.e. environmental pollution, diseases and decreasing prices) that shrimp aquaculture has faced in the past two decades. Several species from diverse trophic levels have the potential to be co-cultured with shrimps. A good knowledge of the species that are candidates for polyculture and availability of an adequately designed culture system are the most important points to consider when co-culturing shrimp is practised with other species (Martínez-Porchas et al. 2010). Modification of age-old traditional brackishwater polyculture is a logical choice towards sustainable intensification of aquaculture.

11.5.1.2 Selection of Compatible Species for Polyculture

Modification of traditional brackishwater polyculture through selection of compatible species for sustainable better production and profitability were tested by KRC of ICAR-CIBA involving tiger shrimp (*Penaeus monodon*), Grey mullet (*Mugil cephalus*), Parsia (*Liza parsia*), and Milkfish (*Chanos chanos*) to assess the optimum species combination. Presence of all species and absence of one fish species in each combination were considered as treatments. The study was carried out at Manmathapur-Mundapara village (21.879493–21.894148°N, 88.263668–88.276199°E) of Kakdwip block in Indian Sundarbans for 240 days during 2013. Ponds were prepared following standard procedure and reared organisms were fed with commercially available sinking pellet feed (Crude Protein: 24%, Crude fat: 3%) @ 2–10% of fish biomass. Tiger shrimp, grey mullet, parsia and milkfish were stocked @ 2, 0.5, 0.5 and 0.25 no m^{-2}, respectively, which were decided based on normal practice in traditional farming as revealed from a semi-structured interview-based survey. Best growth (44.17 ± 1.53 g) of tiger shrimp was achieved in presence of all species with lowest survival (17.9 ± 3.4%), and highest survival was observed in absence of milkfish (41.3 ± 5.6%) with moderate growth (42.65 ± 1.25 g). Best growth of parsia was observed in absence of milkfish (54.16 ± 6.34 g), while highest survival was found in absence of grey mullet (61.9 ± 4.1%). Grey mullet grew best in absence of milkfish (487.17 ± 20.42 g) and survived best in presence of all species (60.5 ± 4.4%). Milkfish grew best in absence of grey mullet (382.91 ± 18.39 g), and highest survival (71.1 ± 6.8%) was found in presence of all species. Significantly ($p < 0.05$) higher total harvested biomass (1931.64 kg ha^{-1}) was produced in presence of all species followed by treatments with absence of parsia (1794.11 kg ha^{-1}), absence of milkfish (1739.42 kg ha^{-1}), and absence of grey mullet (922.51 kg ha^{-1}). Highest total income (INR 520650) was achieved in species combination without milkfish followed by presence of all species (INR 410303), without parsia (INR 360362), and without grey mullet (INR 203099) with respective benefit-cost ratio of 2.798, 2.048, 1.824 and 1.242.

Growth, production and economic parameters of the study indicated technical and economic viability of mullets-tiger shrimp polyculture. Mullets-milkfish-tiger shrimp polyculture was also viable but with lower profitability.

11.5.1.3 Development and Dissemination of Low-cost Farm-Made Feed for Polyculture

KRC of ICAR-CIBA took initiatives to standardize polyculture practices with indigenous brackishwater fish and shrimp, where use of low-cost farm-made feed with locally available feed ingredients helped the polyculture towards sustainable and economically rewarding activity. This successful model of polyculture has been disseminated among the farmers of the Sundarbans, paving the way for its wide adoption in the region. Several experiments using the low-cost feed were conducted in indoor system, on-farm, and in farmers' ponds, in order to standardize polyculture using indigenous brackishwater fish and shrimp species. Six species polyculture with different stocking densities, *Liza Parsia* (5000 ha^{-1}), *Liza tade* (5000 ha^{-1}), *Mugil cephalus* (2500 ha^{-1}), *Scatophagus argus* (2500 ha^{-1}), *Mystus gulio* (30,000 ha^{-1}), and *Penaeus monodon* (2500 ha^{-1}), resulted in 4764 kg ha^{-1} production using low-cost farm-made feed, $Poly^{plus}$ (INR 25.32 kg^{-1}, USD 0.41 kg^{-1}) having feed conversion ratio (FCR) of 1.36, in three consecutive trials over 325 days in farmers' ponds (De et al. 2016).

The farm-made feed (Crude Protein-29.77%) containing different unconventional ingredients (sunflower cake, mung husk) with 10% fish meal performed at par with that of feed containing 22% fish meal in respect of growth and FCR. Economic analysis revealed a net profit of about INR 291000 ha^{-1} (USD 4693.5 ha^{-1}) with a benefit-cost ratio of 1.85. Feeding method standardization experiments suggested that low-cost farm-made pellet feed may be offered @ 2–10% body weight per day. Daily ration has to be distributed at three equal quantities in the morning (9.00 AM), at afternoon (1.00 PM), and at evening (5.00 PM) in trays. Every ration may be offered in two split doses at 1 h interval to meet requirements of fish with size variation (De et al. 2016).

Production improvement of two to fourfold compared to conventional system has been observed and farmers showed increasing interest in adoption of polyculture farming system with low-cost feed ($Poly^{plus}$) developed by CIBA. To cater the need of farm-made feed, the brackishwater farmers of Sundarbans formed a cooperative society and established a pulverizer with the financial help of the State Government. The polyculture practice has been disseminated to 57 farmers of Sundarbans and about 30 ha area have been brought under improved brackishwater polyculture practices with low-cost formulated feed. There is a vast scope for further development of brackishwater polyculture using low-cost farm-made feed in Sundarbans.

11.5.1.4 Production Improvement through Biofloc-Based System

The principle of biofloc technology is based on manipulation of carbon:nitrogen ratio (C:N ratio), and for brackishwater shrimp aquaculture C:N ratio of 10:1 is stated to be optimum. The biofloc is heterogenous mixture of bacteria, algae, protozoa, zooplankton, food particles, and dead cells with bacteria being the dominated component. The cultured shrimp often use the floc particles as their feed. For management of C:N ratio, carbohydrate is applied externally from different sources including molasses, rice flour, wheat flour, tapioca powder, rice bran, wheat bran, etc. In presence of higher carbohydrate, the heterotrophic bacteria utilize ammonia to produce biofloc and thus reduce the level of free ammonia in the water. So, the chances of ammonia toxicity are reduced. This culture system improves the growth rate of cultured shrimp. Apart from these, biofloc-based system reduces the feed requirement leading to reduction of input cost and it also lowers the possibility of diseases. Research work carried out at CIBA showed that biofloc improved the growth rate of juvenile and adult *Penaeus monodon* by 29 and 12.6%, respectively over the control (Sujeet et al. 2017). However, this type of production system produces high level of turbidity, which increases the need of aeration. The dissolved oxygen (DO) level should strictly be monitored regularly and the aeration should be done round the clock (24 h a day) particularly at the end of the culture period.

11.5.1.5 Production Improvement through Periphyton Supported Farming

Artificial substrates for periphyton development have been widely used in fresh water aquaculture, particularly in carps, tilapia and giant fresh water prawn, to augment fish production. Similarly, promising results in terms of growth, survival and production were observed with periphyton in brackishwater penaeid shrimp, *P. monodon* (Khatoon et al. 2009) and *P. vannamei* (Audelo-Naranjo et al. 2011). Like biofloc, periphyton is also a heterogenous mixture of biota including bacteria, fungi, phytoplankton, zooplankton, benthic organisms, detritus, etc. But unlike biofloc-based system, here the mixture of biota is generally attached to any submerged surface such as bamboo stick, plastic sheet, polyvinyl chloride (PVC) pipe, ceramic tile, fibrous scrubber, etc. Periphyton-based system also increases the aquaculture production and develops the resistance to different diseases by augmentation of immune response. Work carried out at Kakdwip Research Centre of ICAR-CIBA reported 17.9% gain in production and 22.3% reduction in FCR compared to conventional culture in case of *P. monodon* (Shyne Anand et al. 2013). The submerged substrates added into the aquatic system improve the water quality (Thompson et al. 2002), and consumption of microbes and algal community present over submerged substrates enhances the growth of penaeid shrimp by providing natural food (Ramesh et al. 1999).

11.5.1.6 Diversification of Species

Brackishwater aquaculture development in India was mostly oriented till 2009 to tiger shrimp, *P. monodon* culture, only. In 2009, the Coastal Aquaculture Authority of India (CAA) permitted the entrepreneurs to introduce a new species, *P. vannamei* (Pacific white leg shrimp), in India with prescribed guidelines (CAA 2009). Before introduction, risk analysis was carried out by Central Institute of Brackishwater Aquaculture (CIBA) and National Bureau of Fish Genetic Resources (NBFGR) following pilot scale initiation in 2003. Since introduction, *P. vannamei* farming showed rapid growth and a shift towards *P. vannamei* from *P. monodon* was observed in India due to its high productivity (6–10 ton ha^{-1}) and international market demand. Another species, Indian white shrimp, *P. indicus*, seems to be promising one as CIBA demonstrated a production of 3–5 tons ha^{-1} using CIBA hatchery-produced seed.

The annual contribution of finfish to total aquaculture production has been increasing in recent years. The diversity provides very promising development opportunities for the brackishwater fish culture. Unlike other aquatic organisms, finfish can be cultured in a number of culture systems like, cages, pens, ponds. Variety of fishes is available suitable for different culture practices, such as for monoculture, polyculture, and can be integrated with livestock and agriculture. Therefore, fish plays major role in aquaculture production and there is lot of scope to expand the farming activities in a diversified manner.

11.5.1.7 Improvement in Finfish Culture Practices

Fishes like Asian seabass (*Lates calcarifer*), Grouper (*Epinephelus tauvina*), snappers (*Lutjanus sp*.), which are high-value carnivorous fishes, and striped grey mullet (*Mugil cephalus*), Tade mullet (*Liza tade*), Parsia (*Liza parsia*), milkfish (*Chanos chanos*), and pearlspot (*Etroplus suratensis,*), which are herbivorous/omnivorous, are available for farming in the coastal ecosystem. In addition to this, fishes like long whiskers catfish (*Mystus gulio*), popularly called as 'Nuna tengra', is being cultured in coastal ecosystem. Successful technology has been developed for the seed production of Asian seabass under controlled conditions and farming by ICAR-CIBA since 1997 (Thirunavukkarasu et al. 2001, 2004). The controlled breeding of grouper (*E. tauvina*), striped grey mullet, and pearlspot has also been successful. In addition to this, an avenue has come by successful breeding and seed production of ornamental fish spotted scat (*Scatophagus argus*). Monoculture of Asian seabass is in practice in some pockets where cheap trash fish is available in plenty. Seabass seeds are stocked @ 10,000–15,000 per ha in well-prepared culture ponds. In this system the stock is totally raised on supplementary feed. Stocked fishes are fed with chopped trash fishes collected from landing centers. As seabass does not feed at the pond bottom the chopped trash fish is broadcast slowly twice a day. Feed is provided *ad libitum* at not more than 100% of total biomass and gradually reduced to 10% at the last phase of culture. In this method, after a culture period of 8–10 months seabass attains average size of 800 g with a survival rate of 60–70%, and a production of 2.5–4 tons ha^{-1} is achieved. Polyculture of Asian seabass following 'predator-prey culture' system using tilapia as prey material has also been tried with considerable success. In this system, fish can grow similar to trash fish feeding system if sufficient prey fishes are available (Biswas et al. 2011a). Scientific farming of brackishwater finfishes is a new intervention for brackishwater aquaculture development with immense potentiality.

11.5.1.8 Improvements in Crab Farming Practices

There is huge potentiality for mud crab farming in India. Still there is no organized aquaculture of mud crab for supporting the export trade. Major reason is the non-availability or inconsistent availability of crab seeds for farming. Technology for seed production, culture and fattening of mud crab, *Scyllla olivacea*, and green crab, *S. serrata*, has been developed by ICAR-CIBA (CIBA 2000). Some farmers are practising crab fattening in the coastal districts of West Bengal with considerable success. Survival up to 70–80% is generally achieved after 20–30 days of fattening operation (Suseelan 1996). After the inception of crab hatchery by The Rajiv Gandhi Centre for Aquaculture (RGCA) in Nagapattinam district in Tamil Nadu, hatchery-produced crab seeds are now available. Some progressive farmers in Kakdwip block, West Bengal have started crab grow-out farming with productivity of 1–1.8 ton ha^{-1} with the help of hatchery- produced seeds. Some compatible fish like parsia, grey mullet, and milkfish can be co-cultured with crab to earn more profit.

11.5.1.9 Ornamental Fish Culture

Ornamental fishery has a very bright prospect not only in the domestic market but in the export market as well. West Bengal is pioneer in ornamental fish culture and ranks first in domestic production and export outside among all the Indian states. Brackish water ornamental fishes like spotted scat (*Scatophagus argus*), Puffer fish (*Tetradon cutcutia*), Loaches (*Botia* spp), and Eels (*Anguilla* spp), which are available in maritime districts of West Bengal, have started to gain importance in domestic and export market. Farming of all those species is going on depending upon natural seed availability. Pearlspot (*Etroplus suratensis*), introduced in West Bengal by KRC of ICAR-CIBA, has gained lots of popularity as ornamental fish. Seeds of pearlspot are produced in captivity using environmental manipulations. Farming of spotted-scat and pearlspot is on the way to fetch substantial profit.

11.5.1.10 Organic Farming

Today, the demand in the importing countries for high quality and safe shrimps/fish/crab, raised in an ecofriendly manner by adopting good management practices, has become an essential pre-requisite for Indian seafood export. The brackish water area available in India for shrimp farming offers good potential for organic farming (Mehta 2009). This includes the vast traditional prawn filtration fields located in West Bengal and Kerala. The traditional type of prawn filtration system is highly environment-friendly as they use no chemicals, drugs or antibiotics. Organic aquaculture ensures that the farming activity is in harmony with the nature, raised with due care for the good health and welfare of the cultured organisms. Organic products have become very popular of late due to the rising awareness in health and food safety. There is a growing demand for organic products in the global market, especially in Europe, USA, China, etc. The purpose to shrimp certification is to enhance the market share for the shrimp produced by responsible methods, inputs and practices, that would meet the expectations of socially and environmentally aware consumers. Certification process has to be simplified and branding of shrimp produced through improved traditional methods as 'organic' may fetch better price. A trial towards organic farming of shrimp was carried out by ICAR-CIBA at KRC showed promising result with better profitability (CIBA 2010b).

11.5.1.11 Other Management Practices for Improvement

Water exchange during lunar cycles is carried out in traditional farms to draw nutrients within the system. During the course of water exchange, silt carried by tidal water gets deposited resulting in swallowing of the impoundment. Shallow depth of the traditional farms enables physical and chemical water quality parameters to fluctuate abruptly triggering viral diseases especially during summer. Desilting of the traditional impoundments to increase water depth to more than 1 m might reduce prevalence of shrimp diseases. Application of yeast-based organic preparation in traditional farms may reduce shrimp disease as glucans contained in yeast acts as immune-stimulant. As traditional farming depends mostly on auto-stocking, natural shrimp seeds may carry pathogens of viral diseases. Closed culture and stocking of PCR- tested hatchery-produced shrimp seeds may improve crop security and farm income (CIBA 2010a).

Efforts towards adoption of improved farming technologies like recirculatory aquaculture system (RAS), improved polyculture, integrated multi-trophic aquaculture (IMTA) may make brackishwater aquaculture more environmentally acceptable, protocols of which are to be explored in order to provide more secured livelihood (Martínez-Porchas et al. 2010).

11.5.2 Challenges and Conflicts

Coastal aquaculture faces number of challenges including disease outbreaks, fluctuating market prices, rising input costs, etc. These challenges need to be tackled by appropriate management tools for sustainable development of aquaculture. These tools include social mobilization of aqua producers, technology assessment and refinement, participatory planning, and capacity building of key stakeholders. There is a need to create more awareness and knowledge among the stakeholders on various aspects of management tools for ensuring sustainable aquaculture development.

11.5.2.1 Enhancement of Area under Cultivation

High potential and high return areas need to be identified. Out of 0.21 million ha, only 28% of brackishwater aquaculture resources of West Bengal are brought under culture (Govt. of India 2017). As the fishery resources of the state were estimated quite some time back, due to considerable changes made on land and water use so far, the resources need to be reassessed qualitatively and quantitatively to launch specific programmes in high potential areas.

11.5.2.2 Improvement of Traditional Farming System

'Bhery' farming is an age-old traditional system with low productivity. Sludge removal from *bhery*s to increase water depth and adoption of improved polyculture are needed for sustainable production improvement (Ramsundar 2011).

11.5.2.3 Availability of Quality Seed

Quality of seed is of prime importance in aquaculture. Due to absence of shrimp hatchery in West Bengal, farmers depend on southern states for hatchery-produced shrimp seeds brought through commission agents (Knowler et al. 2009). Farmers are compelled to pay more cost and often receive poor quality seeds (Umesh et al. 2010). Establishment of seed bank and viral disease screening facility is required. Hatchery-produced fish and mud crab seeds should be made available to the farmers through seed bank by establishment of nursery rearing facility (Ghoshal et al. 2016).

11.5.2.4 Availability of Quality Feed at Low-Cost

Feed accounts for about 60% of operational cost in aquaculture. Feed price is increasing by leaps and bounds due to low availability of fish meal as the key ingredient. Development of low-cost feed using locally available ingredients is very much required (Ghoshal et al. 2016). As brackishwater fish monoculture is gaining popularity, species-specific feed is required to be made available to the farmers through establishment of small and medium scale feed mills. Traditional farmers have to be encouraged to use low-cost farm-made feed to improve production.

11.5.2.5 Providence of Extension Services

Proper farm design and construction is of immense importance in aquaculture to improve productivity and profitability (Jayanthi 2007). This aspect is the most ignored one at present state of aquaculture in West Bengal. Providence of extension services on engineering aspects during farm construction phase will surely lead to improved production and profitability. Proper pond preparation and culture management is the key to successful aquaculture. There is a need to educate farmers on the scientific ways to manage ponds for a specific culture practice. Farmers should be trained on better management practices (BMPs) and methods for quality improvement of farmed materials (Kumaran et al. 2017).

11.5.2.6 Soil and Water Testing Facility

Establishment of small laboratories for water and soil analysis at strategic locations is very much required for better culture management. PCR test facility should be available within short distances (Khang et al. 2008), which is far from adequate.

11.5.2.7 Storage Facility and Value Addition

Shrimp and fish from brackishwater resources are highly perishable commodities. From the production site to post-harvest processing plant of these export-oriented items, it takes long time to reach. Therefore, proper storage facility for harvested material and value addition are important measures to increase profitability and marketability (Pradhan and Flaherty 2007). This should be addressed with prime importance.

11.6 Conclusions

Brackishwater aquaculture is a capital-intensive venture. In Sundarbans, majority of the farmers being small and marginal, require supports in terms of inputs or money to start modern aquaculture operations. The need for financial agencies to accept the scope offered by the sector in terms of returns to investment must be reinforced through training programmes, awareness campaigns, and other extension media.

In the brackishwater sector, on the environmental front, there are issues like waste generation, conversion of agricultural land, salinization, and degradation of soil and environment due to extensive use of drugs and chemicals, as well as destruction of mangroves (Primavera 2006). Farmers should be made aware about environmental issues related to aquaculture so that they act accordingly.

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Embankment and paddy agriculture (Courtesy A. A. Danda)

Chapter 12
Risks and Profitability Challenges of Agriculture in Sundarbans India

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Abstract In spite of the vast resource potentials in the Sundarbans, the enhancement of the agricultural productivity in this coastal land is much below the expected level. The region is lagging behind many inland areas in terms of agricultural productivity and livelihood security of the farmers and other inhabitants. The agricultural system is heavily dependent mainly on climate change and related environmental factors, besides other constraints, like soil salinity, drainage congestion, flooding, inadequacy of freshwater for irrigation, etc. Risk factors involved in agricultural practices, and recommendations for improvement, based on location-specific constraints, developed, are the most important factors for decision-making in farm management, adoption of new technologies, as well as enhancing farm income. Suitable cropping system intensification, with emphasis on introduction of high-value crops, can be one of the ways to agricultural risk mitigation. Complementarity between agriculture and industry/non-farm entrepreneurship are suggested as yet other ways for risk management. Several strategies to increase farm income, along with appropriate remunerative price and marketing support, in the Sundarbans region have been highlighted in this chapter. Study concluded that enhancing farmers' income in Sundarbans of West Bengal (India) is a challenging task, needs technology and policy support. The most critical concern for the farmers in the region is not only to achieve the higher farmers' income but also to sustain it across the farmers' groups.

Keywords Sundarbans · Agricultural productivity, Profitability and risks · Climate aberrations · Strategies to improve farm income · Sustainability in production · High-value crops · Agriculture-industry complementarity · Remunerative price and marketing · Livelihood · Policy support

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12.1 Introduction

Coastal ecology is one of the most fragile ecologies in many parts of the globe and the problem is acute in a country like India which is encircled by seas on all its 3 sides along the 7517 km-long coastlines spreading over 9 coastal states and 3 union territories including a large number of islands (SAC 2012). The coastal region is likely to face severe challenges in future due to rise in sea level following global warming. The region is, however, endowed with rich diverse natural resources. Sundarbans is one of the important coastal regions in the state of West Bengal, India, for scope to improve its agricultural and allied sectors' contribution. The management of the natural resources and sustenance of ecology in the region are some of the vital issues. Agriculture, horticulture, aquaculture, animal husbandry, etc. are the primary livelihoods of the people living in the Sundarbans region of the state, but the productivity of all these sectors are much below that of the national average because of various constraints related to soil, water and climate of the former. The socio-economic status of the population dwelling in this area is also much below the national status. It is essential that coordinated strategies for conservation and scientific utilization of the rich diverse natural resources of the region are adopted for improving the productivity and the livelihood of millions of resource-poor farmers dwelling in the region, and also to protect coastal environment from the potentially catastrophic effects.

Development of technologies by scientists/researchers alone cannot solve the problem of farming communities sustainably unless the process of technology dissemination is complemented by desired policy initiatives. Very often the technologists failed to understand in the past as to why despite being their technologies economically viable, farmers were reluctant to own them. Was it because the farmers' behaviour was stubborn or irrational, or they were afraid of any change? But the fact is farmers have had to operate their farming operations under a host of socioeconomic conditions, often non-compatible, that affected their decisions to adopt new technologies. Most of the farming operations are done by the aged farmers. Young rural population is not engaged in the farming business. Case studies through primary survey in Sundarbans areas indicated almost all the farming activities were taken care of by the aged farmers, indicating that the young generation in the villages were out of agriculture and were in search of alternative livelihoods. The reason being non-farm income options fetched better return and able-bodied workers were more likely to engage gainfully. Socio-economic factors, like input prices, market environment, fragmented and small/marginal land holdings, availability of own or hired human labour, labour wage rates, financial and credit needs, availability and capacity to absorb, risk preferences, etc. – all affected the adoption behaviour towards new technologies. Resource-poor farmers, particularly of this region are naturally risk averters and prefer to be safe than, say sorry. They tend to prefer a lower outcome that is relatively stable, to the prospect of a higher return with a greater degree of instabilty attached. Farmers in the region thus prefer certainty of output even with a lower return rather than the high-cost-high-return technologies where the unceratinty of output is much higher.

12.2 Economics

12.2.1 Performance in Terms of Net State Domestic Product (NSDP)

Performance and contribution of coastal districts of West Bengal (North 24 Parganas and South 24 Parganas) have been analysed with the secondary information available during the period 2004–2005 to 2010–2011. Sundarbans is the constituent of a large area falling under these two coastal districts of West Bengal. Almost 74% of the population from South 24 Parganas and rest (26%) from North 24 Parganas constitutes the population base (3.76 million) of Sundarbans (Govt. of West Bengal 2009). In terms of area, Sundarbans region is accounted for 33% (0.44 million ha) of total area (1.33 million ha) of these two coastal districts, South and North 24 Parganas. These coastal districts' contribution to the Net State Domestic Product (NSDP) was hovering around 28–29% and the share was almost static during this period. The Annual Compound Growth Rates (ACGR) of the district level NSDP at current prices of 2004–2005 was accounted to be 14–15% in West Bengal (Table 12.1). Further, the agricultural development performance in these coastal districts of West Bengal has been analysed through estimating ACGR of Net Cropped Area (NCA), Gross Cropped Area (GCA) and Cropping Intensities for the period of 2000–2001 to 2013–2014 (Table 12.2). The NSA and GCA during this period indicated decelerating trend in the coastal districts. The NSA of North 24 Parganas decelerated sharply at (1.45%) as compared to South 24 Parganas (0.03%) and West Bengal as a whole (0.46%). Similarly, the GCA also decelerated at 1.55% in North 24 Parganas as compared to South 24 Parganas (0.08%) and West

Table 12.1 Contribution of coastal districts (West Bengal) (NSDP in Rs. Crores at 2004–2005 prices)

Year	North 24 Parganas	South 24 Parganas	West Bengal	% share to WB
2004–2005	24,417	16,885	2,08,656	27.81
2005–2006	27,833	18,090	2,29,669	27.79
2006–2007	31,333	21,655	2,61,682	28.09
2007–2008	36,277	24,613	2,99,483	28.08
2008–2009	42,658	27,591	3,41,942	28.32
2009–2010	49,298	31,384	3,98,933	28.10
2010–2011	58,513	37,493	4,67,421	28.54
ACGR %	15.66	14.28	14.50	

Note: ACGR stands for Annual Compound Growth Rate (%) calculated by author. Source: Database on District wise GDP at current prices of 2004–2005, accessed from https://data.gov.in on December 15, 2017

Table 12.2 Trend in Net Sown Area, Gross Cropped Area and Cropping Intensities in coastal districts of West Bengal

Year	NSA (ha)			GCA (ha)			Cropping Intensities (%)		
	N24PGS	S24PGS	WB	N24PGS	S24PGS	WB	N24PGS	S24PGS	WB
2000–2001	259,865	378,294	5,417,382	513,692	538,791	9,116,597	198	142	168
2001–2002	277,231	381,859	5,521,576	579,227	543,016	9,778,815	209	142	177
2002–2003	264,381	380,096	5,354,196	506,801	539,759	9,510,423	192	142	178
2003–2004	257,453	383,454	5,427,672	481,854	562,734	9,661,325	187	147	178
2004–2005	265,514	378,258	5,374,104	471,766	505,302	9,522,930	178	134	177
2005–2006	260,537	370,367	5,294,702	495,911	507,604	9,532,607	190	137	180
2006–2007	259,978	372,785	5,296,005	516,214	539,085	9,634,535	199	145	182
2007–2008	259,225	372,295	5,295,773	520,413	531,258	9,751,508	201	143	184
2008–2009	257,405	373,660	5,294,040	510,901	539,916	9,801,516	198	144	185
2009–2010	219,634	357,535	5,255,807	472,177	523,839	9,530,276	215	147	181
2010–2011	223,017	358,401	4,981,222	452,778	513,605	8,832,348	203	143	177
2011–2012	230,061	464,087	5,198,146	359,296	539,713	9,352,952	156	116	180
2012–2013	231,265	360,574	5,204,902	459,972	530,202	9,458,675	199	147	182
2013–2014	232,803	361,545	5,233,726	470,108	546,950	9,618,451	202	151	184
ACGR (%)	−1.45	−0.03	−0.46	−1.55	−0.08	0.08	−0.10	−0.04	0.59

Note: N24PGS and S24PGS stands for North 24 Parganas and South 24 Parganas districts, respectively and WB stands for West Bengal. Source: Directorate of Economics and Statistics, Govt. of India (http://aps.dac.gov.in/lus), accessed on December 15, 2017

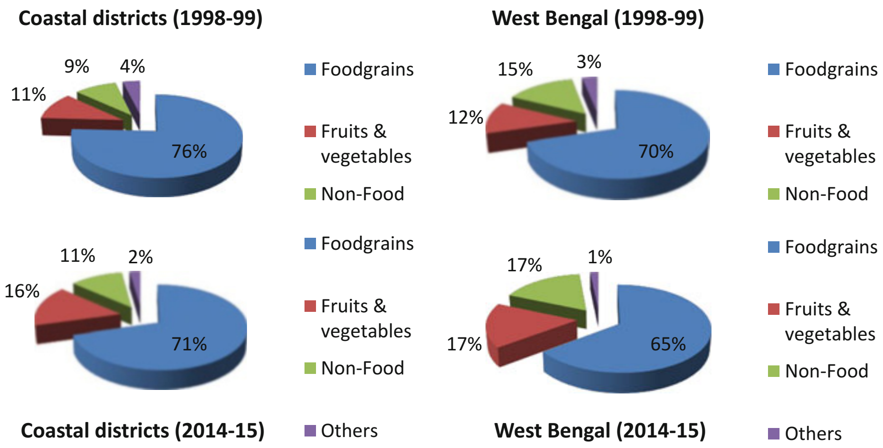

Fig. 12.1 Cropping pattern change in coastal region vis-à-vis West Bengal. (Source: Agriculture Census, Online Database, accessed on December 15, 2017 from http://agcensus.nic.in/)

Bengal (0.98%). Also, the trend in cropping intensities indicated almost static or decelerating at 0.10% North 24 Parganas and 0.04% in South 24 Parganas, whereas, overall cropping intensities of the state (West Bengal) increased by 0.59% during the same period. This indicated that the cropping intensification in the coastal districts of West Bengal is quite low during this period. The Sundarbans region is accounted for 51% of NSA and 39% of GCA of these two coastal districts and the cropping intensity is much lower than (125–130%) these districts as a whole (over 150%). The reason being, the entire Sundarbans cropping systems are characterised by salt-affected soils. Also, there was a dip in the cropping intensities in Sundarbans West Bengal after 2010 due to cyclone-*Aila* in 2009 that made large extent of cultivable area highly saline which remained uncultivated during subsequent years. Change in cropping pattern in coastal West Bengal indicated small shift from area under food grains towards high value fruits and vegetables during 1998–1999 to 2014–2015. It was observed that around 5% area under food grains crops (from 76 to 71%) was shifted to high-value fruits and vegetable crops, and also there was 2% increase in the area under non-food crops, like oilseeds, cotton, sunflower, etc. during 1998–1999 to 2014–2015 (Fig. 12.1). Similar trend was however observed in case of the whole state, since crop diversification towards use of high-value crops was given special thrust in the state during the previous decades also.

12.2.2 Occupation Pattern and Household-Level Income

Primary survey was conducted to understand the baseline income and occupation pattern of the farm households in Sundarbans of West Bengal through different socioeconomic research projects carried out by ICAR-Central Soil Salinity Research

Table 12.3 Occupation and income pattern of sample households in Sundarbans of West Bengal

Sl. no	Particulars	% Household primarily dependent	Average income (Rs/year)	Average income (Rs/month)
A	Agriculture	43	18,683	1557
B	Business	6	47,660	3972
C	Service	4	112,000	9333
D	Fisheries	1	12,877	1073
E	Migration (seasonal)	32	46,768	3897
F	Agril. labourers	7	14250	1188
G	Daily labourers (non-agri)	4	14235	1186
H	Others (incl. handicrafts)	3	14536	1211
I	Overall	100	45,278	3773

Source: In-house study on households' level primary survey during 2015–2016 and 2016–2017, Mandal et al. 2017

Institute (CSSRI), Regional Research Station, Canning Town, West Bengal (Mandal et al. 2017). The occupational pattern indicated agriculture was the dominant occupation (43%), followed by migration of labourers (32%) and agricultural labourers (7%) (Table 12.3). In Sundarbans, large number of agricultural labourers migrates (seasonally) to nearby cities or to distant places for alternative livelihoods options. The migrant labourers are mostly the agricultural labourers and they migrate, particularly during non-*kharif* season, due to lack of daily jobs in farming operations back home. Overall, the household-level income was estimated to be Rs. 45278 per year or Rs. 3773 per month for all sources. However, the income from agriculture was quite low (Rs. 1557 per month per household) and much lower than income from the migrant labourers earning (Rs. 3897 per month) justifying reason behind large-scale seasonal migration from this region.

12.2.3 Risk and Uncertainties

12.2.3.1 Farm-Level Risk and Farmers' Response

The operational area of farms in the districts of Sundarbans region of West Bengal is dominated by marginal farmers with average farm size of less than a hectare. The trend in size of operational holdings is gradually declining over the period, and further the lands are fragmented to different plots/parcel. The small and marginal holdings, and that too, when fragmented to several plots, reduces the risk-bearing abilities of the farmers and, in turn, the capacity to withstand risk and cope up with uncertainties. Farmers choose to operate at low-investment, low-return options that have less risk attached instead of preferring high-investment, high-return options

Table 12.4 Sources of farm-level risks in Sundarbans of West Bengal

Source	Cause	Response of farmers	Extent
Salinity	Inherent to soil	Water management	Low to very high
Acid sulphate soil	Inherent to soil	Water management	20–25% yield loss
Damage by pest and disease	Weather	Plant protection	15–20% yield loss
Waterlogging	Poor drainage during heavy rain	Delayed harvesting	15–20 days delay in sowing fetched market price (e.g., tomato, cucumber, bitter gourd etc.) by 10%
Flash rain	Heavy downpour in short time	Early harvest but not always possible	Sometime up to 100% crop loss (eg., potato, chilly), higher labour to harvest lodged paddy
Long dry spell	Erratic weather	Delayed sowing	Increased irrigation cost by 25%, labour 15%
Market price	Production glut, poor transport linkage	Delay in selling (future market)	Loss of income varies
Govt. policy (say, demonetization)	Cash crunch	Selling at lower volume, buy input and sell produce in credit	Paddy prices fall (8–10%), delayed payment

Source: In-house study based on primary survey on agricultural households during 2016–2017, Annual Report 2016–2017a

with more risks. Farmers, being resource- poor, prefer output with more stability rather than attempting for high return as they are naturally risk-averters. The sources of various farm-level risk factors in Sundarbans of West Bengal are salinity stress, presence of acid sulphate soils, damage caused by pest and diseases, prolonged waterlogged situation, flash rain, long dry spell, market price uncertainty, and lack of favourable government policies (Table 12.4). All these risk factors affect the crop cultivation, limit crop choice, reduce yield, and finally have significant impact on farm income and livelihood (Annual Report 2016–2017a).

12.2.3.2 Profitability of Paddy Cultivation

Paddy is the major crop in Sundarbans both in *kharif* (wet) and *rabi* (dry) season. Risk and uncertainties in profitability of paddy cultivation has been analysed through estimating output-input ratio, returns to investment (ROI), comparison between costs of cultivation with market price realization, co-efficient of variation (CV) in yield, and net return (Table 12.5). In terms of realizing market price, *rabi* paddy fetches higher price primarily due to better quality as compared to that for *kharif* paddy. Minimum support price (MSP), formulated by the government, is an instrument to ensure remunerative price and to encourage farmers into their farming

Table 12.5 Economics of paddy in Sundarbans, West Bengal (2016–2017)

Particular	*Kharif* paddy	*Rabi* paddy
Total cost (Rs./ha)	35,588 (32.85)	56,325 (45.23)
Total return (Rs./ha)	39,975 (41.42)	76,538 (50.46)
Net return (Rs./ha)	4388 (37.11)	20,213 (48.43)
Yield (t/ha)	3.83 (25.56)	4.98 (55.47)
Output-input ratio	1.12	1.36
Return to Investment (ROI) %	12.33	35.89
Unit cost of production (Rs./kg)	9.29	11.30
Selling price realised (Rs./kg)	10.00	15.00
Min. support price (Rs./kg)	14.70	14.70

Source: In-house study based on primary survey 2016–2017, Annual Report 2016–2017a
Note: Figure within the parenthesis shows coefficients of variation (CV) in per cent

business gainfully. Selling price of *kharif* paddy was observed to be less than the MSP, since the former just covers the cost of cultivation. It is not uncommon, farmers are forced to make distress sale at lower than MSP in hours of financial or other form of crisis. *Rabi* paddy is providing better yield, higher net return, and better return to investment as compared to *kharif* paddy, however, these gain is also attached with higher level of CV, indicating growing *rabi* paddy is more profitable although subjected to more risk. Under high uncertainty, the risk of investing additional amount of capital also increases risk further, and expansion of area under particular crop becomes difficult. Therefore, farmers prefer to grow more *kharif* paddy even though it provides lower yields.

12.2.3.3 Intensification of Cropping System

12.2.3.3.1 Cropping System Models

Cropping system in the Sundarbans of West Bengal is dominated by mono-cropping with *kharif* paddy. The cropping intensities are low (around 120%) and more than 80% of the farm land remains fallow during *rabi* season. However, despite many constraints, the farming in the region has good potential to enhance farmers' income through scientific interventions of soil and water resources. For example, implementation of land-shaping models (modification of land suitable for on-farm water harvesting) like farm pond, paddy-cum-fish, and deep-furrow-and-high-ridge system along with scientific management of soil, water and nutrient management were capable to increase the cropping intensities significantly (from 114 to 186 percent) (Mandal et al. 2015a). Increased cropping intensities helped enhancement of farmers' income significantly. Such interventions (say, land-shaping) created the opportunities of higher cropping system intensification from existing practice of mono-cropping. Various options were rice-rice, rice-fish, rice-vegetables, and rice-fish-vegetable cropping systems. All these cropping systems have been demonstrated in large number of farmers' fields in Sundarbans and were found to be quite successful in terms of increasing farmers' income substantially and sustainably. Results from demonstration indicated, farmers' income (net income) could be increased from merely Rs. 470 per month (*kharif* paddy alone) to as high as Rs. 11,999 per month (paddy-fish-vegetable cropping system). Besides, growing betel vine (perennial crop) alone was also a good option to realise higher farmers' income (Rs. 5667 per month). The results showed, based on0.60 ha being the average land holding in the region, the net return (income) per month could increase from Rs. 282 per month (*kharif* paddy alone) to Rs. 7199 per month (paddy-fish-vegetables), and to Rs. 3400 per month for betel vine cultivation alone. The cropping system intensification in the Sundarbans region indicated, there were feasible options to increase the farmers' income significantly, and in fact, with much higher than the baseline income with traditional practice at regional level (Rs. 3773 per month) or at state level (Rs. 3980 per month).

12.2.3.3.2 Impact Study

Long-term sustainability of the land-shaping models was affected by many factors, which were evident from the post-project impact study (Annual Report 2016–2017b). The impact study of the land-shaping techniques/models demonstrated in the farmers' fields was carried out in different villages in Sundarbans area during 2015–2016 following their successful interventions over the last four years (Table 12.6 and Figs.12.2 and 12.3). During the year of impact study, all support (input or financial) from the implementing agencies (ICAR-CSSRI, Canning or Ramakrishna Mission Ashram Krishi Vigyan Kendra, RAKVK, Nimpith) were withdrawn, and all management interventions were done by the farmers themselves. It was noted that although the land-shaping techniques were successfully managed by the farmers in different locations, harnessing the extent of benefit out of the technologies varied in different fields. The reasons of differential benefits accrual depended on the farmers' own capacity (financial) to manage the system, and also his/her access to resources due to remoteness of the place. Often, it was noted that extent of adoption (25–30%) depended on the non-agricultural factors (backwardness, other than remoteness, of the area) rather than technologies *per se*.

12.3 Challenges for Increasing Farmers' Income

Real concern for the farmers in the Sundarbans region in the state is not only to achieve higher farmers' income (say, doubling the present level by 2022 as per the target set by the Government of India), but also to sustain it across the groups.

Table 12.6 Cropping system intensification through land-shaping technique interventions towards higher income in Sundarbans of West Bengal

Particular	Cost/Return					Cropping system intensification option			
	Kharif rice	*Rabi* rice	Vegetable	Fishery	Betelvine	Kh. rice-*rabi* rice	Kh. rice-fish	Kh. rice-vegetable	Kh. rice-fish-vegetable
Total cost (Rs/ha)	32,419	56,325	39,130	66,632	98,663	88,744	99,051	71,549	138,181
Gross return (Rs/ha)	38,063	82,725	98,500	145,600	166,668	120,788	183,663	136,563	282,163
Net return (Rs/ha)	5644	26,400	59,370	78,968	68,005	32,044	84,612	65,014	143,982
Yield (t/ha) (no in 0.1 millionor lakh for betel leaves)	3.83	5.4	9.88	1.95	2.91	9.23	5.78	13.71	15.66
Output-input ratio	1.17	1.47	2.52	2.19	1.69	1.36	1.85	1.91	2.04
Net return per month (Rs/ha)	470	2200	4948	6581	5667	2670	7051	5418	11,999
Net return per average size of holding (0.60 ha)	3386	15,840	35,622	47,381	40,803	19,226	50,767	39,008	86,389
Net return per month (Rs)	282	1320	2969	3948	3400	1602	4231	3251	7199
Gross return per average size of holding (0.60 ha)	22,838	49,635	59,100	87,360	100,001	72,473	110,198	81,938	169,298
Gross return per month (Rs)	1903	4136	4925	7280	8333	6039	9183	6828	14,108
No of observation	85	35	48	32	80	22	28	44	25

Source: In-house study, Mandal et al. 2017; cost-return of betel vine cultivation has been taken from Mandal and Mandal 2016

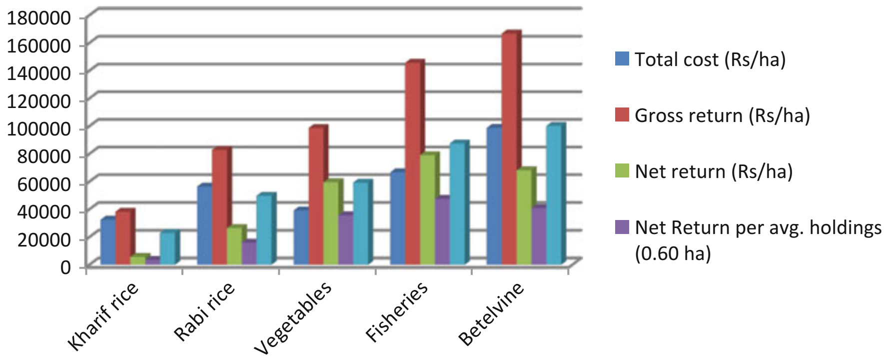

Fig. 12.2 Cost-return of existing cropping systems in Sundarbans, West Bengal. (Source: In-house study, Mandal et al. 2017)

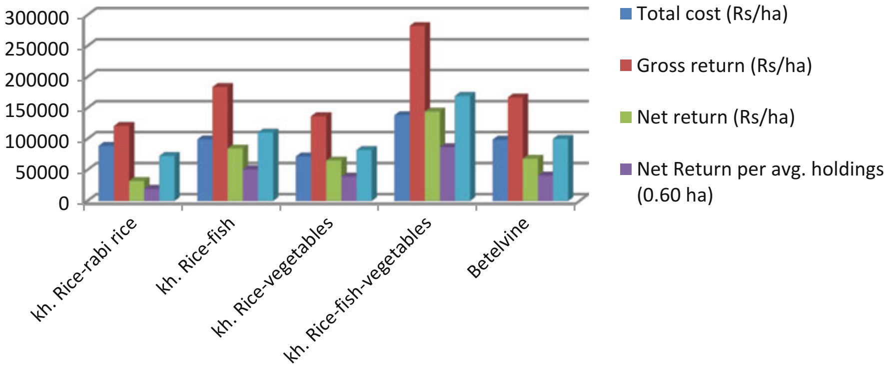

Fig. 12.3 Cost-return after cropping system intensification in Sundarbans, West Bengal. (Source: In-house study, Mandal et al. 2017)

Farmers were operating under different socioeconomic conditions, and although technologies could be replicated, 'social cloning' is not always possible in the region. Therefore, enhancing farmers' income across all groups would be a challenging task. Income of each segment of the farming communities, like potato farmers, vegetable farmers, flower farmers, fish farmers, integrated farming system practitioners, etc. could be enhanced within a short period of time. But enhancing income for all farmers' groups including agricultural labourers needed more comprehensive strategies, like increasing production through technology dissemination, enabling market environment for ensuring remunerative price, supply-chain management for both input delivery and output disposal, and risk mitigation under unforeseen happenings. Some of the challenges which need to be addressed are discussed in the following section.

12.3.1 Strategies for Agricultural Development

12.3.1.1 Natural Resource Development

The strategies for improving the farming conditions in Sundarbans, West Bengal have been focused primarily on two ways, firstly by developing salt tolerant crop varieties, and secondly by rainwater harvesting through different land-shaping models, and the same has been discussed in details by Sarangi and Rahman in a separate chapter in this book.

12.3.1.1.1 Rice Varietal Development

Information on rice variety adoption by farmers has been collected through households' level primary survey on rice growers. Contribution in terms of area coverage and economic gain due to adoption of major salt tolerant rice varieties, produced by ICAR-CSSRI RRS Canning and those purchased by farmers indicated, salt tolerant rice varieties have good potential to contribute national exchequer and there is a growing demand for such varieties among farmers. Impact study on salt tolerant rice varieties as developed by ICAR-Central Soil Salinity Research Institute showed that during 2010–2015, 8.30 tonnes of Amal-Mana rice variety seed has been produced and disseminated to the farmers (over 500 farmers), Over one-fourth of the farmers have grown the Amal-Mana rice variety during subsequent years, after purchasing seeds from CSSRI RRS Canning Town. Farm-level impact of CSSRI rice variety, Amal-Mana has been quite encouraging in terms of incremental yield (34%) and income (22%) during kharif season. During 2010–2015, over 500 farmers have grown Amal-Mana rice varieties spread over 850 ha and produced 3265 tonnes of rice. The contribution of Amal-Mana rice variety to farmers' economy has been valued at Rs. 264 million during 2010–2015 (Annual Report 2015–2016).

12.3.1.1.2 Land Shaping Models

These land-shaping techniques, particularly the farm pond and paddy-cum-fish models, are unique technology for addressing the key challenges, like land degradation (salinity), drainage congestion, and scarcity of fresh water for irrigation, and, in turn, to enhance production, productivity, income and employment. These techniques particularly farm pond and paddy-cum-fish, are financially viable and attractive proposition for the region. Some of the key impediments for large-scale implementation of such interventions were marginal land holdings, which are further divided into several parcels. High initial investment is also a serious impediment. Some pockets exhibit the presence of acid sulphate soils, present either at the surface or at sub-surface depths. This makes it difficult to implement the technology on land-shaping and water harvesting, since there is an element of risk of exposing acid

Table 12.7 Financial feasibility of land-shaping models in Sundarbans of West Bengal

Criteria	Farm Pond	Paddy-cum-fish	Remarks
Internal Rate of Return (%)	65	54	>discount rate (14%) so feasible
Net Present Value (Rs)	286394	261385	Positive return, feasible
Benefit Cost Ratio	1.74	1.62	> 1, feasible
Payback Period (years)	1.75	2.24	Recovers initial investment quickly

Source: In-house study, Mandal et al. (2013)

sulphate layers present at the sub-surface, as this is not recommended for the management of these problem soils. For larger adoption of these technologies it is required to address some key issues, like socioeconomic constraints, and others, which can be addressed at research level (land configuration, soil quality), and at policy level (incentives), presented later in this chapter. Community-based rainwater harvesting as well as common pool wasteland may be encouraged in this direction. Case study was conducted to assess impact (Mandal et al. 2015a) of such land-shaping intervention on farm households in South and North 24 Parganas districts of West Bengal. Financial analysis of these land-shaping models, farm pond and paddy-cum-fish system under study indicated that investment on such interventions were financially viable (IRR 54 and 65%, NPV Rs. 2.61 and 2.86 lakhs, BCR 1.62 and 1.74 and Payback period 2.24 and 1.75 years) (Mandal et al. 2013) (Table 12.7). For out-scaling of these technologies to a greater level there is need to address some socioeconomic constraints and policy support. Such proposition of crop-fish integration in agriculture through these land-shaping models is highly suitable for augmenting the income of intra-agricultural sectors in Sundarbans.

12.3.2 Homestead Production Systems

Homestead production systems (HPS) are an integral part of the daily household activities to produce food (fruits, vegetables, fish, and livestock) for household consumption in Sundarbans. They contribute significantly towards meeting daily food and nutrition requirements, generate income when surplus produce is grown and can therefore help to mitigate price or output shocks due to unforeseen events, and can help to reduce poverty. Case study in the Sundarbans region was conducted to understand the current status of HPS and opportunities to improve HPS and livelihoods of rural communities (Table 12.8). Aquaculture in homestead ponds (average area 445 m^2) and homestead gardens (vegetables and fruits; average area 120–240 m^2) were the two key components of the system. The ponds were mostly perennial, but some retained limited amount of water during non-monsoon months. On average, 70–75% of the total vegetables produced (average total of 340 kg per household) in the HPS were consumed by the households (HH), and this accounted

Table 12.8 Contribution of HPS to the households' food security in Sundarbans

Items	Contribution (%)			Average production (kg/HH)
	Home consumption	Fulfilling the total requirement	Marketed	
Vegetables	70–75	30–40	25–30	340
Fish	30–35	50–60	60–65	143
Fruits	85–90	–	5–10	–
Livestocks	80–85	50	10–15	–

Source: In-house study, Mandal et al. 2015b

for 30–40% of the total household requirement. Part of the harvest (25–30%) was marketed at every 1–2 day-intervals. Similarly, around 30–35% of the fish produced (143 kg per household) in the HPS was consumed by the farm family. Around 50–60% of the total fish produced in the HPS were sold (Mandal et al. 2015b). In the case of livestock, production was minimal, resulting in 80–85% of production being consumed by the households. Nevertheless, this provided almost 50% of the households' needs, with a small amount left over to sell at the local markets. Productivity of HPS could be improved and these systems could provide greater contribution to the goal of regional food security. To achieve this, farmers need assured supply of quality inputs and training on production and management of the main components, viz. fish, vegetables and livestock. Since HPS are attended to by all members of the household, training programs should focus on the whole family, including men, women and children (12–18 year of age). In addition to technical training, farmers need advice on financial, as well as access to technical resources and support groups. Enhancing the production level would increase the quantity of marketable surplus and thereby increase the contribution of HPS to regional food and nutrition security.

12.3.3 Policy Needs for Agricultural Development

Development of technologies by Scientists/researchers alone cannot solve the problem of farming communities unless the process of technology dissemination is complemented by desired policy initiatives. Some of the key policy issues are described hereafter.

12.3.3.1 Out-Scaling Constraints on Agro-technologies: Need More Financial Power to the State Government

The research experiments in experimental farm and also in farmers' fields indicated encouraging results for management of salt affected areas with positive gain. The evolved options should be technologically sound and profitable in terms of output-input ratios, but often the success stories are sporadic and limited to the areas where research institutes are functioning. Farmers have to carry out their farming operations under diverse socioeconomic conditions to adopt new technologies. Different socioeconomic factors stated earlier might affect the adoption behaviour towards new technologies. For sustaining the benefits farmers need continuous support, like more capital investment, additional knowledge on crop management, and assurance of remunerative price. Over the years, although it is perceived that climate change is happening, the agricultural productions are affected adversely in the extreme events and are likely to be affected in future also. Having looked into the local situation carefully it is evident that there is a need for location-specific micro-management for agricultural risk mitigation. More often, it is weather aberrations, not climate change, that needs to be addressed for which the state government may be made empowered more financially for better decision-making and mitigation of the adverse situations.

12.3.3.2 Community Engagement for Higher Social Benefits

Agriculture is a state subject in India and interventions on land management activities are always complex and sensitive. Understanding local community, private bodies, and common property resources needs particular focus. Technologies for salt affected management have been demonstrated in farmers' fields in various parts and benefits have been accrued to the individual farmers. Field-level demonstration of agro-technologies has been quite successful for increasing the private benefits, but by and large, could not be made socially inclusive under all situations. Adoption of salt affected management technologies requires sizeable investment on land reclamation or modification. Incentives for such investment on land, particularly for the tenant farmers, are not very attractive proposition, and thus impeding to its large-scale adoption. Effective engagement through collaboration with non-governmental organisation (NGOs) and focussing on higher community engagement would be leading to higher social benefits and larger adoption. Besides developing technologies effective for private lands, there is a need for the community-level land management technologies effective for community at large.

12.3.3.3 Remunerative Price and Agricultural Marketing

Case study in Sundarbans on agricultural marketing efficiencies in terms of producer's share in consumer rupee was estimated as 44% for brinjal, 37% for bhindi (lady's finger), 26% for tomato, 45% for guava, and 60% for marigold cultivation (Mandal et al. 2011). Net price received by the farmers was calculated following the method prescribed by Acharya and Agarwal (2001) by deducting transportation cost plus value of loss incurred by farmers (during transportation of commodities to the market) from the absolute price received by the farmers. The marketing efficiencies were estimated at 0.79, 0.58, 0.36, 0.82 and 1.51 for brinjal, bhindi (ladies finger), tomato, guava and marigold, respectively. Average areas under production of these crops were 0.10 ha, 0.08 ha, 0.12 ha, 0.38 ha and 0.10 ha, respectively for brinjal, bhindi (ladies finger), tomato guava, and marigold cultivation. This indicated, although farmers received reasonable share to the consumers' price, it was very small scale of production unit that lowered the profitability in cultivation of these crops. High cost of production (due to escalation of input cost) was most important constraint faced by the farmers to enhance their production and, in turn, the marketable surplus of the produce. Besides, poor transportation facilities, occasional market glut during peak season, lack of remunerative price (observed very often), and intraday price variation (price uncertainty) were the other most important constraints faced by the farmers in marketing of their produce and hence instability in returns in the region.

Small scale of production unit, even if it produces crops with high production efficiency, is severely constrained with poor marketing efficiency. In the era of market-led growth, the volume of trading must be increased to ensure greater share in the consumers' rupee to primary producers. For this, establishment of market linkages and functioning of efficient marketing system areof utmost importance. The system was operating under a vicious cycle, like – large number of small producer – producing low marketable surplus – resulting in low bargaining power, and finally low profit. Then these commodities are transferred to large number of small traders who were handling these produce in a small scale subjected to high degree of post-harvest losses – ultimately resulting in the whole marketing system turned into a non-commercial venture (Mandal et al. 2011). Besides this traditional agro-marketing system, the agricultural marketing environment throughout the country, including Sundarbans region, is also undergoing the process of rapid transformation due to large-scale corporate entry into this marketing system. So far, the share in total volume of retail through such marketing was very less. Existing market environment and marketing status of agro-products, particularly the un-processed commodities, availability of remunerative/reasonable prices, are very crucial to change the cropping pattern towards high-value crops and also crop diversification.

The current agricultural system is primarily production-based. Agricultural price variability is very high across time and region. The risk of low-price affects the primary producers very badly and the risk is easily transmitted to the primary producers only. As a result, farmer's income falls drastically in the event of either production or price instability. The problems are more pronounced for farmers operating in salt affected areas as the instability of crop output is much higher than cultivation in normal (good) land. Analysis on the effectiveness of agricultural price policy, minimum support price (MSP) by comparing with Farm Harvest Price and Cost of Production during 2004–2005 to 2014–2015 indicated that such price policy was not so effective for ensuring remunerative price for most of the crops like paddy (Mandal et al. 2017). The FHP of paddy remains below the COP. Despite lower FHP as compared to COP for paddy in the state, rice has remained the major crops over the period of time. Because paddy has larger value to the farmers other than merely earning profit, like its contribution to household-level food security, adaptability to different stressed conditions, and for low-risk as compared to other crops. Market prices were the key drivers to change the farm economy and high price instability in agro-marketing sector that adversely affect the out-scaling of these agro-technologies. Some of the agricultural marketing strategies needed are (1) To delineate the clusters of districts/areas, which have favourable resources, climate, and socioeconomic conditions for growing each of these high-value commodities (horticultural crops), and thus to formulate differentiated strategies that could be used for triggering the development of the sector; (2) On one hand, corporate retailers are consolidating rapidly asking for bulk purchase of agro-commodities, while, on other hand, producers are becoming more and more fragmented and producing small quantity of marketable surplus; so farmers need to be organised/consolidated (like community participation by promoting Farmers Producers Organisations, Self Help Groups) to increase their volume of trading to increase their bargaining power to take advantage of these marketing systems, and (3) Developing agro-marketing infrastructure calls for large-scale investment both from public and private players.

12.3.3.4 Who Are Farmers? Addressing them Adequately

Most of the farming operations are done by the aged personnel across different states. Young rural population is not engaged in the farming business. Case studies through primary survey in Sundarbans indicated, almost all the farming activities were taken care of by the aged farmers (average age of the respondents above 50 years), while the young generation in the villages were out of agriculture in search of alternative livelihoods. The reason being non-farm income options fetch better return and able-bodied workers are more likely to engage gainfully. Accepting the situation that young would be out of agriculture, there is a need to focus on higher mechanisation so that even aged farmers can do the farming. Alternatively, the agriculture policy needs to be focussed to keep rural folk engaged in farming through gainful employment by providing positive trade-offs in favour of agriculture over non-farm income sources. To retain rural youth in agriculture, merely technology push, however sound it might be, will not suffice; rather agro-entrepreneurship needs to be invoked. The fact remains, rural youth aspires to be engaged as salaried class, and not as wage earners. There is a need to create professional service providers and technology managers in professional way through attracting private investment in the sector.

12.3.3.5 Can Farm Income Be Increased through Agriculture Only?

Indian agriculture is primarily production-based. Agricultural price variability is very high across time and region. The risk of low-price affects the primary producers very badly and the risk is easily transmitted to the primary producers only. As a result, farmer's income falls drastically in the event of either production or price instability. For example, West Bengal is a champion in production of many high-value crops (other than paddy) like jute, potato, fruits, vegetables, flowers, and fish, etc. However, the income from agriculture is one among the lowest in the country.

Lower income from agriculture cannot be blamed on agriculture *per se* rather it is due to the low purchasing power of the people in the state. Small and marginal farmers are producing these commodities, and even if they operate with higher production efficiency, their earning is low and surviving with low cost of living in their respective regions. The key driver of change in income from agriculture is pegged with income of people from sectors other than agriculture. As the consumer demand for the high-value commodities is highly elastic, overall consumers' income in the state needs to be enhanced significantly to increase the return to agriculture. Complementary relationship between agriculture and industry is well known, therefore to increase agricultural income of the state, it needs support from other sectors, industry and service. Merely pushing agriculture may not suffice to achieve the targeted income enhancement from agriculture. Investment on non-agriculture sector would be paying rich dividend to farmers rather than focusing on agriculture itself.

12.4 Conclusions

Technology options are available for increasing cropping intensities and the Sundarbans agriculture is waiting for policy thrust like attracting private investment, value-addition to agricultural commodities, and marketing innovations. Farmers need timely supply of quality seed and other inputs (irrigation, fertiliser, pesticides, etc.), particularly before the two cropping seasons, and remunerative prices to their produce. Professional help is needed, who could act as key service providers to supply inputs and facilitate availing credits, buying insurance products, and selling of produce through single-window system. Such professionals will act as the facilitator between farmers and government agencies and help risk mitigation in agriculture. The chapter concludes that that enhancing farmers' income in Sundarbans, West Bengal is a challenging task but can be enhanced substantially through technology interventions and policy support. The most critical concern for the farmers in the Sundarbans region is not only to achieve higher farmers' income level, but also to sustain the enhanced level across the different farmers' groups.

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Part V
Flood and Drainage Impacts, and Engineering Interventions for Integrated Water Management

Estuary management using the vast water resources may be a holistic approach for improved water management (Courtesy R. N. Mandal)

Chapter 13
Development of Sundarbans through Estuary Management for Augmenting Freshwater Supply, Improved Drainage and Reduced Bank Erosion

N. K. Tyagi and H. S. Sen

Abstract The Sundarbans delta is a fragile ecosystem facing the multiple hazards in the forms of increased flooding, shrinking & sinking, and acute shortage of freshwater, all of them constraining the economic development. Based on the extensive review, partial or complete closure of estuaries for creation of freshwater reservoir, *beel* management in tidal rivers (TRM) to reduce drainage congestion, and managed realignment of embankments for re-naturalizing the low-lying areas are identified as scientific knowledge-based interventions to ease the development constraints. The important pre-closure investigations and prospective locations for initiating the estuary-closure in Sundarbans are described. The concept of tidal river management (TRM), the new name for an old practice, and the experiences of TRM in Bangladesh, are briefly elucidated. In India, the idea of creating a freshwater storage by damming Saptamukhi river or elsewhere, using suitable state of the art technology through phased development, which is likely to reduce the vulnerability of Sundarbans to natural hazards, needs a serious re-look. Finally, the concept of managed realignment of estuary embankment and the need for such realignments in Sundarbans in order to minimize embankment failure, which causes immense damage in the region, is discussed.

Keywords Sundarbans · Estuary management · *Beel* · Embankments · Morphodynamical behaviour · Realignment · Equilibrium

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13.1 Introduction

“Sundarbans is one of the richest ecoystems in the world, celebrated for its ecological attributes, ... but it is a difficult place to live in;” that is how the recent World Bank report describes, as the world’s largest delta (Sánchez-Triana et al. 2014). Frequent threat of cyclonic storms, sea level rise, and flooding leading to seawater intrusion, and consequent salinization of soil and water, and scarcity of fresh water during non-monsoon period have sapped the resilience of land and people in this region located in the delta of three mighty rivers Ganges-Brahmaputra and Meghna in South Asia. The region’s resource base has deteriorated and is unable to sustain the economic development. The annual cost of this damage which is associated with ecosystem was put at INR 6.7 billion in 2009 (Strukova 2010). The Indian Sundarbans delta, being a moribund part of the lower delta plain of the GBM system, is experiencing both declining freshwater supplies and net erosion (Danda et al. 2011). The embankments, once constructed to protect the area, are increasingly becoming prone to erosion and failure. Shrinking and sinking of delta due to the twin hazards of reduction in sediment in river flows due to water diversion in upstream reaches and sea level rise put together pose a serious threat of land loss, which has been put at 50% of the present delta area (Dandekar and Thakur 2014).

The scope of the present paper lies, away from the upstream hydrology of the river Ganges, to the geological setting of Sundarbans delta in the south. From the standpoint of vulnerability to the forces of nature as well as anthropogenic impacts, the area lying between the core zone (legally protected areas of the Sundarbans) and the stable boundary zone i.e., the densely populated area away from the core zone of Sundarbans, which may be called as the transition zone (comprising areas along major tidal rivers), is considered most susceptible (Fig. 13.1). An important approach for the development of coastal protection, which involves “hard” and “soft” structural methods, emanates from coastal engineering measures (Wiegel and Saville 1996). In the strategy paper for sustainable development of Sundarbans, the World Bank has identified vulnerability reduction through estuary (coastal regions where salty ocean water mixes with fresh water from rivers) management as one of the important interventions (Sánchez-Triana et al. 2014). The three important issues concerning the estuary management with substantial engineering inputs are: a) protection of embankments which are constructed as tidal defence structures; b) estuary closure dams for creation of freshwater reservoirs, flood control and reclamation of low-lying tidal flats, and creation of tidal basin power plants; and c) *beel* management to reduce drainage congestion and reclaim land (tidal river management). Examples may be drawn from practices worldwide.

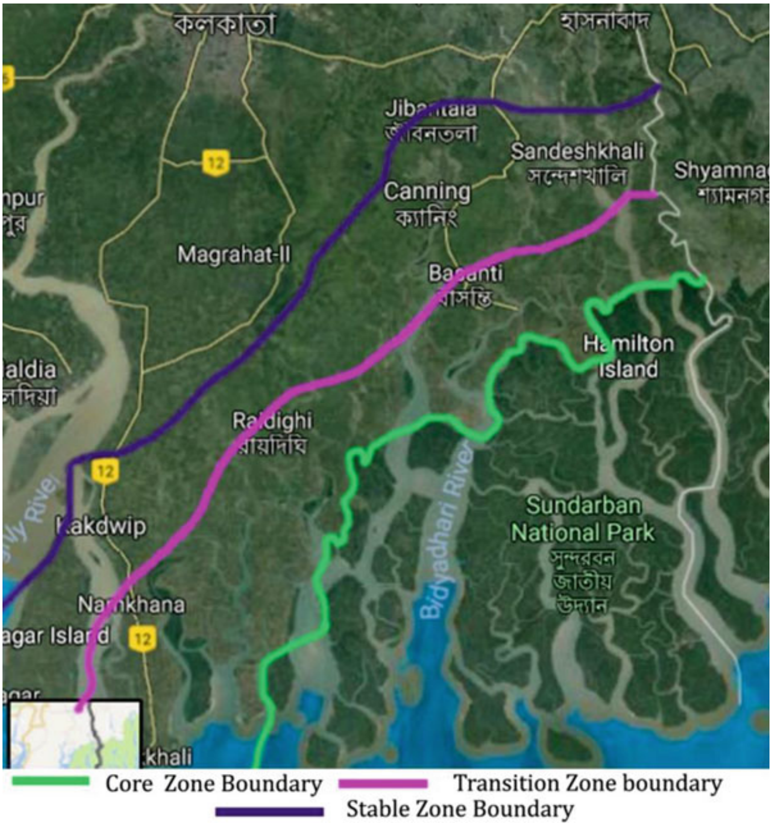

Fig. 13.1 Map of Sundarbans showing approximate zone outer boundaries. (Redrawn on Google map following Sánchez-Triana et al. 2014, World Bank, open domain)

13.2 Review of Estuary Closure Works for Freshwater Storage

The estuary closure involves construction of structure which could be permanent (dam), partial (weir), and temporary (coffer dam). The estuary closure has been practised for thousands of years with one or more of the following purposes.

Reclamation of Low-lying Tidal Land Most of the estuary closures were primarily undertaken elsewhere to reclaim land for agriculture and other such purposes. The Zuiderzee and Delta works are two success stories under this category (Schultz et al. 2013).

Creating a Fresh Water Reservoir Providing for shortages during dry season, tidal inlets have been used in several places including The Duriangkang reservoir on Batam island in Indonesia, and closure works in Korea (Young et al. 2009, Verhagen 1995).

Creation of a Tidal Energy Basin In the initial phases, the Kalpsar project also had provision for generating electricity by harnessing tidal energy (Anonymous 1999). But the proposal was later on dropped for cost reasons. But the closure dam of the Siwha estuary in Seoul in Korea is the one for the creation of tidal power, which has been successfully operated.

Shortening of the Length of a Sea Defence Closing the estuaries causes reduction in embankment lengths and decreased maintenance costs. This has been one of the major gains from Brouwersdam project in the Netherlands and Feni river closure in Bangladesh (Stroeve 1993).

It would be worthwhile to review how the estuary closures have been useful in augmenting the freshwater and land resources in different countries, which faced similar constraints to development as those in Sundarbans. A global inventory of the closed off tidal basins, which has been subject to closure through dams, was undertaken in 2007 on the eve of the 75th anniversary of Zuiderzee Scheme (Schultz et al. 2013). They have reported that in 25 such schemes covering a total area of about 0.74 m ha, freshwater reservoirs were created in 0.40 m ha area, while the remaining land was reclaimed for agriculture and other purposes. Though originally the water within the enclosed space was saline, over a period of time, it was transformed into freshwater by a suit of judicious management practices. The post-reclamation issues in respect of water quality in the reservoir, land subsidence, sea level rise and host of other issues dealing with sustainable development have been flagged. Few Important estuary closure projects include:

13.2.1 Zuiderzee in Netherlands

It was perhaps in the flood-threatened deltaic alluvial plain of the Netherlands, where the practice of estuary closure for flood control and reclamation of low-lying land for agriculture began several hundred years ago (Rijkswaterstaat n.d.). Twentieth century saw far reaching science and technological developments which made it possible to undertake large projects. The Netherlands had a vulnerable coastline, was densely populated, and needed space for housing, industry and agriculture. The Zuiderzee Scheme in the northwest of the country involved damming of the Zuiderzee, a large but shallow inlet in the North Sea, and the reclamation of land in the newly enclosed water, using five big polders. Flood protection and reclamation of additional land for agriculture were the main objectives. The barrier allowed a large freshwater lake, the IJsselmeer, improving the supply of fresh water (Lonnquest et al. 2014). Globally, Zuiderzee is considered a marvelous piece of hydraulic engineering. The dam, called the Afsluitdijk, which was built in 1932–1933, separated the Zuiderzee from the North Sea.

13.2.2 Saemangeum Scheme in South Korea

In modern times, *Saemangeum Scheme* in South Korea on an estuarine tidal flat on the coast of Yellow Sea is considered another landmark tidal basin closure project. A 33-km long sea dike was constructed in the mid-west area of South Korea over an area of about 40,000 ha by damming the estuaries of the Mangyeung and Dongjin Rivers, replacing tidal flats and sea shallows with land, and a huge freshwater reservoir (Ha et al. 2010).

13.2.3 Hachirogata Project in Japan

Hachirōgata is a lake, also called Hachirōgata Regulating Pond in Akita in northern Japan, is 4 m below sea level. It used to be the second largest brackish water lake in Japan, having a surface area of approximately 22,000 ha (Schultz et al. 2013). Reclamation in this area began in 1957 and a village was established on part of the reclaimed land, while 4830 ha remained under the lake. As the salinity of brackish water declined, it was reported that fishery of shijimi shells (*Corbicula japonica*), which was a thriving industry before reclamation, also declined.

13.2.4 Kuttanad Polders in India

Large farming areas near Vembanad Lake have been reclaimed for paddy cultivation. In earlier times, reclamation was carried out mainly from the shallow part of the Vembanad Lake or from the periphery of the Pamba River. These reclamations constituted small areas of paddy fields called padsekharams. It involved pumping out water from small polders for cultivation of paddy, and subsequently water flowed into these padsekharams by gravity through small channels from the lake. Technological advancement in subsequent years enabled better regulation of water from the lake. To provide a permanent solution to flood problem in Kuttanad, Thottappilli Spillway Project was envisaged in such a way that flood water from Pamba, Manimalayar and Achankovil rivers were diverted to the sea before it reached Vembanad lake. A *bund* (dam) was constructed across the river, which prevented seawater from entering inside Kuttanad during summer. So, farmers are now able to cultivate an extra crop per year.

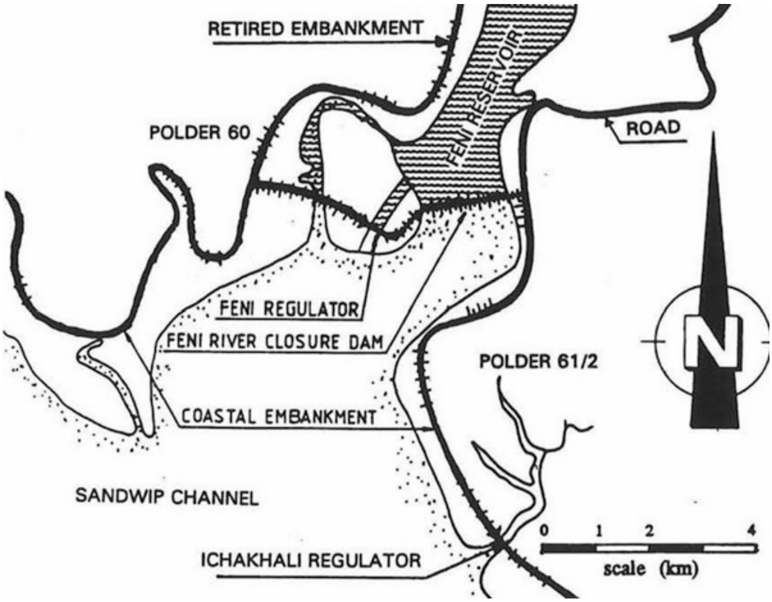

Fig. 13.2 Feni River closure dam. (Source: Stroeve 1993, open domain)

13.2.5 Feni River Closure in Bangladesh

The Feni River Closure Dam in south eastern part of Bangladesh was built in 1985 to store fresh water, prevent flooding and saline intrusion, as a part of Muhuri Irrigation Project, and this comprised development of 27,000 ha of arable land located in the tidal zone of the Noakhali and Chittagong Districts (Fig. 13.2). The Feni estuary is connected to the Bay of Bengal by means of the Hatia and Sandwip channels. There are large changes in the coastlines and bathymetry in the area due to the huge sediment loads of river Mehgna, and these get deposited in low lying delta creating a secondary problem, however. As a result, there are huge accretions of sediments directly in front of the dam, which have resulted in increased elevation of foreshore downstream of the Feni Dam (Stroeve 1993).

13.2.6 Kalpsar Project in Guelph of Khambat, India

The Guelph of Khambat is a multipurpose project, being executed on west coast in Gujarat by closing part of the Guelph, though a 30-km dam (Fig. 13.3). Once completed, the project will create a freshwater reservoir of 1000 MCM by storing the runoff from Sabarmati, Mahi, Dhadar and Narmada, and the rivers in Saurashtra, to be used for irrigation, industry and water supply (GoG 1999). Once the tidal flow

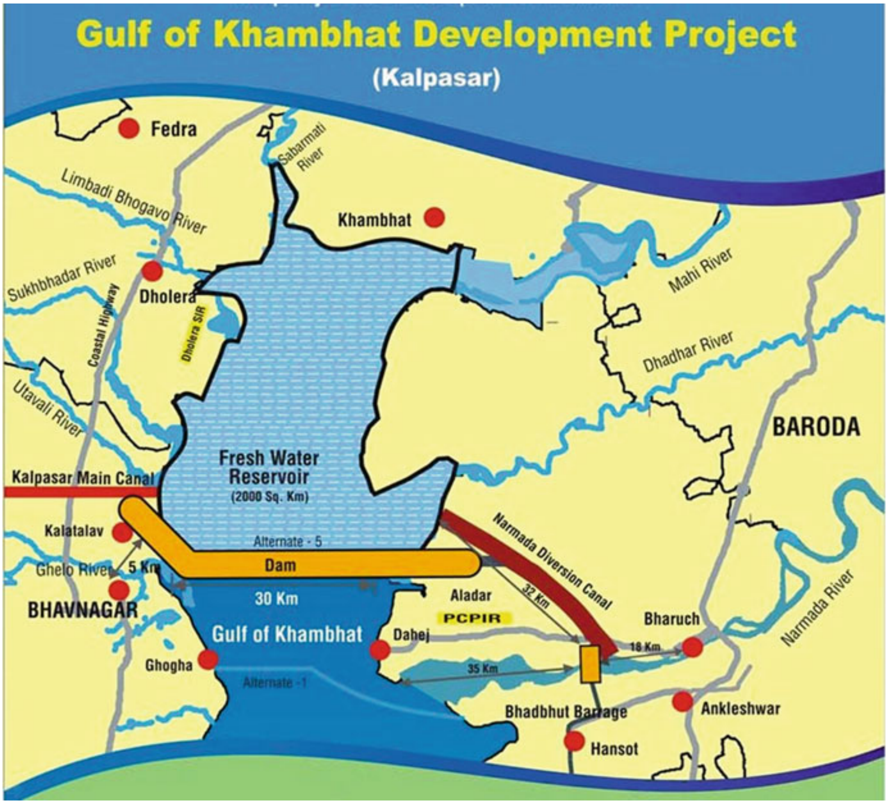

Fig. 13.3 Location map of Kalpsar project. (Source: GoG 1999, open domain)

upstream of dam stops, about 200,000 ha of tidal flats over 2000 sq. km reservoir area will be spread for reclamation. The ten-lane highway and a railway track on the dam would reduce the distance between South Gujarat and Saurashtra by 200 km. A number of issues, which have implication on sustainability of the project because of quality of river water draining into the reservoir, impact on brackish water fisheries, damage of the plants and benthic which survive in salt water, have been raised. Detailed field investigations and modeling studies have been conducted and some are underway to assess the impacts and propose remedial measures (Annonymous 1999).

13.2.7 Some Common Problems Encountered in Estuary Closure Projects

The creation of freshwater storage by a closure dam may result in several externalities of such changes in composition like presence of brackish water beyond the closure dam, pollution and siltation in the reservoir itself reducing its storage capacity, and reduction of brackish water fishery (Schultz et al. 2013). The water entering from upstream catchments may be loaded with increase in pollutants of anthropogenic constituents including organic compounds, as the use of agrochemicals would increase with expansion of irrigation. For example, in the multidisciplinary field studies conducted in Yeongsan Reservoir (YSR), Korea, where a 4.35 km-long dam was constructed in 1981, resulted in disappearance of brackish water zones, change of microbial diversity in habiting patterns, and a decline in fish diversity (Young et al. 2009). There was significant reduction (33.6%) in storage capacity since the dam was constructed due to sedimentation from freshwater entering the reservoir. Also, water quality in YSR was affected by complex physico-chemical and hydrological phenomena, including saline and thermal stratifications, and pollutant loadings leading to eutrophication. Since the dissolved oxygen was reduced in deeper layers, the benthic communities could be adversely affected by occurrences of hypoxia. Similar effects were noticed in Lake Hachirogata project, where sedimentation rate increased after reclamation in proximity to the agricultural zone. Higher levels of dissolved total nitrogen and dissolved total phosphorus (DTP) were found in both surface and bottom waters. Large amount of mobile phosphorus (42–72% of TP) trapped in the sediment increased the risk of phosphorus release and intensification of algal blooms. (Jin et al. 2016). It has been inferred by the authors that high sediment phosphorus and phosphorus mobility is a source of pollution in the coastal environment. In Kuttanad polders, though crop farmers gained economic benefits from the project, there are reports of severe environmental problems (Asha et al. 2014) leading to deterioration of fish varieties and infestation of water weeds. The overview of the estuary closure projects that construction of dam alone is not sufficient. The post-closure studies (Schultz et al. 2013) suggest that water within and outside the closure should be carefully controlled and regulated for environmental sustainability of the freshwater reservoir.

13.3 Cases for Creation of Freshwater Reservoir in Sundarbans Estuaries

13.3.1 Sundarbans in India

There can be no two-opinion that India needs to augment its freshwater availability to meet the growing demands. The opportunities for augmentation though closure of the estuaries may be limited to only few selected coastal regions on east and west coast. As early as 1980, tidal channel in Guelph of Khambat was visualized as possible site envisaging building a dam for establishing a huge fresh water reservoir for irrigation, drinking and industrial purposes. Considerable experience was gained in planning the development of large estuary project in the course of feasibility studies over last two decades (Anonymous 1999). Additional freshwater supplies are essential for imparting the resilience to the degrading socio-economic and biophysical systems in Sundarbans. It is for this reason that exploring the feasibility of estuary closure to create freshwater storage has been identified as part of the action plan by World Bank (Sánchez-Triana et al. 2014).

It was as early as 1960's, that the River Research Institute in West Bengal, India in collaboration with Netherlands prepared a proposal, which remained unimplemented**,** to build a barrage across the Saptamukhi River to store freshwater and to protect area from natural disasters (Delft Hydraulics 1968). During last 57 years since the inception of the idea of creating a freshwater storage by damming Saptamukhi River, the technology of creating such infrastructures has vastly improved, at the same time the demand for freshwater has gone up. Based on the assessment of various options to reduce the vulnerability of Sundarbans to natural hazards and the intensive scientific deliberations in the Conclave of Indian National Academy of Engineering (Anonymous 2013), idea to build fresh water reservoir across the Supathamukhi River got reinforced. A phased development, undertaking Saptmukhi in the first phase, was recommended. Based on the experience gained (Phase-I), Calachura- Cruzan creek (Phase-II) and Takurayan (Phase-III) was recommended (Anonymous 2013). The areas covered under each phase are shown in Fig. 13.4.

The proposed location of dams and sluice gates are shown in Fig. 13.5. If undertaken, these developments will lead to rationalized lengths of embankments, creation of freshwater storage, and protection of precious land from tidal surges.

13.3.2 Sundarbans in Bangladesh

Bangladesh has the experience of implementing Feni River closure dam as early as in 1985. Coast and polder development are important components of their integrated land and water resources management programme under which Nijhum Dwip and surrounding area were selected (Fig. 13.6) as a pilot project for first track study (GoB 2015). Activities under the project would involve construction of two cross dams at both ends of Nijhum dwip channel and development of 5 sq. km fresh water reservoir; construction of cross dam between Njhum Deep and Damar Char for Land Reclamation; establishment of mangrove afforestation for disaster reduction and land accretion; and reclamation of about 40 sq. km of sub-aqueous shallow delta.

13.3.3 Important Pre-closure Investigations

The construction of the barrier/dam to impound freshwater towards land side requires construction of barriers to prevent tidal influence. The consequences of such closures are prevention of fish migration, changes in groundwater levels, water quality issues resulting from discharge of sewage water and other chemicals-laden

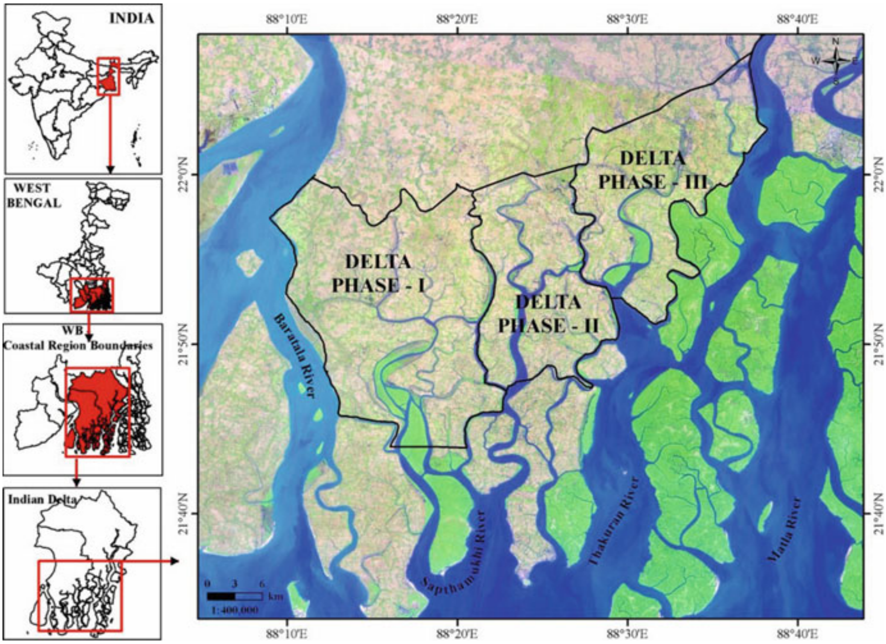

Fig. 13.4 Map showing locations for proposed phased Sundarbans Delta Project. (Anonymous 2013, open domain)

runoff from the catchments, upwelling from reservoir bottom and seepage across the dams. It is beyond the scope this paper to discuss all these issues in detail. However, some important influencing items, which are very specific to tidal basins, are briefly described.

Bathymetry of the Estuary and Closure Site *Bathymetry*, the study of underwater depth of lake or ocean as an underwater equivalent to topography is becoming increasingly important to learn more about the effects of climate change on the environment. The cross-channel bathymetry impacts the flow patterns in curved tidal channels. The currently available techniques enable preparing sea bed maps with details similar to the topographic maps as gridded datasets can be displayed as shadow-grams to enhance particular morphologic features (Bosco et al. 1992), and various types of models have been developed to describe flow as linked estuary cross-section.

Wave Climate *Wave climate* is defined as the distribution of wave height, period, and direction averaged over a period of time for a particular location (Wiegel 1964). The waves are characterized by five parameters – period, frequency, amplitude, wavelength, and velocity. In locations close to the shore, the prevailing winds, storms and bathometry modify the waves. The wave climate in Sundarbans has changed in recent years and has become tide dominated with tidal range varying

Fig. 13.5 Location of delta structures in phase -I. (Redrawn from Google map and Anonymous 2013, open domain)

between 3.7 and 5 m (Hazra et al. 2002). There is a progressive sedimentation of estuaries like Saptamukhi resulting in increase in the height of tidal bore to more than 6.4 m. The statistics on heights and periods of wave constitute an important factor in estuary structure design works.

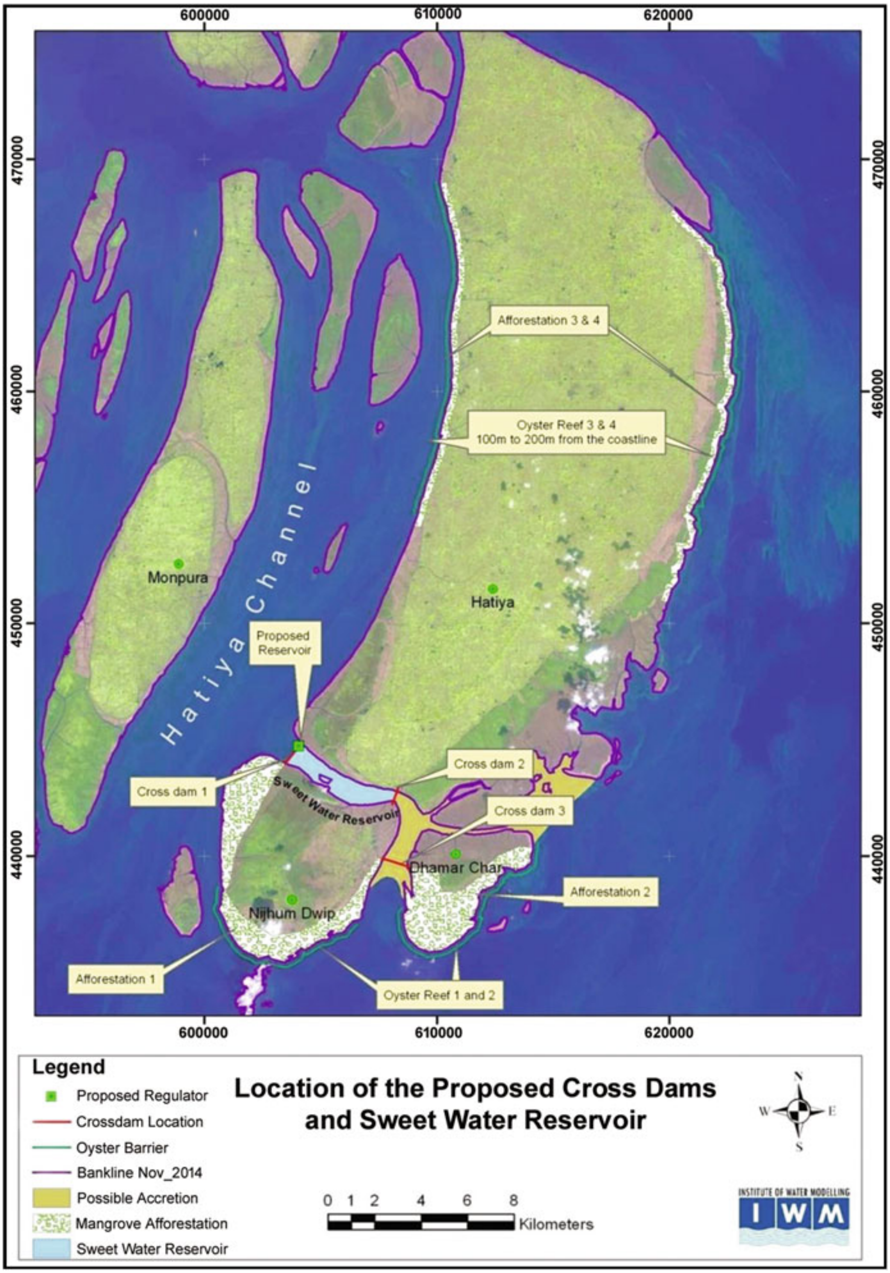

Fig. 13.6 Location map of proposed cross dams freshwater water reservoir. (Source: GoB 2015, open domain)

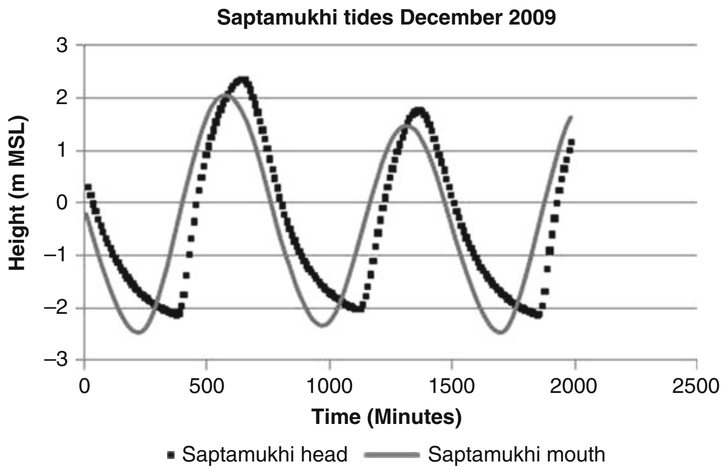

Fig. 13.7 Tidal curves for Saptamukhi Estuary. (Source: Bhattacharya et al. 2013, with permission from the copyright holders, IWA Publishing)

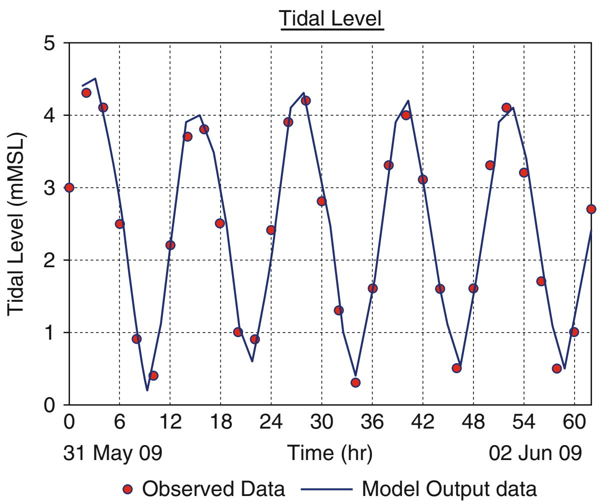

Fig. 13.8 Tidal curves for Feni Estuary. (Source: Komol 2011, open access)

Tidal Characteristics and Their Annual Variation The data on tidal surge constitute an important design parameter. The tides in the estuarine areas of Sundarbans are semi-diurnal in nature with two successive tidal cycles per lunar day of 24 h 48 min and influence the hydraulic behaviour of the estuaries. Two representative tidal estuary curves from Sundarbans are shown in Figs. 13.7 and 13.8. There is urgent need to establish tidal gauges at different locations to strengthen the data base.

Cyclone Phenomenon The Sundarbans are located in the cyclone- prone region. In tropical regions cyclones are intense low-pressure area with organized convection and wind at low levels. The amount of pressure in the center and at the rate at which it increases outward gives intensity of the cyclones and the strength of wind. A cyclone is characterized by its maximum pressure drop, maximum wind speed, and its radius to maximum wind speed. For example, Cyclone Aila that hit the coast of West Bengal, Bangladesh and Myanmar on May 25, 2009 had a wind speed between 74 and 120 km per hour (severe cyclonic storm), while the lowest pressure was 968 mbar. A storm surge of 2–3 m above tide levels was experienced along the coasts of West Bengal and the adjoining areas of Bangladesh (Sen et al. 2010). The design of the closure dams has to be such as to keep the surges created by such cyclones.

Salinity Balance in the Reservoir One of the important issues which has to be resolved include the duration flushing brackish from the tidal reservoir, before it becomes useable for different purposes. Gaining appreciation of the salinity concentration in the freshwater reservoir after the closure of the dam would require the sources of salt inputs to and output from the reservoir. Initial flushing period would depend upon the concentrations and volumes of: fresh water entering the reservoir, resident water existing in the reservoir, leakages through the tidal basin and closure dam. The sources and loading to the reservoir will change over a period of time (Anonymous 1999).

Stratification of Fresh and Saline Water Layers in the Reservoir The water masses of different properties form different layers, which act as barrier to mixing, and this process is known as stratification. The stratification can be caused by differences in salinity (halocline), oxygenation (chemocline), density (pycnocline), pressure (barocline) and temperature (thermocline). The water layers are arranged according to density and therefore least dense water floats over the higher dense water. Since both temperature and salinity affect density, the combination of salinity and temperature difference defines the resultant density of water mass. The water of lower salinity and higher temperature, which is less dense, floats over water of high salinity or lower temperature (Fig. 13.9). The variation in density with temperature and salinity is often expressed by empirical equation of the form (Crowley 1968).

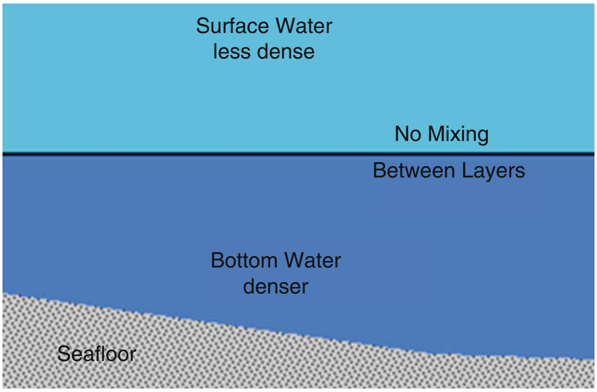

Fig. 13.9 Stratification of fresh and saline waters layers

$$Dts = 1 + (10 - 3[(28.14 - 0.073t - 0.00469t2) + (0.802t)(s - 35))$$

D = density in kg/m^3, t = temperature, °c and s = salinity in ppt

As may be seen from the equation above, salinity has much higher influence on density as compared to temperature, and therefore the differences in density will have dominant influence on the vertical stratification in the reservoir (Schumann et al. 1999). Maintenance of stratified conditions enables flushing of saline water from the reservoir through sluice outlet and makes water useable in shorter time. But high velocity winds act as mixing agent and can destroy stratification through air entrapment. The entrainment process is governed by Richardson number, represented by the relative density differences between the upper and lower layers ($Ri = \varepsilon g h_0 / u^2$, where ε is the relative density difference between two layers $[\rho_s - \rho_r]/\rho^2$, h_0 = thickness of the upper layer; u = wind introduced shear velocity).

13.4 Tidal River Management for Improved Drainage

There is a group of rivers, which form an intricate network with a number of criss-cross inter-connecting channels, in the deltaic zone to the east of the Hooghly river. These rivers drain off through the principal estuaries in the area namely, Bartala of Muriganga or channel creek, Saptamukhi, Matla, Gosaba, Hariabhanga, Raimongal, etc. in India and Kobadak, Hari and Minhaj rivers in Bangladesh. There is considerable reduction of flow in the Ganges due to upstream offtakes, which reduce the flushing capacity of the southwest delta in tidal rivers (Kawser and Samad 2016). The construction of polders has also reduced the tidal prism ("tidal prism," defined as the volume of water that flows into and out of a channel during a complete tidal cycle excluding the upland freshwater discharges) by preventing it to flow into the tidal basin (Rahman 1995, de Die Leendert 2013). As the drainage capacity of the rivers decreases it leads to waterlogging, as is the case with some areas in the southwest delta (IWM 2012). The drainage congestion has been a matter of grave concern in delta region as it led to serious flooding of agricultural land and the rural habitats with considerable impacts on economy of the region (WARPO 2004, ADB 2007, IWM 2010).

13.4.1 Tidal River Management (TRM)

The cutting of embankment (de-poldering) in tidal rivers (rivers that do not receive much upstream flow and are therefore under heavy influence of the tides), is known as Tidal River Management (TRM). The TRM is an eco-technological concept, designed to solve the waterlogging problem, while at the same time improving the environment (Amir et al. 2013). It is essentially an old practice, perfected by the local communities over a long period of time (Kiberia 2011, de Die Leendert 2013), with a new name, as the first mention of the term TRM is found in the Environment Assessment Report by Center for Environmental and Geographical Information Services in 1998 (CEGIS 1998). Incidentally, the wise use of this community practice was first recorded by Willcocks (1930), who observed that sediment management was the main water management issue in coastal Bengal. This practice, in some ways, has been in use in Netherlands, United States and Belgium (de Die Leendert 2013).

13.4.2 Theoretical Aspects of Drainage Congestions in Tidal Delta of Sundarbans

The widths of estuarine channels keep on changing because of natural and anthropogenic factors. In the Sundarbans, the major anthropogenic intervention has been the construction of embankments, as a defence system against high tides, cyclonic storms and sea level rise. This intervention has disturbed the equilibrium of the tidal flow regime, as the equilibrium depends on the velocity of water flow. If velocity is "too fast" in comparison to an equilibrium case, channel bank erosion will occur and the channel cross-section will become larger; with a larger cross-section, flow velocity will be reduced, as will the levels of erosion (Sánchez-Triana et al. 2014). But, if velocity is "too slow", the estuary deposits sediments, which results in reduction of the cross-sectional area and increase in flow velocity. These opposite trends are kept in balance under equilibrium condition and therefore neither erosion nor sedimentation (accretion) takes place. An important variable which gets affected by embankments and poldering of tidal basins is the "tidal prism". If the tidal prism is made larger by extending the reach of tidal flows to supply estuarine waters to upstream fishponds, velocity of tidal flow is increased. On the other hand, by cutting off the upper portions of a channel to create reservoirs of fresh water, the tidal prism is made smaller and tidal velocity is reduced. There appears to be a direct correlation between the amount of erosion and submergence, with the rate of relative rise and fall of sea level in different island segments.

13.4.2.1 Process of TRM

In the estuarine rivers, daily there are two cycles of tides; the high tide brings in muddy water flow with high concentration of sediments, which when let into the flood plain by cutting the embankment, settles there when the water flows back into the river during low tide. Generally, a low-lying depression in the floodplain (tidal basin), locally called' *beel*', which is filled with water throughout the year and lying

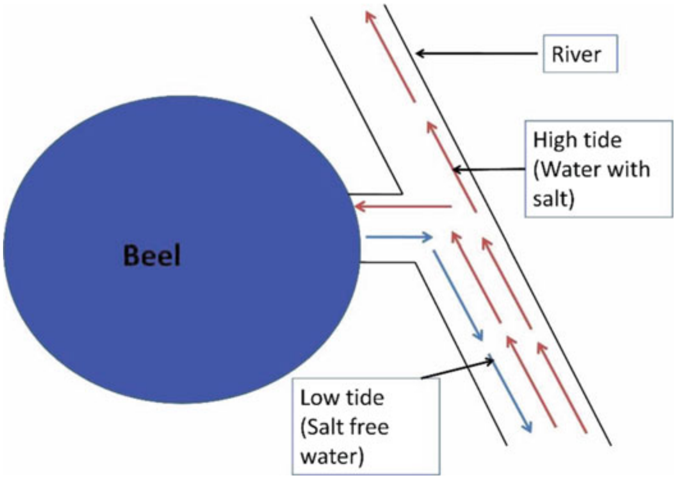

Fig. 13.10 Process of *beel* reclamation in a tidal river. (*Source*: Shampa and Pramanik 2012, open domain)

adjacent to the sediment-laden tidal rivers, is part of this system (Wester and Bron, undated). While returning to the sea during low tide, the water stored in these tidal basins pushes its way through the narrow rivers with increased flow velocity. This causes erosion of the riverbed, thereby increasing the size of the rivers (Fig. 13.10). In this process, the land level in the floodplain is raised, while the riverbed deepens as there is no deposition of sediment in the riverbed, thereby increasing the drainage capacity of river.

Attempts to develop scientific basis for understanding the process were made, which led to establishment of relationship between the cross-sectional area of the river and the tidal volume (LeConte 1905, Williams 1919). Williams (1919) noted that the section at any particular point bears a direct relationship to the tidal reservoir capacity above that point. Later O'Brien (1931, 1969), based on analysis of field data from inlets through sandy barriers on West Coast of United States, proposed the following relationship between the size of a tidal inlet and the tidal prism (mean tidal volume):

$$A = cP^n$$

where, A = minimum inlet cross-sectional area in the equilibrium condition, c = an empirically determined coefficient, P = mean tidal prism and n = an exponent usually ≤ 1.

Shampa and Pramanik (2012) applied this relationship in Hari River tidal basin, and observed that the cross-sectional area of a tidal channel reduced in size if the tidal prism is reduced. It is for this reason that delinking of a tidal channel from the tidal system causes reduction in the tidal prism on the downstream of the closure point. The usefulness as a tool to prevent waterlogging caused by riverbed sedimentation was upheld by scientific and financial institutions like Institute of Water Modeling and Asian Development Bank (IWM 2010, ADB 2007).

13.4.3 Major Consideration in TRM Implementation

In TRM a number of complex issues arise due to interconnectivity, and interdependence of river system as well as the diverse interests of the croppers and fish pond farmers as stakeholders (ADB 2007). The successful implementation should give due importance to structural as well as non-structural measures.

Sequential Availability of Beels For success of this practice, it is important that *beel*s are available along the river course. This system operates best on rotational basis. After the level of *beel* or tidal basin has been raised to a certain level, the cut in the embankment has to be closed (re-poldered); and the operation has to shift to the next *beel*. The reemergence of drainage problems could be a problem, if tidal river basin management is rotated on time as was the case with Khulna-Jessore Drainage Rehabilitation Project during 2005–2006 (ADB 2007).

Limits on Siltation in the Tidal Basin To ensure the required environmental flow in the tidal basin, siltation should be limited to raise the level, no more than 1–1.5 m (Shampa and Pramanik 2012). This is important from consideration of serving the interest of crop farmers and fish pond farmers, as well as from environmental considerations as it may destroy the biodiversity of the *beel* otherwise.

Duration of TRM For successful implementation of TRM in a tidal river basin it is important to determine how long a particular site will be available for operation. The availability of particular site for operation depends upon the sedimentation rate. Towards this end procedures have been evolved and tested (Khadim et al. 2013), which would be very useful in planning the TRM operation.

Size of Tidal Basin (Beel) The size of the *beel* gains importance from manageability consideration. Based on experimental evidence 500–550 ha area of *beel* has been suggested as effective (Rahman et al. 2013). In case of a larger *beel*, it may be sub-divided into several sub-*beel*s from operational considerations.

Sustainability Operation and Maintenance Mechanism Drainage congestion is a continuing problem and so are the maintenance requirements. Therefore, robust arrangements with adequate financial provisions should be put in place.

13.4.4 TRM Practice in Bangladesh

The concept of TRM has been implemented in several tidal basins of Jessore in the southwest coastal zone of Bangladesh where waterlogging was rampant due to river silting (Kibria 2011, Amir et al. 2013, Khadim et al. 2013). In their evaluation of TRM (Khadim et al. 2013) in Beel Bhaina tidal basin, it was found that about 26% of the sediment and silt entering the *beel* was retained, thereby raising the land elevation by1.82 m in an area of 770 ha over period of 14 years (1997 and 2011). Further, just in 4 years (1997–2000), the depth of the Hari river just upstream of Beel Bhaina increased by 4 m, and as much as by 14 m in some downstream locations indicating the success of TRM. It can be inferred from these studies that tidal basins could be used to mitigate riverbed sedimentation and the experience gained would be useful in developing and implementing TRM in similarly placed areas. The rapid assessment made by the Institute of Water Modeling (IWM 2010) on the basis of data generated by CEGIS confirmed that the rotational TRM approach was not only technically suitable, economically viable, and socially acceptable option but it took care of the interest of different stakeholders such as crop growers and fishers, etc. (Shampa and Pramanik 2012). Evaluation of the impacts of integrated water resources management (IWRM) and TRM, which were based on extensive use of RS and GIS technology as well as Digital Elevation Model (DEM), have indicated considerable improvements over different cropping intensities in Khulna and Jessore districts of Bangladesh (Khadim et al. 2013). The TRM was also found quite effective in the upper Bhadra Basin for reducing the drainage congestion of the Beel Dakatia area. This approach can be replicated in other coastal region if institutional challenges are overcome.

13.5 Managed Realignment and Shifting of Estuary Embankments

The concept of managed realignment deals with problems that are caused by coastal defence structures that constrain water flow hindering hydro-morphological processes of a water body. These problems also get exacerbated by the effects of climate change which causes the sea level to rise. Managed realignment facilitates the process of re-naturalizing the low-lying areas in a controlled way by making space for water in an economically efficient and ecologically beneficial way. Managed realignment creates new intertidal areas for flood protection and biodiversity and has been applied in several locations (Morris 2013). The design aspects of realignment are amply detailed in Leggett et al. (2004). Realignment forms part of the comprehensive strategy developed by World Bank to increase the resilience in Sundarbans (Sánchez-Triana et al. 2014).

13.5.1 Need for Embankment Realignment in Sundarbans

In recent times, the fluvial sources of sediment in the Sundarbans estuaries have been lost due to upstream abstraction of river flows and the sediments are now mainly of marine origin. On the other hand, the intertidal sediment-receiving areas have also been reduced due to land reclamation, and therefore sediment is carried landward by flood flows and gets accreted in the smaller channels. During this long period, there has been a relative rise in sea level between 0.2 m and 1.6 m (Bhattacharya et al. 2013). The three processes which have been responsible include: land subsidence at the rate of 3–5 mm per year (Khan and Islam 2008), eustatic sea level rise due to sedimentation in the order of 2–8 mm per year, and the climate change. Though overtopping of the embankment, which causes breaches and flooding, is a problem, major cause of embankment failure is attributed to mass failure resulting from over-steepening of the embankment face and increased pore pressure in the earthen *bund*s (embankment) due water penetration.

The channel erosion, which undercuts the intertidal footings of the *bund*s, makes it unstable and the failure is then triggered during storm surge actions. The construction of embankments has exacerbated channel erosion as is evident by the differences in cross-sections (Fig. 13.11) of embanked Kalchera estuary and un-embanked Gosaba estuary (Bhattacharya et al. 2013, Sánchez-Triana et al. 2014).

13.5.2 Regime Modeling

The morphodynamical behaviour of the estuary system is influenced by sediment transport processes and mechanisms. Generally, regime models are used to describe the functional relationship between cross- sectional area and the tidal prism. A number of researchers have used the simple power function to relate discharge with channel morphology (hydraulic geometry) (O'Brien 1931, 1976, Gao and Collins 1994); and a number of significant experiments were conducted at Hydraulic Research Station at Wallingford, England. For several tidal rivers of Indian Sundarbans delta, this approach has been used by Sánchez-Triana et al. 2014) to study the changes in channel cross-sections. In their study under Non-landing Technical Assistance (NLTA) project, three main factors that affect the size tidal prism and, thereby, discharge velocities and erosion or accretion of channel banks have been identified:

(1) The sea level rise of 0.2–1.6 m that has taken place in the Sundarbans during the past 100–200 years.
(2) Increasing prevalence of aquaculture ponds, for which channel networks are created.
(3) Creation of freshwater storage on the upper reaches of channels and closures that restrict upstream estuarine flows.

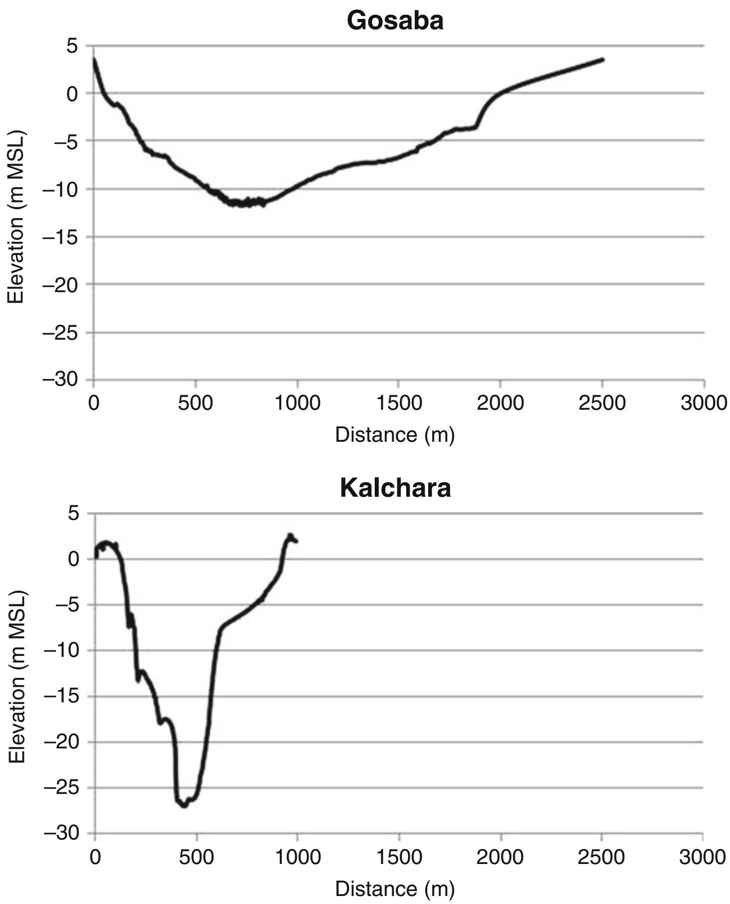

Fig. 13.11 Cross-sections of embanked (Kalchara, Saptamukhi Estuary) and un-embanked (Gosaba Estuary) channels (vertical exaggeration x10). (Source: Bhattacharya et al. 2013, with permission from the copyright holders, IWA Publishing)

The sea level rise and creation of channel network for fish pond results in increases of tidal prism, while freshwater storage in upper reaches by blocking the channel reduces the prism.

Model predictions of equilibrium channel morphology, assuming no sea level rise, show wide disparity between the degree to which estuaries have attained such an equilibrium, as a result, small channels such as Banstala and Ghugudanga Gang are predicted to be over-sized on average while larger channels such as Bidya are significantly under-sized; and if the predictions for width of the estuaries in response to future 1 m sea level rise are compared with the equilibrium values for zero sea level rise the differences are found to be small; while, in contrast, the differences between the predicted values in response to 1 m sea level rise and existing channel widths are relatively larger (Sánchez-Triana et al. 2014) (Fig. 13.12).

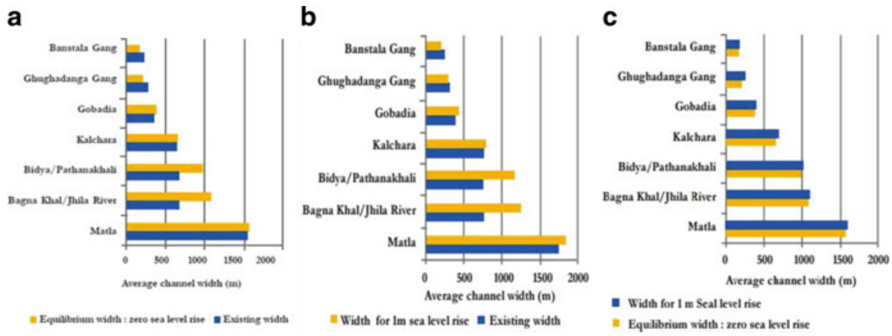

Fig. 13.12 Existing and equilibrium widths for zero sea level rise (**a**); existing and predicted widths for 1 m sea level rise (**b**); and (iii) existing and predicted widths after 1 m rise in sea level (**c**). (*Source*: Sánchez-Triana et al. 2014, World Bank, open domain)

On the basis of the simulation studies (Bhattacharya et al. 2013, Sánchez-Triana et al. 2014) it has been inferred that in Sundarbans all types of estuaries – accreting type, as well eroding type existed. When compared with their size under equilibrium condition, some were over-sized (Banstala, Ghughudanga), while others were under-sized (Pathanakhali, Bhanga Khal/Jhila) or were in equilibrium (Kalchara, Matla); and differences were ascribed to anthropogenic impact on morphology. The over-sized channels are experiencing accelerated accretion, large accommodation space, while in case of equilibrium for channels there is no space to accommodate any future sea level rise, and the embankments may simply collapse. The under-sized channels have negative space for accommodation and simply collapse due to mass failure during surge events.

13.5.3 Displacement in Realignment and Cost

The rise in sea level being imminent, there is need for realignment of the existing embankments to provide space to allow wider tidal channels. In case of non-realignment, the region will run the risk of embankment failure due to under-cutting of embankments and consequently flooding of vast areas. The displacement of the embankments would vary with location and could be of the order of 100–300 m. It may however be added that realignment will require surrender of some land to the estuaries to accommodate future sea level requiring some resettlement of the people.

The capital cost of realignment of existing embankment had been estimated at about US$4–5 billion in the next 20 years, while retreating and building new embankments would cost about US$8–10 billion in the next 20–100 years (Riebeek 2010).

13.6 Conclusions

The Sundarbans delta is facing several transitions including population pressure, climate change, degradation of natural resources and loss of biodiversity. Because of these adverse conditions the economic development of Sundarbans has lagged behind. The upstream developments in the Ganges basin have reduced lean season flows with adverse impacts on the dynamics of coastal estuaries. The reduction in flow and sediment abetted by sea level rise has led to increased flooding of low-lying agricultural lands. The freshwater availability during non-monsoon is highly deficient. Estuary management by way of closure though engineering structure has been adopted in several countries to create freshwater storage and holds promise for Sundarbans as well.

The gradual sea level rise over a period of time, which is getting further accentuated due to global warming, would require shifting of embankments. Managed realignment, which facilitates the process of re-naturalizing the low-lying areas in a controlled way, has been identified by World Bank to increase resilience of Sundarbans to several adversities. Regime model in few estuaries confirms the need for such realignments, but it would need careful technical assessments.

Tidal river management, a practice which has been adopted in Bangladesh, has the potential of reducing the flood hazard. However, introduction of this ecotechnology requires careful considerations including: sequential availability of *beel*s, limits on trapping silt, and the duration for this can be practised at a given location. In India, the idea of creating a freshwater storage by damming Saptamukhi river or elsewhere, using suitable state of the art technology through phased development, which is likely to reduce the vulnerability of Sundarbans to natural hazards, needs a serious re-look.

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Part VI
Risk Factor Analyses on Climate Change and its Impact on Livelihood, Biodiversity, Disaster Mitigation and Forecast

Conservation and forest protrection activities (Courtesy WWF-India, photo Sunit Das)

Chapter 14
Global Climate Change and Human Interferences as Risk Factors, and their Impacts on Geomorphological Features as well as on Farming Practices in Sundarbans Eco-Region

Uttam Kumar Mandal, B. Maji, Sourav Mullick, Dibyendu Bikas Nayak, K. K. Mahanta, and S. Raut

Abstract Substantially resourceful and densely populated Sundarbans delta, covering India and Bangladesh, experiences numerous extreme events linked to various hydro-meteorological processes. Further, anthropogenic activities in the coastal zones are accentuating environmental degradation causing wide spread suffering. While large tracts of the Sundarbans were cleared, drained and reclaimed for cultivation during the British colonial era, the remaining parts have been under various protection regimes since 1970s to protect the various flora and fauna. Spatio-temporal study using satellite remote sensing showed, while the mangroves' areal extent has not changed much in the recent past, accretion rate of coastline has declined as against erosion rate which has remained relatively high in the recent years. As a result, the delta front has undergone a net erosion of ~170 km^2 of coastal land during 1973–2010. Thus, the various factors affecting such changes are direct human interference, upstream development in the river hydrology, climate change, extreme weather events including cyclones, tidal surges, floods, sea level rise, salinity intrusion, etc. acting individually or through their interactions. Impact of such factors on agriculture and aquaculture being the main components towards livelihood security has been discussed. There is a need for integration of traditional coping practices and wisdoms with modern scientific management approach in this eco-region to reduce the effects of climate change- and other natural or human factor-induced disasters, and arrest nature and extent of human sufferings for improvement of livelihood enterprises, agriculture and aquaculture being the most important.

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Keywords Sundarbans · Bengal delta · Climate change · Anthropogenic interferences · Geomorphology · Farming for livelihood

14.1 Introduction

Climate change impacts are being witnessed all over the world, but countries like India and Bangladesh are more vulnerable than any others in view of the high population, depending mainly on agriculture and aquaculture, excessive pressure on natural resources, and relatively weak coping mechanism. The Sundarbans, essentially low-lying, located in the southern part of West Bengal (India) and Bangladesh lies on the delta of Ganges, Brahmaputra and Meghna rivers in the Bay of Bengal, and falls in the most vulnerable zones of abrupt climate change. The Sundarbans, the largest single tract of mangrove eco-region in the world, was declared as Ramsar site no. 560 in 1992 and as a World Heritage site by UNESCO in 1997. The pristine eco-region is home to an estimated 505 species of wildlife, including 355 species of birds, 49 species of mammals, 87 species of reptiles, 14 species of amphibians as well as emblematic species such as the Bengal tiger (Rahman et al. 2013). Additionally, there are about 234 species of flora and more than 300 species of fish, including 237 species of finfish, 38 species of shellfish and 34 species of molluscs to enrich the eco-region. Sundarbans mangrove forest belt acts as a buffer, protecting inhabitants of numerous human settlements against cyclones, rising sea levels, and other hazardous weather events.

Owing to its unique geographical location the entire Sundarbans are also under constant threat of powerful nor'westers, bay cyclones, tidal surges, and constant change of courses by the numerous distributaries in the active part of the delta. The eco-region being located at the extreme south and at the lowest elevation before meeting the Bay of Bengal are dynamic in terms of hydrology of numerous rivers, and the resultant effects like accretion, sedimentation and erosion, etc., because of scores of human interferences, besides the effect of global warming on the melting of glaciers in the extreme north, in the mighty Ganges and Brahmaputra in the long stretch at the upstream. The lower Ganges delta of both India (south of Farakka) and Bangladesh (south-west) share the same ecology and face threats due to dwindling water diversion via Farakka Barrage and deteriorating water quality of the river in the upstream at different places within India (Sen and Ghorai 2014). Expected effects of changes in global climate, besides the effect on glaciers, include warming of air temperatures, rising sea levels, and potentially more frequent and severe extreme weather events such as hurricanes and tropical cyclones. The coastal impacts in this region are very large because of the low and flat coastal terrain, high density of population, poor awareness of community towards improved livelihood technologies, inadequate response and preparedness to warning forecasts to combat the damaging effects due to extreme weather events, and absence of clear-cut hedging mechanism. More than 40 million people of Bangladesh and 25 million people of West Bengal living in this region have been directly affected and millions of lives and livelihoods are threatened by frequent weather-related disasters.

In addition, the lands in the regions are highly degraded due to phenomena like saline water flooding following storm and presence of brackish groundwater table near the soil surface on account of the influence of sea or saline river water, etc. Some of the areas are under acid sulphate soils which have limited productivity potential. Though the region receives very high rainfall, which is concentrated only over a few monsoon months, most of the rainwater goes waste as runoff and creates widespread water logging of the low-lying agricultural fields. The entire coastal region is under mono-cropped, growing traditional rice in monsoon season with very poor yield. Thus, subsistence agricultural management and climatic extremes have significantly contributed towards the land degradation and deterioration of soil quality in these regions. Over a period, the problem of salinity has become a threat to this entire coastal belt in this eco-region. Changing rainfall patterns and increased frequency of extreme hydrological events attributed to climate change are inflicting on added vulnerabilities to livelihoods and resources in the eco-region across India and Bangladesh. Despite the value and vulnerability of the coastal delta, very little data exist on the spatio-temporal dynamics of the land and the impacts of anthropogenic and natural disturbances of the eco-region (Rahman et al. 2011). There is a need for integration of traditional coping practices with appropriate water and land care system for this coastal area to make this fragile ecosystem into climatically more resilient.

14.2 Ganges–Brahmaputra–Meghna (GBM) Basin

The Sundarbans are situated on the delta created by the Ganges, Brahmaputra and Meghna rivers in the Bay of Bengal. The Ganges-Brahmaputra-Meghna (GBM) river system is ranked as the third largest freshwater outlet to the sea (after the Amazon and Congo River systems) covering an area of about 1.75 million km^2 stretching across six countries – Bangladesh, Bhutan, China, India, Myanmar and Nepal (Fig. 14.1) (Renaud et al. 2013; Brown and Nicholls 2015). The long term mean annual discharge for the Ganges is estimated at 1.14×10^4 m^3 as compared to 2.01×10^4 m^3 for the Brahmaputra with wide variation in flow between the wet and dry seasons. The channels of both rivers are extremely unstable and bank lines can migrate as much as 400 m in a single season. The delta front of GBM is around 380 km long (Allison 1998). Many parts of the tidal influenced delta are less than 3 m above mean sea level and with the tidal influence extending up to 100 km inland, around one-quarter of Bangladesh can be considered ‘coastal’. The combined seasonal discharge of the Ganges–Brahmaputra river system outputs is approximately 1 billion tonnes of sediment per annum, and this accounts for approximately 10% of the world’s sediment output from rivers to the ocean. Almost entire area is filled with fluvio-deltaic sediment and alluvium from the Ganges–Brahmaputra river system deposited in the last 66 million years and is up to 16 km thick (Brown and Nicholls 2015). The fertile alluvial flood-plain is characterized by gently undulated landscape with hills and hillocks in the north, east; a central undulated red soil terrace, the Madhupur Tract; and a huge coastal zone with highly fertile land, rivers, estuaries, mangroves, seashore and islands adjacent to the land-water interface in the southern part of Bangladesh.

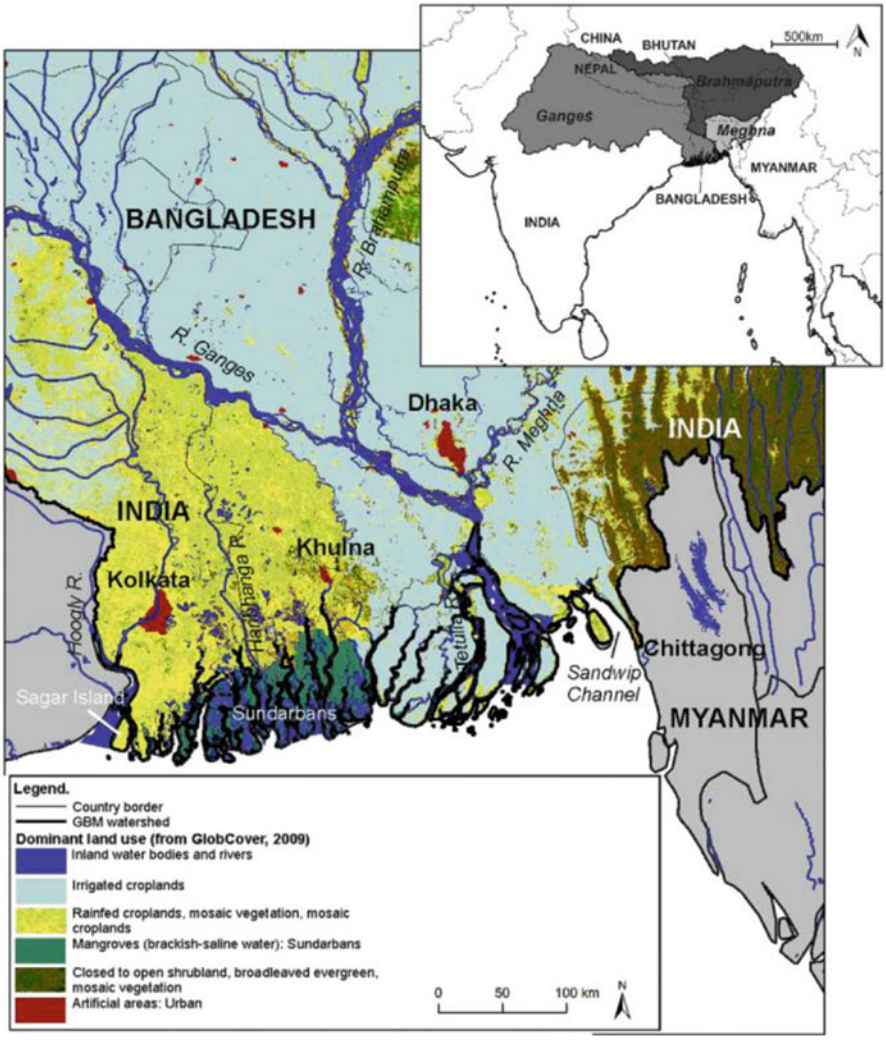

Fig. 14.1 Geographical setting of the Ganges–Brahmaputra–Meghna basin and delta, including dominant land use. (Brown and Nicholls 2015, permission obtained)

14.3 Sundarbans Delta

The Sundarbans is the largest contiguous mangrove forest in the world located in the GBM basin. It consists of a network of mudflats and islands created by accumulated sediment loads that these rivers carry from their Himalayan headwaters separated by anastomotic channels and tidal waterways. The Sundarbans, found within 21°32′ to 22°40′N and 88°05′ to89°51′E, covers an area of approximately 10,000 km^2, of which 62% lies within Bangladesh and 38% in India (Ghosh et al. 2015). The region is characterized by a tropical climate with a dry season between November and April and a wet monsoonal period over the rest of the year. The total annual amount of precipitation is between 1500 and 2000 mm. During the monsoon season, tropical cyclones and smaller tidal events regularly hit the area, causing severe flooding and wind damage. Seasonal mean minimum and maximum temperatures vary from12°C to 24 °C and 25 °C to 35 °C, respectively.

The Sundarbans mangroves belong floristically to the Indo-Andaman mangrove province within the species-rich Indo-West Pacific group. According to Barik and Chowdhury (2014), 24 true mangrove taxa belonging to nine different families are found within the Indian Sundarbans. The dominant mangrove species *Heritiera fomes* is locally known as *sundri* or *sundari*. There is a kind of zonation within the Sundarbans mangroves, both from land to sea and from east to west. Tectonic uplift in the west and subsidence by sediment compaction and human activities in the east, in combination with varying freshwater inputs, create different salinity zones – hyposaline in the eastern and western part, where huge rivers deliver melt water from the Himalayas, and hypersaline in the central part, where the ground is higher and freshwater input from the Matla, Bidyadhari or Harinbhanga rivers is negligible. The least salt-tolerant taxa, found in riverine environments and more common to the east, are the eponymous Sundari-tree *Heritiera fomes*, *Excoecaria agallocha* and *Sonneratia caseolaris*.

The surroundings of the Sundarbans mangroves – both in India and Bangladesh – are some of the most densely populated areas in the world. More than half of the population is impoverished and depend heavily on the goods and services that the forests provide. Indirect (regulatory) benefits of mangroves for coastal population include erosion control as well as protection from tropical storms and tsunamis.

14.3.1 Historical Overview of the Sundarbans Development

It may be relevant to know the factors leading to recent physiographic changes of Sundarbans delta and consequent effects on demography and land use pattern because of several administrative actions over time, and in turn their effects on livelihood pattern accentuated by climate change and extreme weather adversities.

Before the nineteenth century, Indian Sundarbans were very sparsely settled, with only scattered human settlements. In 1771, British collector general Clod Russell initiated a plan to divide the Sundarbans into plots and to lease them out to prospective landlords for timber extraction and the collection of revenues. These lease-holding land owners encouraged poor farming communities from other parts of Bengal as well as from neighbouring states to come and settle in the Sundarbans. These people were put to work clearing the forests and developing the land (Hunter 1885). Rennell's map from 1776 (Fig. 14.2) (Ghosh et al. 2015) shows the extension of the mangrove forest up to Kolkata at the end of the eighteenth century. One hundred years later, in 1873 (Hunter 1876), the northern border of the mangrove forest shifted by about 10–20 km at most to the southeast (Fig. 14.2 top right).

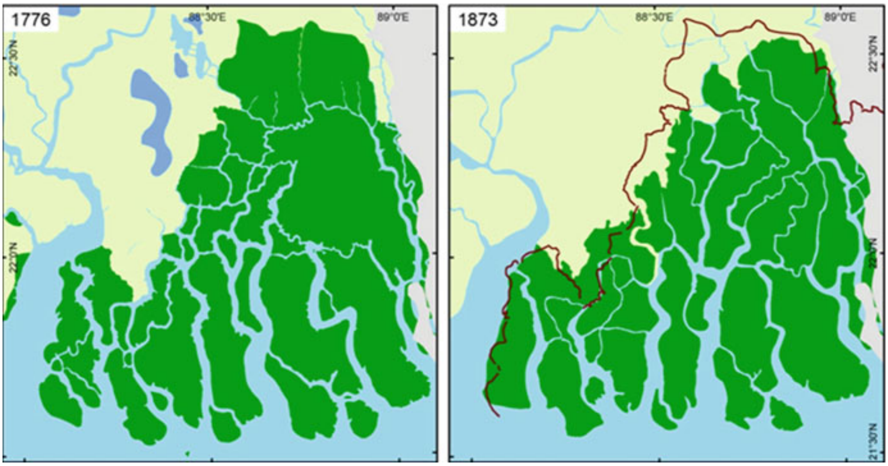

Fig. 14.2 Extent of Sundarbans mangrove during 1776 and 1873. (Ghosh et al. 2015; Rennel 1780; Hunter 1876, 1885, Open access)

Settlement in the Sundarbans mainly comprised of migrant populations from the adjoining districts of Midnapur, and also from central India, predominantly the marginalized and tribal populations who came in search of work and land, and who were initially brought in by the British to construct the embankments. As early as 1875/76, the British government set aside all unleased mangrove areas under protection and conservation. As the general regional population expanded by the late eighteenth century, dikes and dams were constructed to hold back flood water from the river, prevent salinization, and provide agricultural lands, via conversion from mangroves (Islam 2006; Kausher et al. 1996).

The human population in the Sundarbans increased rapidly in the post-colonial era, especially following the partition of India and East Pakistan (Bangladesh). The population of Indian Sundarbans grew from 1.15 million in 1951 to 4.44 million in 2011, which led to a growing demand for its resources. Between 1873 and 1968 the mangrove-covered area decreased by about half (from 6068 km^2 to 2307 km^2) on account of conversion of forest to agricultural land and settlements (Ghosh et al. 2015). The mangrove forest boundary shifted further to the south and the mangroves were cleared between the Hooghly river and the Matla river. Since the 1970s, the Indian Sundarbans mangroves have been protected under various legal measures which were established primarily to protect and help increase the threatened species.

In 1984 a (subordinate) protection of the forests came into law with the establishment of the 1330 km^2 Sundarbans National Park, designated as a UNESCO World Heritage Site in 1987, with the primary objective for biodiversity conservation; and a biosphere reserve in 2001, where no human interference is permitted. In addition, there are less strictly administered wildlife sanctuaries namely, Sajnekhali (362 km^2), Lothian (38 km^2), and Haliday (6 km^2), and the Sundarbans Reserve Forest, where limited human use is allowed. In total, the protected forest covers an area of about 4260 km^2. Despite the high population density, the areal extent of the Indian Sundarbans mangrove forest remained more or less stable since the 1960s (Ghosh et al. 2015).

After independence, the population of Bangladesh (the then East Pakistan) was also grown up significantly. During 1960s Bangladesh initiated massive coastal embankment project funded by the World Bank and other organisations for building of a larger, planned network of earthen embankments to create land from flooding, keep them away from areas under salinity intrusion, to satisfy agricultural production for the growing population. The land was polderised and drained. However, by the 1990s, adverse effects were noted, including drainage congestion inside and heavy siltation outside of the polders in south-west Bangladesh. This made some of the land unsuitable for agriculture (Islam 2006).

14.4 Climate Change Scenario

Increasing anthropogenic emission of greenhouse gases and their subsequent accumulation in the troposphere are the driving force for future climate change (IPCC 2007). The adverse effects of atmospheric changes are presently felt and are predicted to worsen in the future. Table 14.1 summarizes the principal findings of the recent Fourth Assessment Report of the IPCC (IPCC 2007), which ranks the probability of given impacts into different classes. A gradual increase in temperature, as reflected in fewer cold days and more frequent hot days, is already discernible in most regions and will intensify in the future (Wassmann et al. 2009).

IPCC has projected rising trend of Earth's surface temperature of 0.74° ± 0.18 °C over a period from 1906 to 2005. Climate change projections made for India indicate an overall increase in temperature by 1–4 °C and precipitation by 9–16% toward 2050s (Krishna Kumar et al. 2011). Another significant aspect of climate change is the increase in the frequency of occurrence of extreme events such as droughts, floods, and cyclones. All these expected changes will have adverse impacts on climate sensitive sectors such as agriculture, forest, and coastal ecosystems and also on availability of water for different uses and on human health.

In Bangladesh, average temperature has registered an increasing trend of about 1 °C in May and 0.5 °C in November during the 14 year-period from 1985 to 1998 (IPCC 2007). It was also reported that decadal rainfall anomalies are above long-term averages since 1960s (Rahman and Rahman 2015). For the Indian monsoon, extreme rain events have an increasing trend between 1901 and 2005 and the trend is much stronger after 1950.

The impact of climate change in future would be quite severe for the mega deltas in Asia. IPCC (2007) has projected that with the rise in temperature and subsequent rise in sea level in the coasts of Asia, including the Indian Sundarbans, the delta will be exposed to increasing risks like coastal erosion. The people of the delta are experiencing extended, extreme and hot summer, whereas the winters are becoming shorter, warmer, and drier. A study on air temperature of Sagar island in Sundarbans

Table 14.1 Principal conclusions of the IPCC Fourth Assessment Report

Climate change impact direction of trend	Probability of trend[a]	
	Recent decades	Future
Warmer and fewer cold days and nights over most land areas	Very likely	Virtually certain
Warmer and more frequent hot days and nights over most land areas	Very likely	Virtually certain
Frequency of warm spells/heat waves increases over most land areas	Likely	Very likely
Frequency of heavy precipitation events increases over most land areas	Likely	Very likely
Areas affected by drought increases in many regions	Likely	Likely
Intense tropical cyclone activity increases in some regions	Likely	Likely

[a]Probability classes: likely >66% probability of occurrence; very likely >90% probability of occurrence; virtually certain >99% probability of occurrence
Source: IPCC (2007) and Wassmann et al. (2009), permission obtained

revealed that for 80 years (1891–1970) the average daily temperature increased by 0.1 °C. However, in general, the air temperature over the Bay of Bengal is rising at a rate of 0.019 °C per year and if this trend continues, the air temperature in this area is expected to rise by 1 ° C in next 50 years (WWF-India 2010). Regarding surface water temperature, the delta has shown significant rising trend and over the past 30 years (1978–2008) it has increased at a rate of approximately 0.05 °C per year. In case of Bay of Bengal, sea surface temperature (SST) near Sagar island showed a rising trend at the rate of 0.0453 °C per year during 2004–2009.

Analysis of long term rainfall data (1966–2014) at Canning under Indian Sundarbans indicated that the region receives a mean annual rainfall of 1818.5 mm (±344.8 mm) with a considerable variation (CV = 18.95%) (Annual Report 2015–2016). Out of 49-year rainfall data, 35 years received normal (within long period average ± CV), 6 years received deficit (25–43%) and 8 years received excess rainfall (35–19%), and the results revealed that total annual rainfall trend decreased non-significantly at the rate of 1.00 mm per year. On an average, pre-monsoon during the month of March, April and May contribute 13.2%, monsoon rainfall during the month of June, July, August and September contribute 74.3% and post-monsoon rain during October to February contribute 12.5% of total annual rainfall. On an average 84 rainy days in a year was recorded in the region, whereas during last 10 years (2005–2014), the number of rainy days was reduced to 78.8 days per year. Bright sunshine hours declined significantly at an annual rate of 0.05 h per year during 1966–2014. Reference crop evapotranspiration (ET_0) calculated using FAO Penman-Monteith method revealed that annual ET_0 significantly decreased at the rate of 5.60 mm per year, which may be due to gradual decline in bright sunshine hours in the region.

Table 14.2 Number of cyclones in the Bay of Bengal and hitting the littoral countries (1877 to 1995)

Type	Bangladesh	India	Myanmar	Sri Lanka	Dead	Total
All types	154	848	71	35	115	1223
Depressions	68	539	24	15	69	715
CS (cyclonic storm)	43	197	23	12	35	310
SCS (severe cyclonic storm)	33	112	24	8	11	198
CS + SCS	76	309	47	20	46	508
Percent of total CS + SCS	0.93	3.34	0.51	0.22	0.50	5.5
Percent depressions	9.5	75.38	3.36	2.1		

Source: Rahman and Rahman (2015), permission obtained

14.4.1 Tropical Cyclones

The major natural disaster that affects the coastal regions of world is tropical cyclone, which causes devastating hazards via high winds, intense rainfall, terrestrial flooding and storm surges. Effects vary depending on the locations of origin and landfall. About 5% of global tropical cyclones originate in the Bay of Bengal, but adjacent countries including Bangladesh, India and Myanmar experience more than 75% of the global casualties. Bangladesh is hit by about 0.93%(~1%) of the world's total tropical storms, India by 3.34%, Myanmar by 0.51%, Sri Lanka by 0.22%, and 0.50% die in the Bay without hitting any country (Table 14.2). If the world's tropical cyclones with death tolls in excess of 5000 are considered, it is found that 16 out of the 35 such disasters occurred in Bangladesh and 11 in India. About 53% of the world deaths from these cyclones took place in Bangladesh and about 23% in India, for a combined total of 76% in these two countries. Bangladesh and India suffer most in terms of casualties, although both of them together are hit by only 4.27% of the world storms (Rahman and Rahman 2015). Two notable tropical cyclones that occurred in AD 1970 and AD 1991 killed 500,000 and 140,000 people, respectively, in Bangladesh. As tropical cyclones are a 'hydrometerological hazard', climate change together with its associated increases of sea surface temperature (SST) has the potential to drive variations in the frequency and intensity of tropical cyclones. Furthermore, sea level rise is expected to result in more devastating effects as storm surges penetrate further in land.

Alam and Dominey-Howes (2014) developed a tropical cyclone catalogue that maximizes the use of available sources. The catalogue consists of 304 tropical cyclones that occurred between AD 1000 and AD 2009 and made landfall along the coasts of Bangladesh, eastern India and Myanmar (most important historical events of tropical cyclones are mentioned in Table 14.3). There is a paucity of data about tropical cyclones before AD 1900. Inconsistencies in reported storm surge height, wind speed and exaggerations in the reporting of deaths are identified. Some 2,072,509 human deaths in Bangladesh are associated with 71 tropical cyclones that occurred between AD 1484 and AD 2009. Between AD 1923 and AD 2009, 11 tropical cyclones caused 9,435,000 people to become homeless, and between

AD 1961 and AD 2009, 10 tropical cyclones resulted in economic damage of over US$ 4.6 billion.

The oldest tropical cyclone – also the first palaeo event in the catalogue – is derived from geological data and dates to approximately AD 1000 and affected the North Cinque Island located south of the Andaman Islands. The oldest historical tropical cyclone (also the second oldest event listed) dates to AD 1484 and is reported to have affected the Chittagong coast. An analysis of the events listed in the catalogue suggests that during the fifteenth, sixteenth and seventeenth centuries, the number of reported tropical cyclones were 3, 2 and 21, respectively. The number of reported tropical cyclones has increased markedly, reaching 99 in the eighteenth century and 169 in the nineteenth century, while eight tropical cyclones occurred after AD 1999. The lack of tropical cyclones prior to AD 1582 and the low reporting of events before AD 1900 hint at the probability that more tropical cyclones remain to be identified within the region's archival and geological records.

Despite remarkable success achieved in the reduction of deaths, the number of people being displaced and economic damage they suffer from are continuing to rise. Although there is no obvious change in the occurrence of intense tropical cyclones in the Bay of Bengal, the increase in losses may be attributed to greater exposure (the number of people, animals, crops, fishing and industry to such catastrophe (Alam and Dominey-Howes 2014).

Singh (2007) reported that In Bay of Bengal, over a period of 120 years (1891–2010), disturbances like depressions and cyclonic storms occurred at a rate of 10.79 per year. However, in the last 40 years (1971–2010), the total number of disturbances has reduced but the frequency of 'severe' storms and their intensity increased remarkably. This increasing trend is reflected on an increasing trend in rainfall. According to Singh (2007), severe cyclonic storms over Bay of Bengal registered 26% increase over the last 120 years. During the last part of decade (2006–2009) the northern part of Bay of Bengal registered cyclones *viz. Sidr-2007, Nargis-2008*and *Aila-2009* which have caused significant damages to live and properties of the coastal zones (Table 14.4).

14.4.2 Floods

About 45.5 million people in Bangladesh are exposed to severe and moderate floods like river flood, flash flood and tidal flood. Floods occured in 1974, 1987, 1988 and 1998 caused death of 30000, 1657, 2379 and 1000 lives, respectively, and damaged crops and infrastructures (Rahman and Rahman 2015). Recurring floods during 2002, 2003, and 2004 caused huge damages of crops, structures and road transportation. In 2007, flood inundated 32,000 km^2 area twice in July–August and in September, and 16 million people were affected in 3 million households of which 85 thousand houses were totally damaged and more than 1 million damaged partially.

Due to incessant rainfall during the month of July 2015, Komen, the cyclone that hit West Bengal on the 30th of July 2015, caused over 1.06 crore people from West

Table 14.3 A catalogue of historical tropical cyclones and palaeostorms in the Bay of Bengal region with a particular focus on India and Bangladesh

Date of event			Type		Affected areas	Physical Characteristics		Effects of tropical cyclone						Comments
Year (AD)	Month	Day	GTCCA	Country	Landfall locations	Wind speed (kmph)	Height (m)	Deaths	Injuries	Affected	Homeless	Total affected	Damage (000US dollars)	
1000	*	*	Hurrican	IND	Nor Cinque Island	*	*	*	*	*	*	*	*	Radiocarbon dating of sediments used to infer storm surge event occurred in AD 1000
1484	*	*	Hurrican	BNG	Chittagong	*	*	200,000	*	*	*	*	*	The reported round figure of deaths of '200000' seem to be unrealistic
1760	*	*	Hurrican	BNG	Khulna	*	*	*	*	*	*	*	*	The entire west coast of Bangladesh was destroyed
1833	*	*	Hurrican	BNG	Khulna	*	*	50,000	*	*	*	*	*	The entire Khulna coast was completely destroyed. The inhabitants

(continued)

Table 14.3 (continued)

Date of event			Type		Affected areas	Physical Characteristics		Effects of tropical cyclone						Comments
Year (AD)	Month	Day	GTCCA	Country	Landfall locations	Wind speed (kmph)	Height (m)	Deaths	Injuries	Affected	Homeless	Total affected	Damage (000US dollars)	
														who survived left the area and settled elsewhere
1833	5	21	Hurrican	IND	West Bengal	*	3.05	50,000	*	*	*	*	*	The tropical cyclone crossed the Sagar Island. 100,000 cattle were lost
1864	10	5	Hurrican	IND	West Bengal	*	12	50000or 80,000 or 100,000	*	*	*	*	*	The tropical cyclone is known as the AD 1864 Kol-kata cyclone, occurred at the mouth of Hugli River
1865	*	*	Hurrican	IND	Kolkata	*	*	220,000	*	*	*	*	*	After the cyclone, the British government

														established the Indian meteo-rological department in this subconti-nent in 1875
1876	10	31	Hurrican	BNG	Noakhali	220	12 or 13.7	100000or 200,000 or 400,000 or500000	*	*	*	*	*	The tropical cyclone is called the AD 1875 great Bakerganj cyclone, people were died due to diseases and hunger
1897	10	24	Hurrican	BNG	Chittagong	*	*	32,000, 175,000	*	*	*	*	*	Diseases par-ticularly chol-era caused many deaths. Many deaths occurred in the Kutubdia Island
1919	9	25	Hurrican	BNG	Barisal	*	*	40,000	*	*	*	*	*	The tropical cyclone crossed the Sundarbans coast and

(continued)

Table 14.3 (continued)

Date of event			Type		Affected areas	Physical Characteristics		Effects of tropical cyclone						Comments
Year (AD)	Month	Day	GTCCA	Country	Landfall locations	Wind speed (kmph)	Height (m)	Deaths	Injuries	Affected	Homeless	Total affected	Damage (000US dollars)	
														passed over Khulna. Gopalganj and Dhaka
1960	10	11	Hurrican	BNG	Noakhali	201	4.57or 6	3000 or 9537	*	*	100,000	100,000	*	62,725 houses were damaged, 94,000 acres of crops were fully damaged and thousands of cattle were perished
1963	5	29	Hurrican	BNG	Chittagong	241	2.44–3.65 or 5.18	9636 or 11,520 or 22,000 or 50,000	*	1,000,000	1,000,000		50,000	32,617 cattle were lost and 367,332 houses, 4787 boats and extensive areas of standing crops were destroyed

1965	5	12	Hurrican	BNG	Khulna	63–117 or 162	3.65	36,000 or 19,279 or 12,000	600,000	10,000,000	5,000,000	15,000,000	57,700	16,456 people were killed in Barisal
1966	10	1	Hurrican	BNG	Khulna	146	4.7–9.1 or 6–7	850	*	1,500,000	300,000	1,800,000	22,400	65,000 live-stock were lost in Noakhali and Barisal
1970	10	23	Hurrican	BNG	Khulna	67–117 or 163	4.7	300	*	*	40,000	40,000	*	It crossed the Sundarbans coast close to the Bangladesh-Kolkata border
1970	11	12	Hurrican	BNG	Barisal	223 or 233	3.05–10.05 or 6.10–9.14	200,000–300,000 or 300,000 or 500,000	*	3,648,000	*	3,648,000	86,400	The cyclone crossed the coast of Bangladesh during high tide period. A total of 38,000 marine and 77,000 Freshwater fishermen were affected

GTCCA Global Tropical Cyclone Climatic Atlas

Source: Alam and Dominey-Howes (2014), permission obtained

Alam and Dominey-Howes (2014) developed a tropical cyclone catalogue that maximizes the use of available sources. The catalogue consists of 304 tropical cyclones that occurred between AD 1000 and AD 2009 and made landfall along the coasts of Bangladesh, eastern India and Myanmar (most important are mentioned in this table)

Table 14.4 Tropical cyclones affected coastal zones

Cyclones	Affected regions	Wind speed (km/h)	Death	Damages (million US $)
Bhola cyclone-1970	Bangladesh, India	205	500,000 (in Bangladesh)	86.4
Bangladesh cyclone-1991	Bangladesh	260	138,000	1500
Sidr-2007	Bangladesh	260	4036	2300
Nargis-2008	Myanmar, India, Sri Lanka, Bangladesh	215	138,366 (126 in Bangladesh)	10,000
Aila-2009	Bangladesh, India	120	325 (26 in Bangladesh)	552.6
Mahasen-2013	Bangladesh	88	17 (in Bangladesh)	200

Source: Rahman and Rahman (2015), permission obtained

Bengal affected. The flooding is mainly due to the high tidal effects and Komen depression-related rainfall. Though the calamity had affected 14 districts covering 21,885 villages in West Bengal, two southern districts, North and South 24 Parganas, were especially badly affected. Crop over an area of 1.29 million hectares has been damaged and 22,800 livestock were lost. Population living in low-lying areas experienced water stagnation in their houses and villages for about 10–12 days. As per meteorological data recorded at Central Soil Salinity Research Institute, Canning Town India) July 2015 recorded the maximum rainfall of 838.4 mm (in 28 rainy days out of 31 days of August month) in a single month since 1966.

14.4.3 Sea Level Rise (SLR) and Salt Water Intrusion

One of the greatest challenges people living on the delta may face in coming years is the threat of rising sea levels caused mostly by subsidence in the region and partly by climate change. Northern Indian Ocean, which includes the Bay of Bengal, is experiencing a relatively high rate of sea level rise compared to other oceans globally. A 2007 report by UNESCO "Case Studies on Climate Change and World Heritage" has predicted 45-cm rise in sea level likely by the end of the twenty-first century in Sundarbans. According to the Intergovernmental Panel on Climate Change, due to climatic and anthropogenic stresses, Sundarbans may lose 75% of its mangroves. A recent study of global deltas showed that the entire Bengal delta is sinking at a perilous rate due to sediment compaction from the removal of oil, gas and water from the inland delta's underlying sediments, the trapping of sediment in upstream reservoirs, flood plain engineering, and rising sea level (Syvitski et al. 2009, The Hindu, Chennai, September 21, 2009). Based on global sea level data and modelling, Ericson et al. (2006) have estimated that the sea level rise of the Bay of Bengal is the world's highest, at >10 mm year^{-1}. Other studies have confirmed this trend, but with rates ranging from 4.0 mm year^{-1} in the western zone to 7.8 mm year^{-1} in the eastern zone (SMRC 2003; Han et al 2010; Unnikrishnan and Shankar 2007). The direct impacts of SLR in deltas include inundation of coastal areas, saltwater intrusion into coastal aquifers, increased rates of coastal erosion, and an increased exposure to storm surges. These threats have implications to human populations in deltaic areas as well as in ecologically sensitive and important coastal wetland and mangrove forests.

WWF-India (2010) reported that the relative mean sea level in Sagar and adjoining areas of the Bay of Bengal was rising at 3.14 mm per year based on the tide gauge data recorded between the periods 1985–2000, when the global estimate of sea level rise was between 0.5 and 3 mm per year. According to this study, such a rise in the Sundarbans area will lead to a 20 cm rise of sea level by 2050. However, in the event of any further rise in temperature and rainfall there is a strong probability that the sea level will rise by 50 cm instead of 20 cm.

Using data extracted from the Permanent Service for Mean Sea Level (psmsl.org), it was illustrated that relative sea level rise varied from 4 mm per year (Hiron Point) to 19 mm per year (Khepupara) in Sundarbans region (Fig. 14.3) (Brown and Nicholls 2015). Permanent service of mean sea level (www.psmsl.org) is the world's archive of mean monthly and mean annual tide-gauge database located the National Oceanography Centre in Liverpool, England founded in 1933. Based on PSMSL data base, the rate of sea level changes for three tide-gauge stations namely, Diamond Harbour, Garden Reach and Haldia in Indian Sundarbans are found to be +4.85, +8.22, and + 3.0 mm per year, respectively (Fig.14.4) (Annual Report 2015–2016).

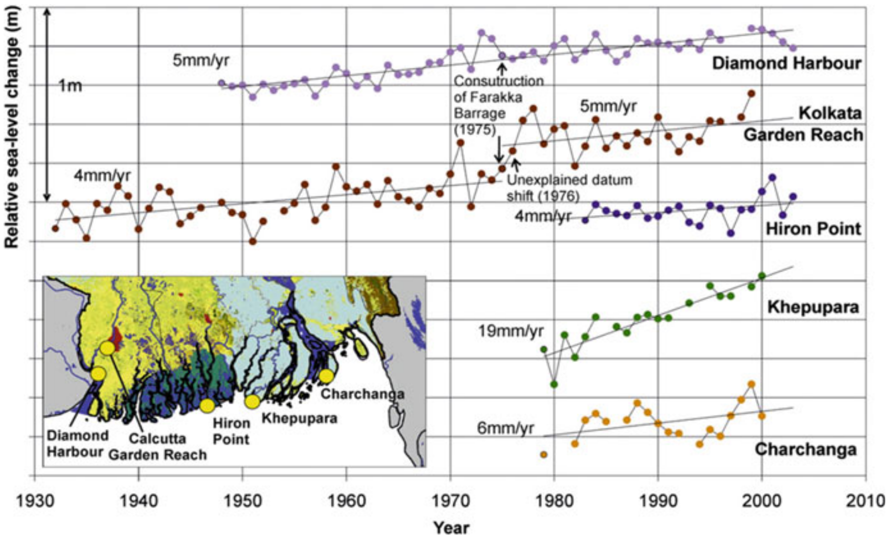

Fig. 14.3 Relative sea level rise obtained via tide gauge data from psmsl data base. (Brown and Nicholls 2015, permission obtained)

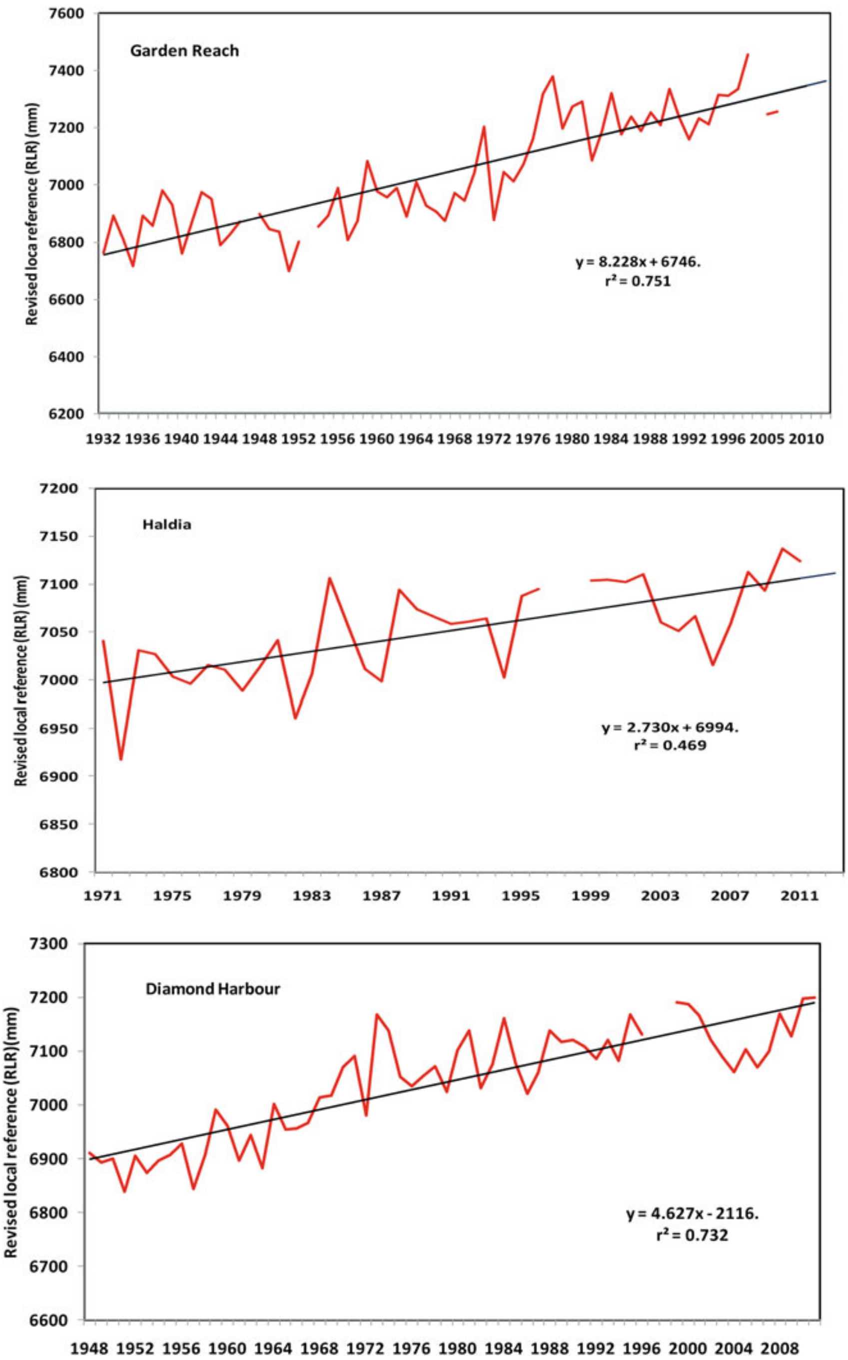

Fig. 14.4 Changes in annual sea level at tidal observatories of the Hugli estuary. (Data from PSMSL, in house study)

In 2008, the Institute of Water Modelling (IWM) studied the impact of sea level rise in coastal river of Bangladesh and assessed the change in the tidal characteristics of the surrounding rivers due to sea level rise and its impact on inundation area of the polder. Studies revealed that high water level at the surrounding rivers of polders may increase in the range of 30–80 cm for sea level rise of 32 cm and 88 cm, respectively, and this might hamper the smooth drainage of the polders causing prolonged water logging (Rahman and Rahman 2015). The potential land loss estimated by IPCC in Bangladesh is 29,846 km^2 by a sea level rise of 1 m making 14.8 million people landless.

14.5 Hazards and Degradation

14.5.1 Hydrological Balance, Soil Properties and Biodiversity

Impact on the mangrove forest by wastewater pollution due to several anthropogenic factors including pollution from large cities and industries, and a reduction in freshwater supply owing to the construction of upstream embankments for diversion of irrigation water, and the facts that such effects have been compounded due to climate change and weather extremes, are significant. The most prominent example is the Farakka Barrage, constructed in 1975, which has altered the regional hydrological balance, altered the soil properties along with increased salinization of soils, and contributed a great deal to differences in freshwater distribution.

Further, indiscriminate construction of circuit embankments to make islands habitable since the British administration, have, over 200 years, altered natural geomorphological processes of delta formation. In many cases the creek beds have risen higher than the low-lying reclaimed areas, turning those areas into vast stretches of permanent marshes. In Indian Sundarbans, out of total 3500 km of embankment, 800 km has become vulnerable to breach during high intensity weather events. Present trend in sea level rise will have serious impacts on the embankments making these more vulnerable and susceptible to breach and overtopping. Apart from exposing populations to inundation and destruction of assets, these breaches also lead to an increase in soil salinity, ruining prospects for agriculture, whilst also affecting the floral and faunal diversity of the eco-region.

14.5.2 Erosion and Accretion

Sundarbans is under the threat of severe erosion and drowning due to relative sea level rise and increasing cyclonic activity. Already, Lohachara Island and New Moore Island/South Talpatti Island have disappeared under the sea, and Ghoramara Island is half submerged in India. In general, the western banks of rivers are more vulnerable to erosion than the east and erosion is more along the sea facing shorelines where it is oblique. Marginal accretion is localized in the inner estuaries particularly along the eastern and northern margins of islands and along the coast where it is mostly east-west oriented and sea facing. The study conducted during 2001–2009 reveals that a total land area of 6402.09 km^2 of the Indian Sundarbans in the year 2001 has reduced to 6358.05 km^2 in 2009 (WWF-India 2010; Hazra et al. 2010).

Erosion and accretion of few Indian Sundarbans islands was also studied at ICAR-CSSRI, RRS, Canning Town under National Innovation of Climate Resilient Agriculture Project (Table 14.5). The shoreline and land-use/land cover changes of Sagar Island under Sundarbans coast was studied using IRS-1C-LISS-III (Indian Remote Sensing Satellite 1C (IRS IC) and linear imaging self-scan sensor (LISS) III) satellite data during 1998–1999 (Dinesh Kumar et al. 2007). A comparison between a topomap of 1967 and satellite data of 1999 established that during these years about 29.8 km of coastline was eroded, whereas the accretion is only 6.03 km^2. A comparison of satellite data from 1998 and 1999 showed that the island had undergone severe erosion of about 3.26 km^2, while the accretion was just about 0.08 km^2.

Rahman et al. (2011) studied the dynamics or current status of the Sundarbans (both in India and Bangladesh part) coastline using Landsat images spanning from 1973 to 2010, and consistently estimated the spatiotemporal dynamics of erosion and accretion for four different time intervals (Fig. 14.5, Table 14.6). The results showed that the erosion was the highest in the 1973–1979 intervals, with 23.2 km^2 year^{-1} of land loss. However, the rate substantially declined in the following

Table 14.5 Year-wise land surface area (km^2) of few Indian Sundarbans Islands (in house study)

Island name	1975	1989	2002	2011	2015	2015–1975	Population (2011)
Sagar	236.59	238.20	23,438	234.44	235.15	−1.44	212,037
Ghoramara	7.20	6.13	4.65	4.30	4.15	−3.04	5193
Jambudwip	6.78	7.67	4.24	4.20	3.91	−2.86	No habitation
Mousuni	30.83	30.74	27.69	27.76	27.10	−3.72	22,073
Lothian	33.95	34.49	33.44	34.46	34.33	0.38	Reserved Forest
Bulcheri	28.71	27.46	20.49	21.76	20.74	−7.97	Reserved Forest
Dalhousie	76.13	70.86	63.34	59.76	57.28	−18.86	Reserved Forest
Bangaduni	41.70	37.97	29.68	24.72	22.72	−18.98	Reserved Forest
Nayachar	30.04	41.04	47.55	44.82	47.35	17.31	2500
Nayachar1		0.54	0.50	3.25	3.04	3.04	Not available
Badford Dwip	3.56	1.33				−3.56	

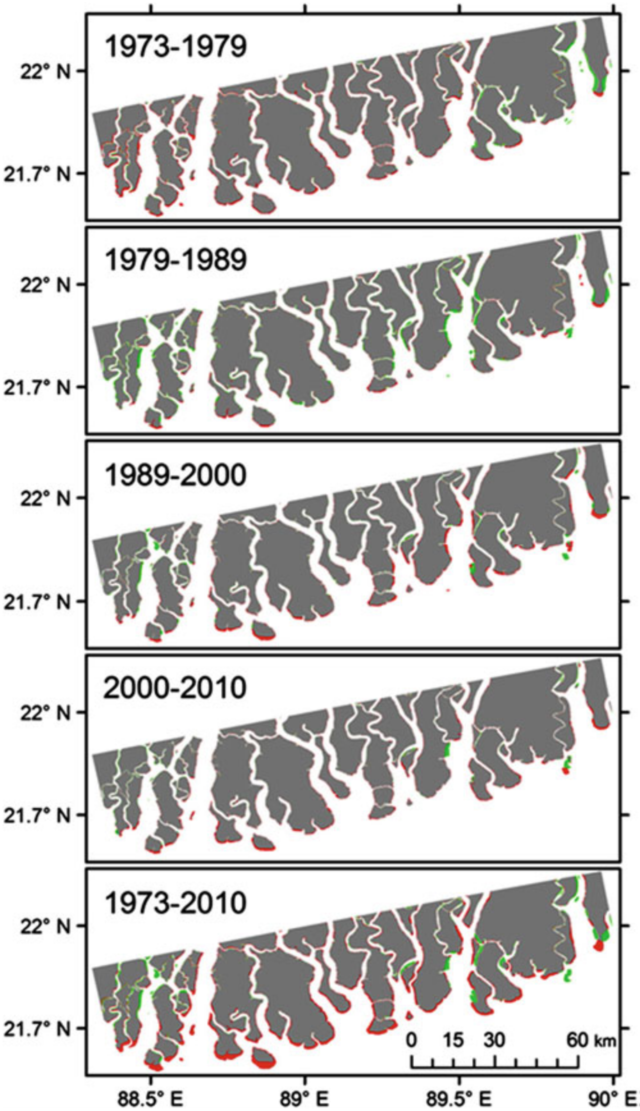

Fig. 14.5 Changes in coastline area as estimated using the Landsat images of 1973, 1989, 2000 and 2010. Red and green areas describe erosion and accretion, respectively. (Rahman et al. 2011, permission obtained)

periods, reaching a rate of 7–10 km^2 year^{-1}. Accretion showed a rate of 10 km^2 year^{-1} between 1973 and 1989, but substantially declined to ~4 km^2 year^{-1} between 1989 and 2010. Accretion rate has declined in the recent years but erosion rate has remained relatively high. As a result, the delta front has undergone a net erosion of ~170 km^2 of coastal land in the 37 years of the study period.

Table 14.6 Accretion and erosion rates in the Sundarbans coastline estimated for each sub-period and for the entire period of 1973–2010. Standard error is shown for the total accretion and erosion rates

Period	Accretion (km^2 $year^{-1}$)	Total accretion (km^2)	Erosion (km^2 $year^{-1}$)	Total erosion (km^2)	Difference (km^2)
1973–1979	9.5	56.8 ± 1.0	23.2	139.4 ± 1.3	−82.6
1979–1989	11	110.8 ± 0.8	6.9	68.7 ± 0.8	42.1
1989–2000	4.2	45.7 ± 0.3	10.2	112.9 ± 0.5	−67.2
2000–2010	3.1	31.2 ± 0.3	9.4	93.5 ± 0.4	−62.3
Total	6.6	244.5 ± 1.3	11.2	414.5 ± 1.6	−170.0
1973–2010	2.4	89.0 ± 0.5	7.2	264.6 ± 0.9	−175.6

Source: Rahman et al. (2011), permission obtained

14.5.3 Loss of Mangrove Forest and Displacement of Inhabitants

Mangrove forests in Sundarbans provide critical eco-region services, fulfil important socio-economic and environmental functions, and support coastal livelihoods. Their unique root systems create a great deal of physical roughness, thus capturing and storing vast quantities of sediment received from upland and oceanic origin. While the total mangrove area did not change significantly over the last few centuries, change detection analyses clearly show natural internal mangrove dynamics with small-scale land loss and gain by erosion and accretion of sediments within the tidal channels.

Change detection studies in Sagar island in India (Dinesh Kumar et al. 2007) based on land-use patterns of the region revealed that the areal extent of mangrove vegetation of the island during 1998 and 1999 was 2.1 km^2 and 1.3 km^2, respectively. The areal extent of agricultural fields during these periods was 130.4 km^2 and 118.6 km^2, respectively. Severe coastal erosion was also mentioned for Ghoramara island in Sundarbans delta region in India during last three decades which rendered thousands of people homeless as ‘environmental refugees’ (Ghosh et al. 2003). They predicted that if no remedial measures were taken the eastern shore of Ganges delta would merge with the Indian mainland while the western part would be completely washed off by next 25 years.

Along the Hooghly river channel new islands have developed on the western side, whereas more land has eroded on the east. Mangrove forests generally possess a high resilience to natural disturbances such as tropical storms and tsunamis. According to Islam (2014), recovery time in storm- disturbed mangrove forests of the Sundarbans is around 25 years. However, following a sequence of recent severe disturbing events, with several cyclones in a row (1988, 1991, Sidr in 2007, Nardis in 2008, and Aila in 2009) and the Asian tsunami of 2004, there is concern that the mangroves’ regeneration ability has been weakened (Ghosh et al. 2015).

14.6 Impact on Farming Practices

We restrict our discussion to agriculture and aquaculture being the most important components under farming for the inhabitants in Sundarbans eco-region. Rice is the predominant form of land use under agriculture in Sundarbans.

14.6.1 Agriculture

Climate change may affect agricultural crops in four ways (Srinivasarao et al. 2016). First, changes in temperature and precipitation will alter the distribution of agroecological zones. Second, carbon dioxide effects are expected to have a positive impact due to greater water use efficiency and higher rate of photosynthesis. Third, water availability (or runoff) is another critical factor in determining the impact of climate change. Fourth, agricultural losses can result from climatic variability and the increased frequency of extreme events such as cyclones, floods, draught, etc. Several crop models including DSSAT series, ORYZA, WTGROWS, INFOCROP, and INFOCANE have been used in large number of studies to evaluate the impacts of changes in CO_2, rainfall, and temperature on agriculture in India. Climate change is also predicted to lead to boundary changes in areas suitable for growing certain crops. Reductions in yields due to climate change are predicted to be more pronounced for rainfed crops (as opposed to irrigated crops) and under limited water supply situations because there are a few coping mechanisms for rainfall variability. Birthal et al. (2014) projected the effects of climate change on crop yields for three timescales (2035, 2065, and 2100) at minimum and maximum changes in temperature and rainfall (Table 14.7).

14.6.1.1 Weather Parameters

Changes in precipitation may exert a stronger impact on rice production than temperature changes. Similarly, frequent floods due to heavy precipitation may result in higher yield losses under progressing climate change. However, higher temperature will increase sea level due to (1) thermal expansion of sea water, and (2) rapid melting of glaciers and ice caps. Consequently, fragile coastal and highly productive deltaic rice cultivation areas will be more exposed to inundation and salinity intrusion. For rice production, increasing CO_2 leads to a cascade of impact mechanisms that have both beneficial and harmful effects on agricultural production in general and rice production, in particular. Figure 14.6 synthesizes the different impact mechanisms, which are explained in Wassmann et al. (2009). The present CO_2 of 380 ppm, projected to double by the end of the century (IPCC 2007), could benefit the rice crop by increasing photosynthesis and biomass depending on rice cultivar, growth stage, and environment. Moreover, higher CO_2 beneficially

Table 14.7 Projected changes in crop yields (%) at maximum changes in temperature and rainfall by 2035, 2065 and 2100. (Birthal et al. 2014)

Crop	2035	2065	2100
Rainy season			
Rice	−7.1	−11.5	−14.4
Maize	−1.2	−3.7	−4.2
Sorghum	−3.3	−5.3	−7.1
Pigeon pea	−10.1	−17.7	−23.3
Groundnut	−5.6	−8.6	−11.8
Winter season			
Wheat	−8.3	−15.4	−22.0
Barley	−2.5	−4.7	−6.8
Chick pea	−10.0	−18.6	−26.2
Rapeseed-mustard	0.3	0.7	0.5

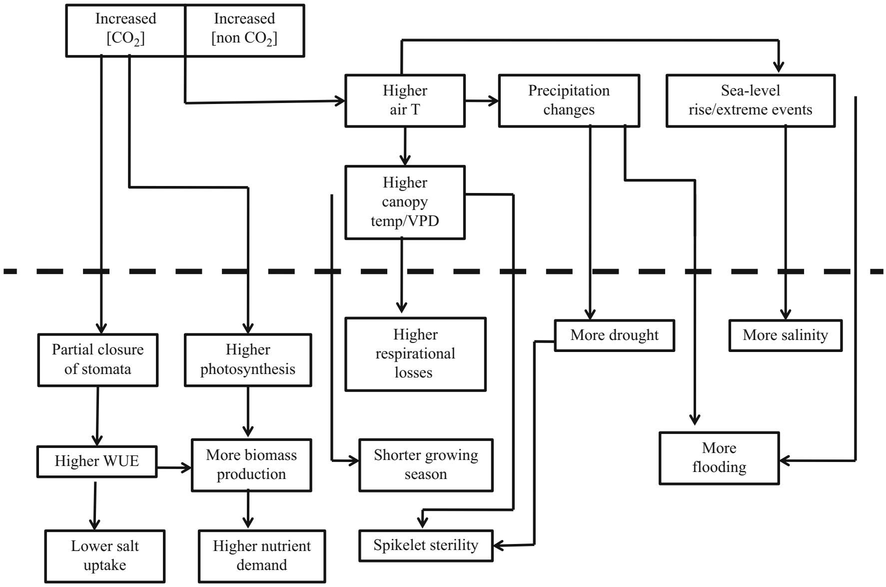

Fig. 14.6 Schematic presentation of potential effects of rise in CO_2 concentrations and temperatures on rice and its growing environment. (Wassmann et al. 2009, permission received)

influences stomatal behaviour, resulting in less water lost through transpiration that is, increasing water use efficiency. On the other hand, an increase in CO_2 and other greenhouse gases increases surface air temperature, further aggravating abiotic stress for crop production. At the plant level, higher temperatures enhance the respiratory rates during the day and more so due to increasing night temperatures. Simultaneously, this temperature rise will result not only in reducing the growth-duration of the rice crop but also the duration for grain filling, resulting in lower yield and lower quality rice grain. Collectively, the disadvantages largely outweigh the advantages for rice cultivation under predicted future climate change. Rice production in eastern regions, including Sundarbans, is predicted to be most impacted by increased temperatures and decreased radiation, resulting in relatively fewer grains and shorter grain filling durations. Although additional CO_2 may benefit crops, this effect is predicted to be nullified by an increase of temperature.

14.6.1.2 Sea Level Rise, Flooding and Submergence

Rising sea level may deteriorate rice production in a sizable portion of the highly productive land in the deltas. In Bangladesh, the “Aman” (monsoon) crop, which makes up 55% of the national rice production will be exposed to higher flood risk during the vegetative stage of the rice plants. Ganges–Brahmaputra deltas have experienced severe cyclones over recent years causing enormous losses in rice production. In Bangladesh, cyclone Sidr caused production losses in the range of 800,000 t of rice during 2007 (IRIN 2008). With higher sea water levels and an increase in storm incidences, flooding and salinity stress for rice in delta areas are likely to worsen.

Submergence is an important abiotic stress affecting about 10–15 million ha of rice fields in South and South-East Asia causing yield losses every year (Wassmann et al. 2009). This number is anticipated to increase considerably in the future given the increase in seawater level, as well as an increase in frequencies and intensities of flooding caused by extreme weather events. Although a semi-aquatic plant, rice is generally intolerant to complete submergence and plants die within a few days when completely submerged. The adverse effects of flooding elicit complex responses of the rice crop that vary with genotype, energy reserves before and after submergence, developmental stage when flooding occurs, duration, and depth of flooding, as well as conditions of the floodwater, particularly the temperature and degree of turbidity. Prolonged partial flooding with 30–60 cm water depths reduces rice productivity in vast areas of rainfed lowlands, and sometimes occurs following shorter-term complete submergence.

14.6.1.3 Salinity in Soil and Water

Increasing threat of salinity has become an essential issue linked to the consequences of climate change. In general, global warming affects the salinity of sea waters in two different ways. First, in the open sea rising temperature would lead to increased evaporation, which in turn would result in increased salinity. Intrusion of sea water inland might also increase salinity of soil and water. In contrast, the salinity of surface water in bays, estuaries and coastal waters would decrease by freshwater input from glaciers, precipitation and subsequent runoff. But this generalization may not hold uniformly in all the segments of the Sundarbans. The western sector showed a significant and continuous decrease in salinity whereas the eastern sector showed an increase in salinity. Global warming and climate change may have the following consequences to salinity levels in Sundarbans:

- Increased evaporation of sea water resulting in increased salinity;
- Changes in upstream river flows due to an initially increased glacial melt potentially decreasing salinity in certain areas depending on the hydrology of rivers and their tributaries;
- Rising sea levels and increased sea water intrusion leading to increased salinity;
- Changes in the severity of extreme weather events potentially increasing salinity as a result of coastal flooding; and
- Changes in precipitation patterns resulting in either increased or decreased salinity depending on the seasonal shift in amounts of rainfall.

A review on salinity of surface waters and groundwater from different locations of Sundarbans estuary reveals distinct trends of increasing salinity in many parts. Comparison of past data (1984) with more recent data (2001) shows drastic increase in salinity of the outer estuary (26 ppt–36.2 ppt) and mid estuary (20 ppt–26 ppt) for the summer data of the Eastern Sector in India (Chand et al. 2012).

Rice can be categorized as a moderately salt sensitive crop with a threshold electrical conductivity of 3 dS m^{-1} (Maas and Hoffman 1977). Rice is usually mono-cropped in tropic and sub-tropic coastal areas during wet seasons due to its adaptation to waterlogged environments while tolerating salinity up to a certain extent. The high adaptability of rice under salt-affected areas makes it the most preferred crop for growing in these unfavourable environments. However, rising sea level and salt water intrusion may deteriorate rice production in a sizable portion of the highly productive rice land in deltas.

The ground water is naturally saline in most areas under coastal region. Secondary salinization, specifically due to the injudicious use of water and fertilizers in irrigated agriculture could increase the percentage of brackish ground water. The ground water table, if it rises and is brackish in nature, becomes ruinous to most of the vegetation.

Higher temperature aggravates the situation by excessive deposition of salt on surface due to capillary action which is extremely difficult to leach below the rooting zone especially in commonly occurring moderate to heavy textured soils in Sundarbans. The increased temperature will also disrupt weather patterns, leading to more frequent occurrence of problems associated with floods, drought, and salinity.

14.6.2 Aquaculture

14.6.2.1 Productivity and Socio-economic Impact

Fishery (fishing and aquaculture) is treated as the backbone of Sundarbans economy. Sundarbans boasts around 172 species of fishes, 20 species of prawn and 44 species of crabs including two commercial species. This region is the top producer of fish and prawn. South and North 24 Parganas districts of West Bengal (India) combined produces roughly 31% of the total inland fish/prawn production of the state. Apart from coastal and brackish water aquaculture, freshwater aquaculture is increasing steadily and contributes parallel economy towards livelihood security in the region. Chand et al. (2012) reported that the fishponds in low-lying areas of Sagar and Basanti block are prone to coastal flooding during rainy seasons. It leads to breach of pond dyke, ingression of saline water into freshwater pond, escape of fish stock from the pond, entry of other (often unwanted) fish species, fish mortality, etc.

In a recent study carried out in the north-western part of Bangladesh (Faruque Hasan and Kabir Alamgir 2016) it has been reported that aquaculture profit is strongly influenced by the climate variables, including extreme weather events and long-term climate changes. According to the survey, most of the fish farmers cited that high temperature, decreased rainfall, seasonal variability, prolonged drought, etc. affected the fish production. Due to climate change fishes were susceptible to diseases and could not recover from disease. As because fish farming becoming less profitable venture due to climate induced factors along with anthropogenic causes in the Rajshahi district, fish farmers are often forced to change their occupation, and thus the fish farmers' socio-economic condition becomes more vulnerable. The changing environment put the fish farmers in great challenge as they have to shift their main occupation to alternative employment opportunities on which they are not adopted.

14.6.2.2 Biodiversity and Impact on Aquaculture Ecosystem

Apart from climate change issues, indiscriminate collection of shrimp seeds from the waters of Sundarbans results in biodiversity loss of the region. According to an estimate to catch one shrimp seed, around 60–70 others fish/shrimp seeds of uneconomical varieties are either injured or killed. Crab catching is another activity affecting the biodiversity (Chand et al. (2012). Due to high demand of gravid females in the export market, matured females are overexploited from the natural water leading to acute shortage of mother crabs, which will affect their natural breeding and thus there is likely to be decline of crab population in Sundarbans water. Chand et al. (2012) also noted that there was drastic reduction of some native fish species in last 30 years. These are *Ompok pabda (Pabda), Wallago attu (Boal), Heteropneustes fossilis (catfish)*, *Clarias batrachus (catfish), Anabas testudineus (Koi), Anguilla bengalensis (Ban)*, *Colisa fasciata (Kholse)*, *Chitala chitala (Chital), Channa marulius (Murrel), C. striata (Murrel)*, C. *punctata (Murrel)*, *C. gachua (Chang)*, *Puntius sarana (SaralPunti), Chanda nama (Chanda), Nandus nandus (Nadosh) etc.* Few invasive fish species like *Pygocentrusnattereri, Clariasgariepinus*are recorded during the survey.

Climate change is modifying the distribution and productivity of marine and freshwater species, and is already affecting biological processes and altering food webs. The consequences for sustainability of aquatic ecosystems, fisheries and aquaculture, and the people that depend on them, are therefore uncertain. Coral reefs will degrade with increasing water temperatures and acidification of the oceans and be more sensitive to the threats of over-fishing, pollution, tourism, and increased population of invasive species. This will affect the quantity and type of fish available to coastal communities.

14.7 Conclusions

The International Institute for Environment and Development set its goal to enhance understanding of the linkages between sustainable development and climate change in least developed countries. Priority themes for the programme include: enhancing adaptation capacity; climate change and sustainable livelihoods linkages; capacity strengthening; information dissemination; equity and; enhancing opportunities for developing countries to take advantage of opportunities offered for carbon trading including clean development mechanism (CDM) (Huq et al. 2003). Sundarbans provides a wide range of important ecosystem services, including: the provision of food and water for millions of its inhabitants; protection against the worst effects of natural hazards, such as cyclones and tsunamis; the ability to act as long-term carbon sink; the retention of terrestrial sediments; and as a habitat for many species, including some rare ones. During the last two-and-a-half centuries, Sundarbans has been affected by human impact, slow onset of climatic change and extreme weather events, the latter two are on increasing trend. While mangroves inherently possess a high resilience to natural disturbances such as tropical storms or tsunamis, the effects due to anthropogenic degradation are often extremely damaging. There is need to address the core problems consisting of local livelihood needs, environmental pollution, upstream diversion schemes, forest clearing and soil and water conservation strategies of the region.

The issue is whether or not to look for improvement in farming practices in view of climate change seemingly irreversible, or else, be content with subsistence farming, the hypothesis, which may be debatable as per the current trend, in view of the above factors, and yet ensure livelihood security in the region. A multi-pronged strategy of using indigenous coping mechanisms, wider adoption of the existing technologies, and/or concerted research and development efforts for evolving modern technologies along with appropriate policy framework are needed for addressing conservation and climate change adaptation and mitigation.

OECD (Organisation for Economic Co-operation and Development) made a case study for Bangladesh, highlighting the importance of the trans-boundary dimension in addressing climate change adaptation. The effect of water diversion as a result of the Farakka barrage on dry season flows and salinity levels in the Sundarbans was in fact comparable (if not higher) than the impact that might be experienced several decades later as a result of climate change. Adaptation to climate change might therefore not just be local but might require cross-boundary institutional arrangements such as the Ganges Water sharing treaty to resolve the current problems of water diversion. Finally, climate change risks should also not distract from aggressively addressing other critical threats, including shrimp farming, illegal felling of trees, poaching of wildlife, and oil pollution from barge traffic, that might already critically threaten this fragile ecosystems even before significant climate change impacts manifest themselves (Agrawala et al. 2003). Nevertheless, the entire issue is extremely complex, particularly in view of climate change, and needs a re-look from trans-boundary perspective.

Sundarbans is gradually becoming inhospitable with time in view of climate change, deteriorating hydrological balance of the rivers and creeks, unscientific anthropological interventions, etc., all acting individually or through their interactions. Climate change, in particular, appears to be irreversible in nature, making the whole situation very complex adding to a host of constraints in soils and water normally experienced in the eco-region, thereby limiting the productivity of agriculture and aquaculture. The issue before us is whether or not it is technically possible to look for 'improvement in farm productivity' by tiding over the challenge with time. Alternatively, we may be content with 'subsistence farming', and yet ensure livelihood security, means of which have to be worked out in the lines suggested.

OECD, while working in Bangladesh, believes that the problems in Sundarbans are essentially trans-boundary in nature. We are also of the opinion that both Bangladesh and India should join hands to mitigate the miseries and find tangible solutions.

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Typical mangrove root system anchored into soil (Courtesy D. Burman)

Chapter 15
Influence of Climate Change on Biodiversity and Ecosystems in the Bangladesh Sundarbans

Ainun Nishat and Junaid Kabir Chowdhury

Abstract Sundarbans, an unique mangrove forest, located in the Ganges delta, with its rich floral and faunal composition has already been badly impacted by adverse impacts of climate change. The average temperature has already climbed by more than 1.0 °C since 1880 and warming rate is on increase. The conservative prediction of IPCC has clearly stated that the sea level may rise by 23 inches by the end of the century, increasing salinity level in the Sundarbans. Up to 30% of animal and plant species could be wiped out by a global temperature rise of 2.7–4.5 °C. Under such change the nature might adjust (i.e. adapt). It is already visible that some species that prefer low saline condition, such as Sundri (*Heritierra fomes*), Shingra (*Cynometra ramiflora*), etc. have started to die in Sundarbans, while Passur (*Xylocarpus* granatum) has become almost rare now. More salt tolerant species, such as Goran (*Ceriops roxburgii*), Jhana (*Rhizophora mucronata*), etc. will come to occupy these sites. Similar impact is seen on aquatic fauna as well. With the climate change impact, availability of both surface water and ground water in the Sundarbans Impact Zone (SIZ) will decline. The intensity and frequency of cyclonic storms and tidal surges will gradually increase. Adverse impacts of climate change on flora and fauna of the forest need to be monitored closely to work out appropriate plans for adaptive steps.

Keywords Bangladesh Sundarbans · Biodiversity · Inventories in the past · Present management · Climate change · Impacts on floral and faunal species · Impact on SIZ area

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15.1 Introduction

The undivided large tract of mangrove forest known as the Sundarbans used to extend, on the western side, from the estuary of the Hoogli River in India, and on the eastern side, to the Meghna River estuary in Bangladesh. Bounded by the Bay of Bengal in south side it used to extend up to Jessore area in the north. In 1875, part of the forest area was declared as Sundarbans Reserved Forests and was handed over to the Forest Department (FD) for management. The Bangladesh part of Sundarbans is located between $89^{\circ}00'$ and $89^{\circ}55'$ East and $21^{\circ}30'$ and $23^{\circ}30'$ North. The area of Bangladesh Sundarbans is 601,700 ha, of which about one-third (190,466 ha) is water such as rivers, *khals*, creeks, etc. (GOB 1995). Bangladesh Sundarbans has been maintained as natural forest with no settlement inside; so far, enchroachment has been prevented. Figure 15.1 shows the location of the Sundarbans and its present major zones. This paper focuses on the Bangladesh part of the Sundarbans.

It is the largest contiguous mangrove forest in the world and harbors about 40 true mangrove species out of the 60, so far globally known (SBCP 2001). The Sundarbans is a tidal forest and most part of the forest gets inundated during high tides twice a day. Some areas that are slightly higher, get inundated once a fortnight during new-moon and full-moon high tides. It is an effective natural barrier protecting its hinterland from cyclones and tidal surges, since time immemorial. It is reported that in every 3 years, on an average, it saves human lives worth 8 billion euro (SEALS 2010).

15.2 Management of the Sundarbans

Early management concentrated simply on revenue collection and the enforcement of felling rules to reduce over-cutting, particularly in the eastern part of the forest. Till 1912, Sundarbans was managed under working schemes. Trafford wrote the first management plan for Sundarbans for the period 1912–1913 to 1931–1932. He suggested two working circles as eastern working circle and western working circle. The eastern working circle had the richer growing stock. He prescribed selection system and suggested a 40-year felling cycle with an exploitable breast height diameters (BHG) of 106.6 cm for Sundari (*Heritierra fomes)* and 122 cm for Keora (*Sonneratia apetala)*. The second management plan for Sundarbans was written by S. J. Curtis that came into operation in April 1931. He prepared a very good map of Sundarbans using simple survey techniques. Curtis developed and applied volume functions for the first time, in the management of Sundarbans. He suggested two working circles but a large number of exploitable BHG limits for given species was prescribed. Different BHGs were prescribed different species; e.g., 12 for *Heritierra fomes*, 11 for *Excoecaria agallocha*, 7 for *Xylocarpus mekongensis*, 2 for Passur (*Xylocarpus granatum)*, 4 for *Bruguiera gymnorhiza*. Curtis' plan was very elaborate and needed professional skill to apply the precise

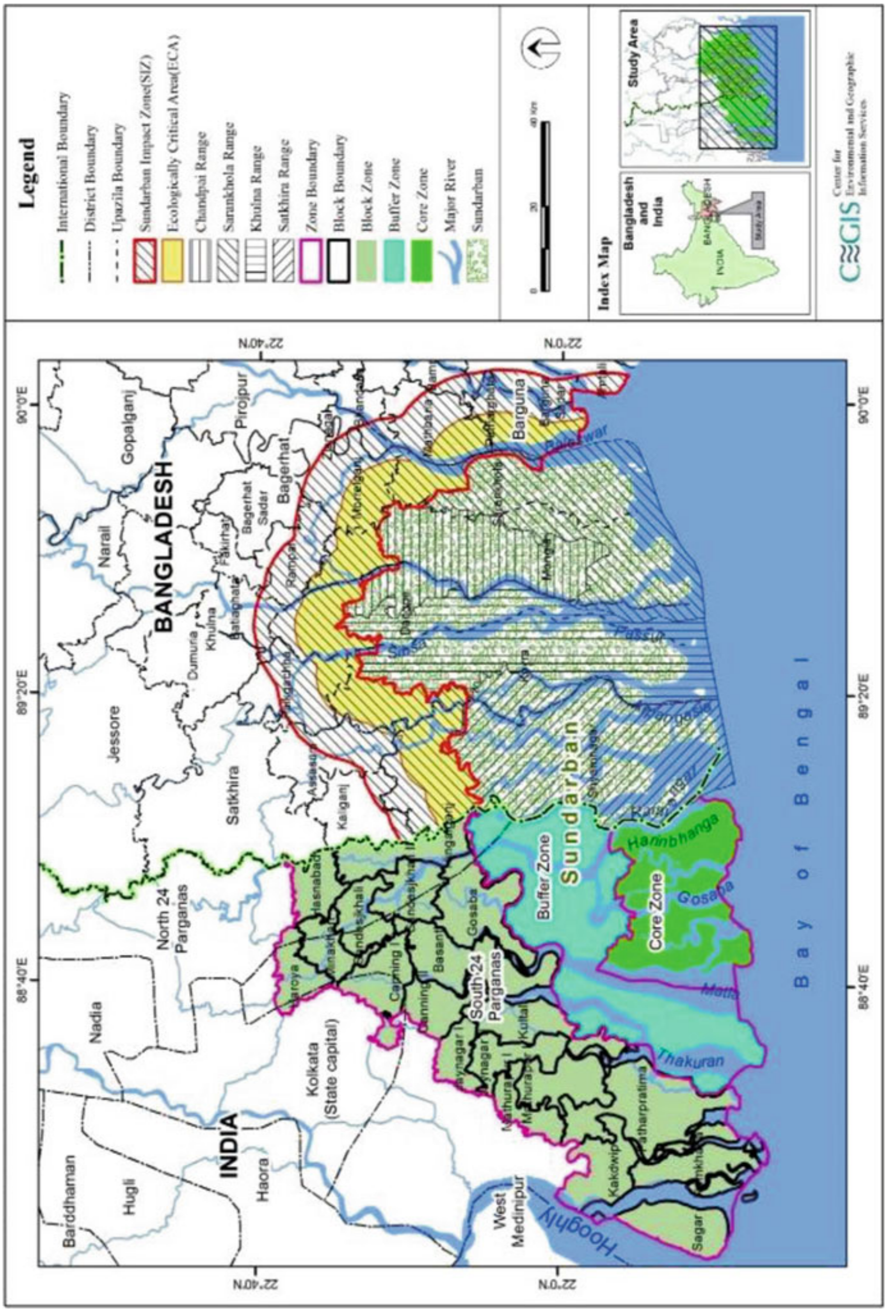

Fig. 15.1 The Sundarbans Reserve Forest

prescriptions. The field staff were incapable to follow these prescriptions and thus, it was revised by S. Choudhury in 1937. Choudhury's plan was in force from April 1937 to 1947. From 1947 to 1959 Sundarbans was managed on short-term schemes.

Forestal Forestry and Engineering International Limited of Vancouver, Canada carried out detailed inventory of Sundarbans in 1960. Based on the data and information generated, A. M. Choudhury prepared the management plan of Sundarbans for the period 1960–1961 to 1979–1980. He recognized 3 quality classes and suggested 3 working circles. He suggested exploitable diameter limits for *Heritierra fomes* as 26.9, 21.9 and 16.8 for site quality I, II and III, respectively. For most of the other important species except Baen (*Avicennia officinalis)*, he suggested same exploitable girths. He prescribed a 20-year cutting cycle for all important species. Choudhury's management plan laid emphasis on the production of industrial wood.

The next detailed inventory of Sundarbans was done by Overseas Development Administration (ODA) of U. K. during 1980 to 85. The report was published in 1985. E. G. Balemforth prepared a set of interim prescription in 1985. In 1990 a temporary moratorium on the harvest of timber was imposed. This moratorium though stopped the felling for sale to the members of the public, felling for the industries such as news print and hard board mill continued. In the meantime, top dying of *Heritierra fomes* became conspicuous. ODA report indicated that about 0.45 million *Heritierra fomes* trees (114 trees/ha) are affected by top dying. ODA report also indicated that there has been more than 40% depletion of the growing stock of *Heritierra fomes* and *Excoecaria agallocha* while the area under pure *Heritierra fomes* forest decreased from 31.6% to 21% and the mixed *Excoecaria agallocha- Heritierra fomes* increased from 24.4% to 29.7% between the Forestall (1960) and ODA (1985) inventories. Under such situation all extraction of wood was stopped.

Bio-geographical zoning has identified 5 major categories that are more or less stable. The ecological zoning, centering on the salinity, identified 3 zones, which shift with fluctuations in tidal inundation (Fig. 15.2). The ODA has produced cover maps using the following.

- Twenty cover Classes based on species composition
- Four Height Classes of 5-m interval
- Three Canopy Closures as < 30%, 30–70%, and > 70%

ODA had identified 14 major forest types and 300 sub-types.

The last inventory of Sundarbans was done in 1995–1996 from Forest Resource Management Plan (FRMP). Summary of these three inventories (Table 15.1) are as under.

Analyses of these data resulted in the following.

Based on this model the number of Sundri trees per hectare are projected as under (Fig. 15.3).

The analyses and projection of the number of Gewa stems based on these inventories resulted in the following (Fig. 15.4).

Similar modeling using the total number of trees resulted in the following (Fig. 15.5).

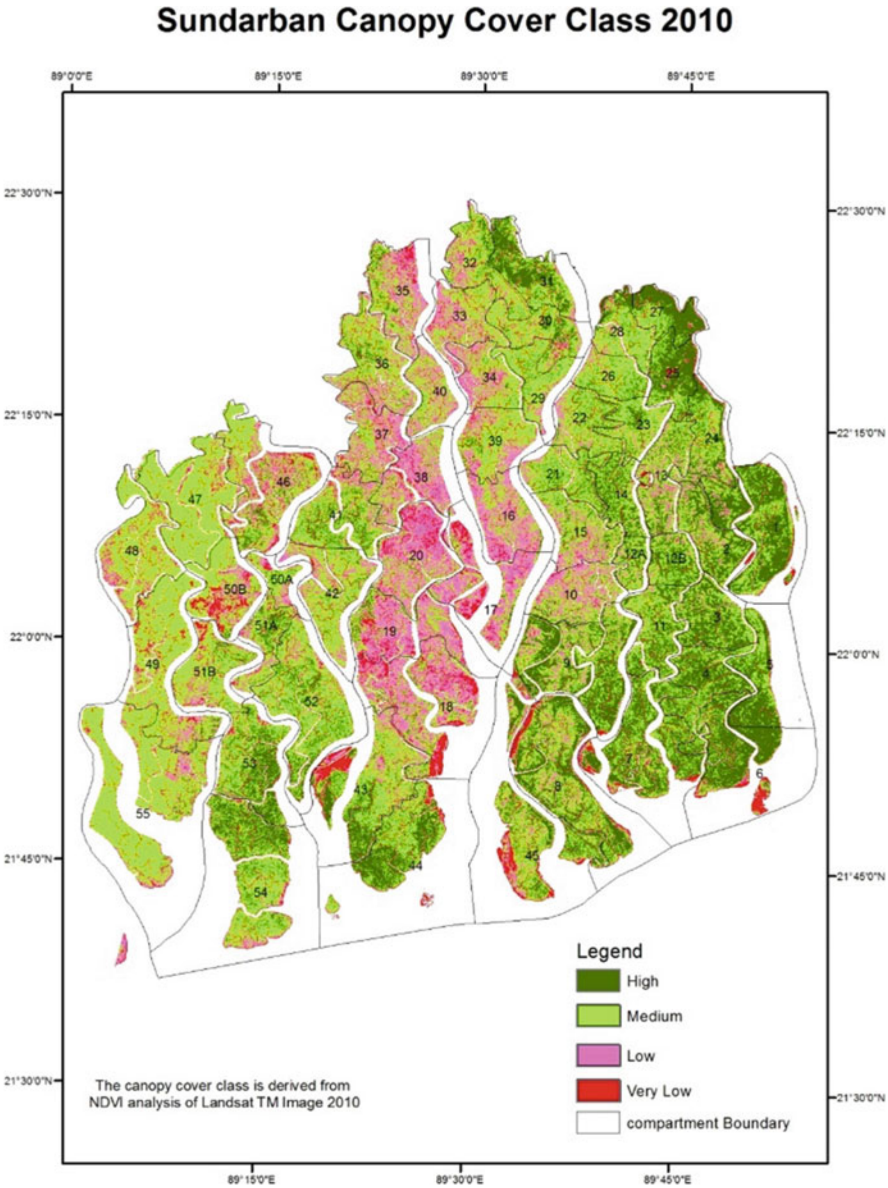

Fig. 15.2 Sundarbans canopy cover class 2010

Based on this model the total number of trees per hectare in certain years will be as under (Table 15.2).

If this trend continues in the year 2020 the number of Sundri trees with DBH 15 cm and above will decline to 80 per hectare, the number of Gewa trees per hectare will decline to 7, and the total number of trees per hectare will decline to 109.

Table 15.1 Growing stock of Sundarbans at different inventory time

Sl no	Inventory done by	Year of publication of inventory results	Sundri (Number of trees per hectare, having DBH 15 cm and above)	Gewa (Number of trees per hectare)	All tree species (Number of trees per hectare)
1	Forestal and Forestal Engineering, Vancouver, Canada.	1959	211	61	296
2	Overseas Development Authority, UK.	1983	125	35	180
3	Forest Resource Management Project (FRMP) Forest Department, Government of Bangladesh	1996	106	20	144

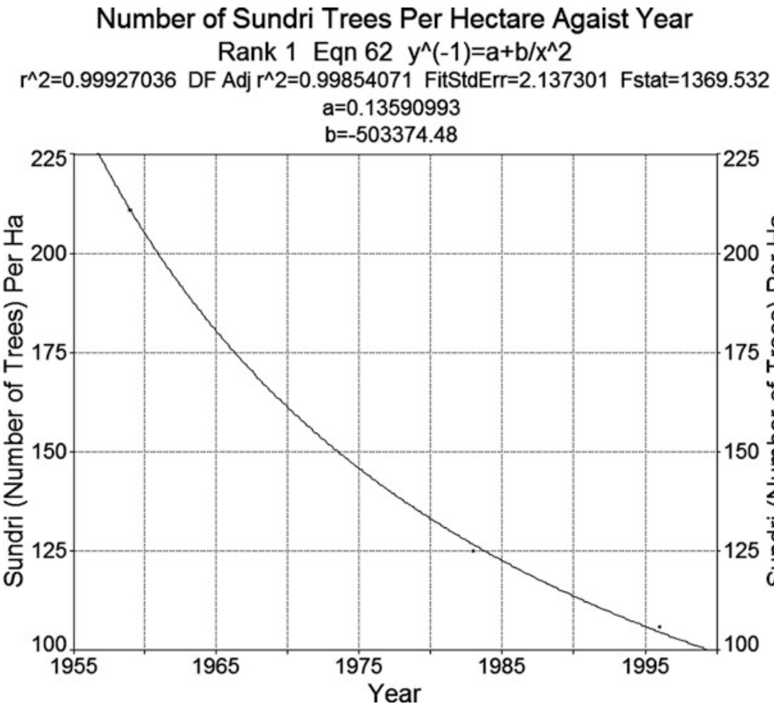

Fig. 15.3 Changes in the number of Sundri tree per hectare with time

15.3 Present Management Strategy

Though in the past the management was for earning revenue for the Government, recently it has shifted towards community involvement. At present (2018) no harvest except NTFP (Non-Timber Forest Product) is allowed and eco-tourism is being

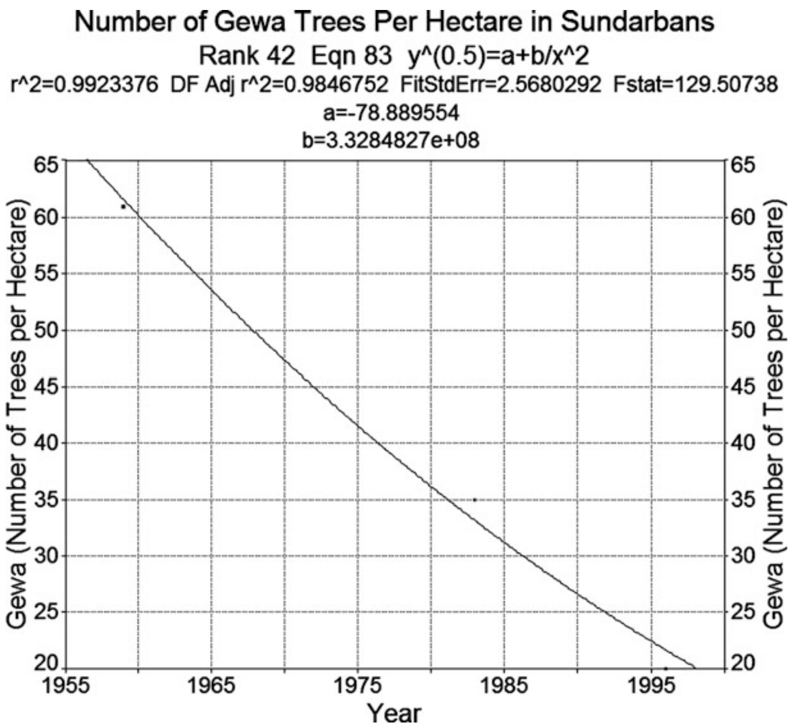

Fig. 15.4 Changes in the number of Gewa trees per hectare with time

encouraged. Choudhury JK (2013) has, however, suggested to impose control on the number of visitors to Sundarbans, which may be ascertained by calculating the carrying capacity of the site in question.

At present (2018) there are three WL centauries:

1. Sundarbans East (Katka, Kochikhali), under Sarankhala Range
2. Sundarbans South (Nilkamal) under Khulna (Nolian) Range
3. Sundarbans West (Dobeki) under Burigoalioni Range

These 3 wild life centauries constitute the 798th World Heritage Site (WHS) and classified as natural heritage under category (ii) and (iv) of the convention. According to the Protected Area Rules 2017, 50% of the revenue earned from NTFP (including eco-tourism) will go to the co-management committee (CMC) (Fig. 15.6).

At present (2018) there are 4 CMCs, namely

1. Chadpani (Chandpai Range)
2. Sarankhala (Sarankhala Range)
3. Nolian (Khulna Range)
4. Burugoalini (Burigoalini Range)

Further, the CMCs are grouped under centuaries as under.

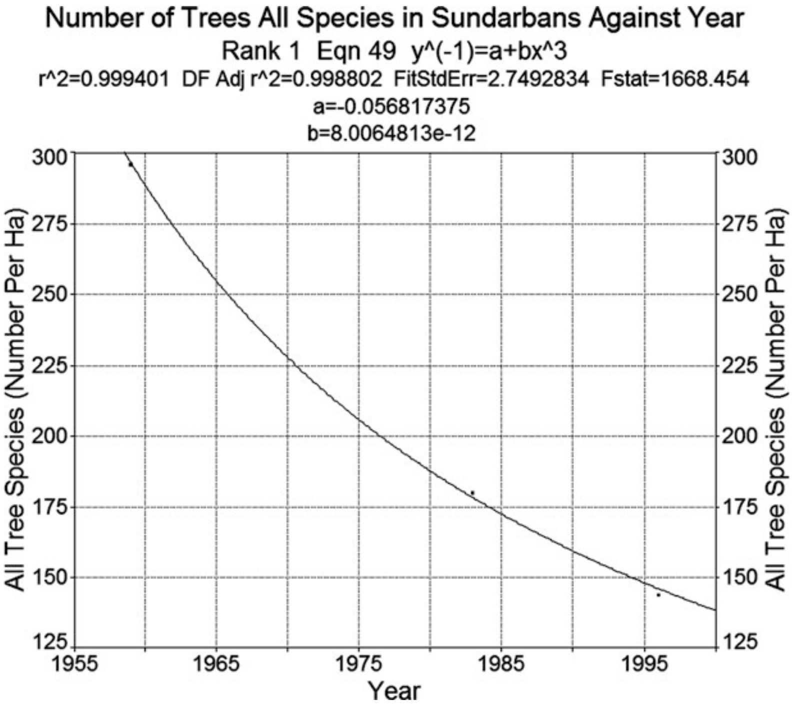

Fig. 15.5 Changes of trees of all species per hectare with time

Table 15.2 Total number of trees predicted

Sl No	Year	Total number of trees per hectare in Sundarbans	95 Pred −	95 Pred +
1	1990	159	124	194
2	2000	138	103	173
3	2010	122	87	157
4	2020	109	74	144

- Chandpani and Sarankhala CMCs are against one WL Centaury (Sundarbans East)
- Nolian CMC is against WL Centaury (Sundarbans South) Nilkomol area
- Burigoalini CMC is against WL Centaury (Sundarbans West)

1. Thus, for Sundarbans East, the two CMCs (Chandpai & Sarankhala) look fine. In future, the people from east bank of Bholashwar (Char Doani area) may want to be party to this WL Centaury. Thus, there may be another CMC in future.
2. For Sundarbans South WL Centaury there is one CMC, wherein people from Dacob and Koyara Upazila are involved. This may have to be split into two, namely Dacob and Koyara CMCs in future.
3. For Burigoalini Range there is one CMC, namely Satkhira CMC. This looks fine.

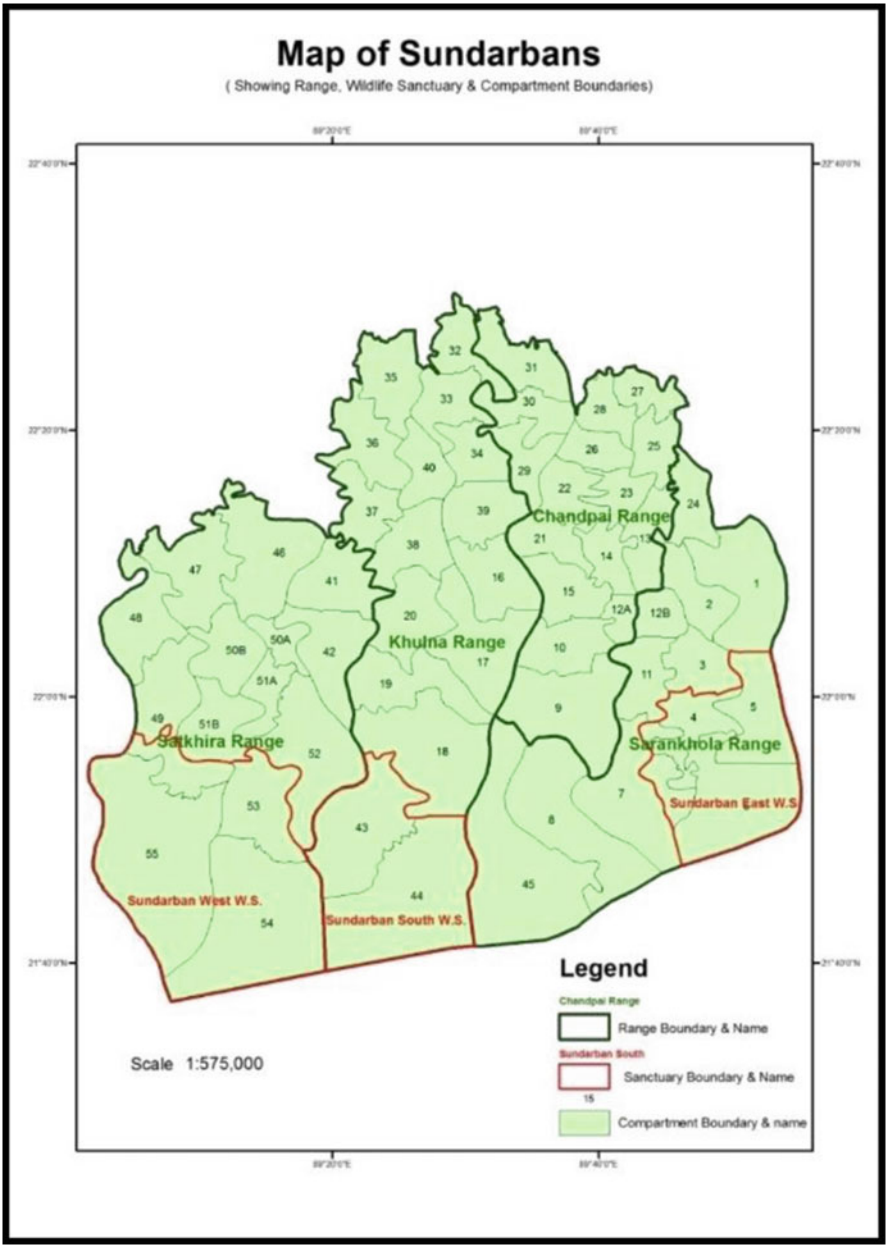

Fig. 15.6 The CMCs are supposed to be constituted against Upazila

Fifty percent of the NTFP revenue is supposed to go to these CMCs which is supposed to be spent for the well-being of the community. The TNOs are the chairs of the CMCs. At present, the yearly revenue of Sundarbans is over 4 crores BDT

(1 crore = 10 million). This means that 2 crores BDT will be going to these CMCs. Unless there is a strict monitoring and audit there are every possibility of heavy pilferage.

However, it is clear that the government is inclined to provide benefits to the adjoining communities to secure effective assistance from these communities for meaningful protection and conservation of Sundarbans Reserved Forests.

15.4 Biodiversity in the Sundarbans

Salinity is a very important ecological parameter for the distribution and species composition in case of mangroves. In general, the southwestern part, being more saline, carries higher proportion of more salt tolerant species such as Goran (*Ceriops roxburghii*) while northeastern parts being less saline carries species such as Sundri (*Heritiera fomes*). The salinity, however, varies with season. The maps, given below (Fig. 15.7), generated by the studies undertaken by IWM (Institute of Water Modeling) will elucidate the salinity in pre-monsoon and post-monsoon periods.

Diversion of natural flow of fresh water from Ganges, just upstream of the entry point of the river, into Bangladesh, has seriously affected the Bangladesh part of the Sundarbans. The reduction of fresh water flow has enhanced the top dying of Sundri in Sundarbans.

The climate change is a phenomenon which is slow but continuous and its impacts can only be realized, when measurements of related parameters are taken at a reasonable time-interval. It is an established fact that impact of climate change has already set in, in Sundarbans. The most visible impact is the change in species composition.

Sundarbans has rich biodiversity of both flora and fauna. The Sundarbans has been classified as a moist tropical forest demonstrating a whole mosaic of forest communities starting from primary colonizers on new accretions to primary beach forest, often apparently dominated by *Heritiera fomes*, *Sonnerita apetala*, *Avicennia alba*, etc. and tidal forests. The floristic composition of the Sundarbans is rich compared to many other mangrove areas of the world. Prain (1903) reported the existence of 334 species of plants belonging to 245 genera of 37 families from Sundarbans and its surrounding. Of these, no fewer than 123 occur in the present reserve forest of the Bangladesh Sundarbans (Karim 1994a). Chaffey et al. (1985) listed 66 species from Bangladesh Sundarbans under 37 families. As regards the plants found in the mangroves of Sundarbans, it has 28 true mangroves out of the 70, recorded worldwide. Members of the Rhizopheraceae, Avicenniaceae or Langculariaceae characterize most of the mangroves in other parts of the world. However, the mangroves of Bangladesh are dominated by the Sterculiaceae and Euphorbiaceae (Karim 1994b). Sundri (*Heritiera fomes*), Gewa (*Excoecaria agollocha*) and Goran (*Ceriops decendra*) are the three-major important commercial species in Sundarbans. Sundri constitutes about 65% of the total merchantable

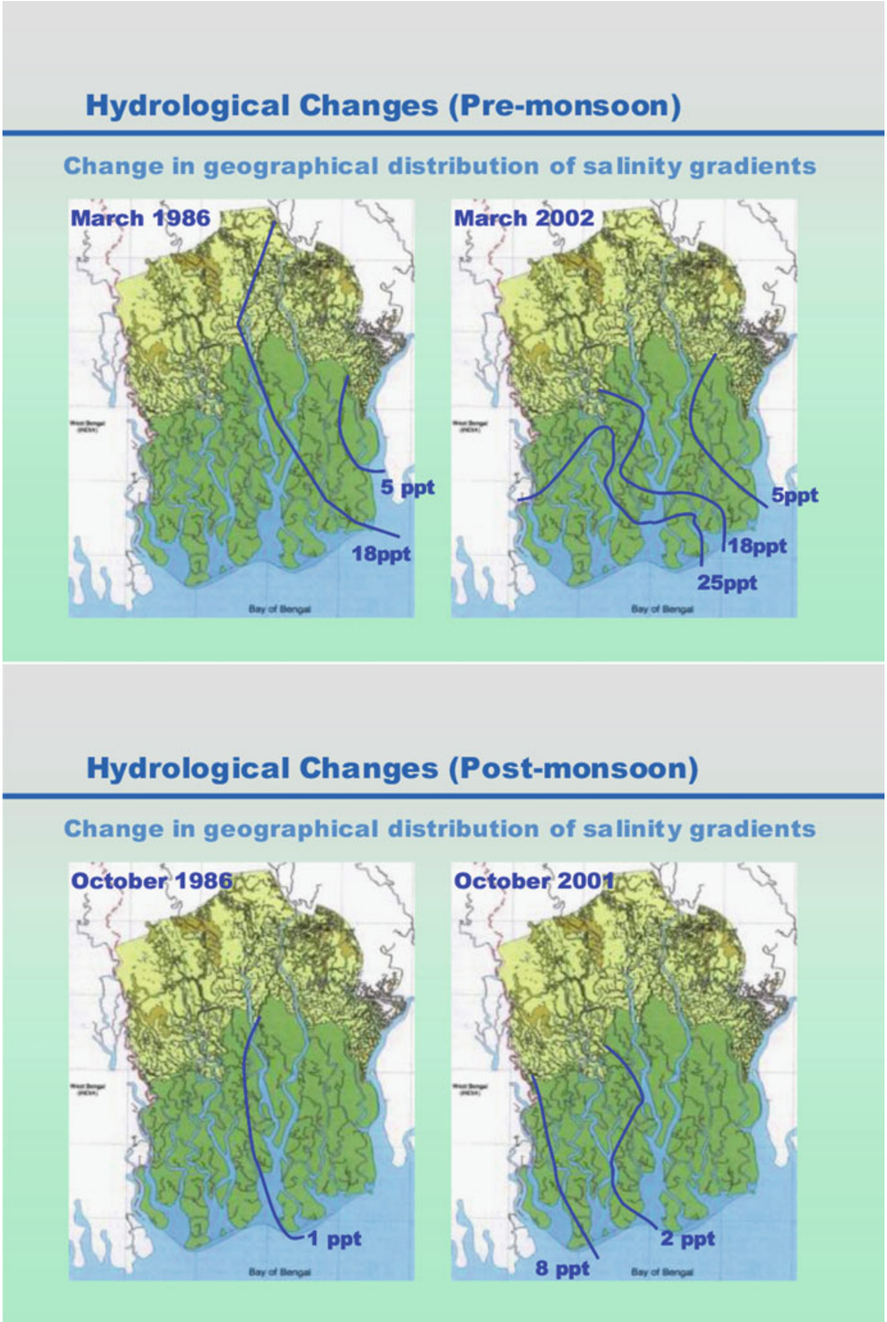

Fig. 15.7 Hydrological (salinity) changes in pre-monsoon and post-monsoon seasons. (Courtesy: Institute of water Modeling, Bangladesh)

timber. Sundri, Sundri-Gewa, Gewa-Sundri and Gewa-Goran forest types cover 21%, 29.7%, 14.8% and 14.46% of the area, respectively (Siddiqi 2001).

About 12 fern species have so far been identified in the selected study sites of SRF during field trips by IUCN, Bangladesh (SBCP) team in 2000. These are as under.

1. *Acrostichum aureum*
2. *Asplenium falcatum*
3. *Ceratoptris thelictroides*
4. *Christella arida*
5. *Drynaria quercifolia*
6. *Lycopodium sp*
7. *Lygodium flexuosum*
8. *Microsorium punctatum*
9. *Ophioglossum reticulatum*
10. *Pyrossia adnescens,*
11. *Stenochlaena palustris*
12. *Vittaria elongata*

Orchid are found mostly on fresh water and Sundri dominated areas in Sundarbans. About 11 species of orchids under 8 families have so far been identified by IUCN, Bangladesh (SBCP) team in 2000. These are as under.

1. *Cirrhopetalum roxburghii*
2. *Luisia brachystachya*
3. *Luisia teretifolia*
4. *Oberonia gammiei*
5. *Pelatantheria insectifera*
6. *Saccolabium longifolium*
7. *Saccolabium papillosum,*
8. *Saccolabium ochraceum*
9. *Sarcanthus insectifer*
10. *Trias oblonga*
11. *Vanda spp.*

There are three types of Lichen (broad group) founds in the Sundarbans, e.g. Crustose, Fruticose and Foliose Lichen. Fruticose lichen is found only in the mangrove forest. The rest of the two types of lichen are also common in non-mangrove area. Lichens are sensitive to salinity as their frequency and abundance were seen to decrease with increasing salinity in the Sundarbans.

Algal flora of Sundarbans (Table 15.3) is a poorly studied component of Sundarbans ecosystem. There is no previous record of algal flora of the Sundarbans. The studies published by Islam (1964, 1965, 1973, 1976) recorded 165 species of benthic marine and brackish water algae from the coast of Bangladesh. Many of these specimens are collected from Mongla, Chandpai, Laodub, Jhaffa, Dubla, etc.; located in and around Sundarbans; from water, muddy banks and shores, mainly from pneumatophores, twigs and abandoned logs. So far, 34 species have been

Table 15.3 Algal flora in Sundarbans

Division	Family	Genera	Species
Chlorophyta	Volvocaceae, Palmelaceae, Ulvaceae, Cladophoraceae, Zymnemaceae, Codiaceae	6	9
Cynophyta	Chroococcaceae, Oscillatoriaceae, Nostocaceae, Rivulariaceae	9	16
Bacillarophyta		16	35
Euglenophyta		2	2

recorded from the Sundarbans. These include varieties of Vaucheria, Cladophorella and Boodleopsis. The details are as under (Islam 1973).

Sundarbans is also very rich in faunal biodiversity. About 289 terrestrial fauna species of 185 genera and 219 aquatic fauna species of 146 genera are found in the Sundarbans forests (Seidensticker and Hai 1983; Chantarasri 1994). Sundarbans is home to at least 315 species of local or migratory birds representing 36% of the total avifauna in Bangladesh (Rashid et al. 1994). However, due to habitat destruction, number of mammal species, residing north of Sundarbans, such as Javan Rhinoceros, Wild water Buffalo, Swamp deer, Hog deer, Leopard, Gaur, etc. have disappeared.

Sundarbans supports 27 families and 53 species of pelagic fish, 49 families and 124 species of demersal fish, 5 families and 24 species of shrimps, 3 families and 7 species of crabs, 2 species of gastropods, 6 species of pelecypods, 8 species of locust lobster, and 1 family and 3 species of turtles (Hussain and Acharya 1994). Eastern part of the Sundarbans is fresh water zone (Das and Siddiqui 1985), which supports some diadromous species, such as *Pangasius pangasius, Teneolosa ilisha, Lates calcaifer* and *Macrobrachium rosenbergii* etc. The Middle part is moderately saline zone, and *Lates calcaifer, Teneolosa ilisha, Pomadasys hasta, Polynemus spp., Colia spp., Johnius dussumieri, Johnius arjentatus, Penaeus monodon, P. indicus, Parapenaeopsis spp., Metapenaeus Monoceros,* and *Scylla serrata* are common in this zone. The Western part of the Sundarbans is highly saline, where *Harpodon nehereus, Trichiurus haumela, Setippina taty, Pampus argentaus, Sardinalla* spp., *Selar* spp., *Penaeus indicus*, *P. monodon, Parapenaeopsis indicus*, *Metapenaeus monoceros, Acetes* spp., etc. are common. This zone is a favourable area for sharks belonging to Carcharhinidae and Sphyrnidae families and rays belonging to Dasyatidae family (Bernacsck and Haque 2001).

Dolphins are common in Sundarbans. Species such as common dolphin (*Dolphinus delphis*) and irrawaddy dolphin (*Orcaella brevirostris*) are commonly seen in Sundarbans. The IUCN team, for the first time in 2003, cited the *Sausa Chinensis,* a species of dolphin reported to live in high saline water. Such citation has been interpreted as an evidence of increased salinity in Sundarbans because of Farakka Barrage.

The estuaries of the Sundarbans are very rich in plankton but so far these have received very little attention. Mahmood et al. (1987) recorded 23 species of ichthyoplankton belonging to 19 families in samples collected from the Coxali

Table 15.4 Butterfly and dragonfly in Sundarbans

Butterfly	Dragonfly
Catopsilia pomona	*Agrion* sp.
Danaus genutia	*Bracaethemis contaminata*
Danaus melanippus	*Ceriagrion coromandelenium*
Danidae sp.	Coenagrids
Euploea crameri nicevillei	*Coenagrion* sp.
Hesperids	*Coenagrionid*
Hypolimnus bolina	*Crocothemis servilia servilia*
Junonia almane	*Ictinogomphus rapax*
Junonia atlites	*Libellulid*
Lycaenid sp.	*Neurothemis fulvia*
Neptis sp.	*Neurothemis tullia tullia*
Nymphalid	*Orthetrum sabina*
Papilio polytes	*Pantala flavescens*
Papilio sp.	*Rhyothemis variegata variegata*
Pieris sp.	*Tholymis tillarga*
Satyrid sp.	
Terias hecabe	

river estuary in Satkhira range. These are abundant during monsoon and post-monsoon months (June to November). Zafar and Mahmood (1989) identified the zooplankters of an estuary of this region, belonging to at least 13 major taxa namely, Copepods, Amphipods, Mysids, Acetes, Chaetognaths, Polychaetes, Lucifers, Hydromedusae, Shrimp larvae, Finfish larvae, Crab larvae, squilla larvae, and Horse-shoe crab larvae.

Insects of Sundarbans are yet to be explored, but it is well known that the honey bee (*Apis dorsata*) is of high commercial and ecological importance. Field studies undertaken by IUCN, Bangladesh in 2003 have identified 17 species of butterfly and 15 species of dragonfly, as under (Table 15.4).

Mollusks are common in Sundarbans. A total of 36 species of mollusks belonging to 14 families have been reported from the Sundarbans. Among these, *Cerithidea obtuse, Telescopium telescopium, Pythia plicata, Pila globasa, Neritina smithii* are very common. IUCN, Bangladesh team has found 33 species of mollusks in Sundarbans during their studies in 2003. These are as under (Table 15.5).

A total of 30 species of crustaceans belonging to 9 families have been reported from Sundarbans (Acharya and Kamal 1994). There are two large families of crustaceans, namely penaeides and palaemonids. Annually about 1300 metric tons of crabs and 3300 metric tons of oysters are harvested from the Sundarbans.

The amphibian fauna of the Sundarbans include one species each under family Bufonidae, Microhylidae and Rhacophoridae, and 5 species under family Ranidae (Rashid et al. 1994). The IUCN team in 2003 for the first time cited *Hoplobatrachus crassus* in the Sundarbans. *Bufo melanostictus* (Kuno Bang) and *Hoplobatrachus tigerinus* (Sona Bang) are common and seen mostly in the fresh water areas adjacent

Table 15.5 List of mollusks in Sundarbans

Species name	Habitat and vegetation association
Neritina smithii	Melia leaves, stems & ground. Root and trunk base of Kewra, Ora and Nipa. On beach and mud flats. Euryhaline & in supra-tidal and intertidal zone. Can tolerate wide range of salinity
Neritina violacea	On Melia leaves and ground. Forest bed, root and trunk base of Kewra tree
	In supra- and intertidal zone
Neritina articulate	On the ground and attached to Gewa tree roots. Supra- and intertidal
Neritina undulate	Dead shell on the ground. In intertidal zone and live- attached to kewra leaves
Pila globose	Canal side, Pond and wet grass field at these fresh water zone
Littorina metanostoma	On Danshi grass leaves associated with Khenja and Dubba grass in low saline area but on ground and trunk of high saline area Gewa and Sundari like in Supra- & inter-tidal zone of Gewakhali (20 ppt)
Littorina articulate	Attached to Dhansi (Uri) grass, leaves of Kewra, Goran etc.) Intertidal and supratidal
Cerithidea obtuse	On Melia and Bottle grass leaves and stem in '0' saline area. Attached to Sundari, Goran, Gewa and Pasur and on forest bed
Cerithidea cingulata	Large colony on hard sandy-clay beach: attached to root and trunk of Gewa, Sundari and Golpata
Cerithidea sp.	Attached to leaves of Goalpata and Kalisha leaves
Telescopium telescopium	Dead shell on '0' saline river/ canal side and beach. Under or near kewra forest trees, live copulating pairs with clean saline (>7 ppt) water on sandy clay soil. Also, under Gewa forest bed with clean water flow. Intertidal area. Low saline area
Bufonaria rana	Dead shell found on beach (northwestern side)
Pujilina cochlidium	Locally known as shonko. Common under Baen tree, forest bed (live and dead) riverside
Onchidium tigrinum	Locally known as Chatta. Common on decayed wood, poles and tree trunk (Keora and Goran trees) and wood block
Ellobium gangetica	Scattered on Sundari forest bed, in low lying grass field in low saline zone and trunk of Goran in saline zone
Pythia plicata	On the leaves and stem of Melia and Hogla in '0' saline zone. On trunk of Keora, Sundari and Gewa tree in dirty humus forest bottom. Supratidal
Thiara tuberculata	Freshwater pondside
Indoplanorbis exustus	Dead shell in ponds, scattered on char, on Chaica grass in freshwater pond. Intertidal
Acatina fulica	A giant snail, found on the tree trunks of Rain tree, Coconut, Jam, Teak, Mahegony, etc
Bellamya bengalensis	Wet muddy grass field, abundant in running water
Thais blanfordi	Riverside ground bed
Bufonaria rana	On sandy beach
Tralia ovula	Attached to trunk and leaves of Goran and Gewa, Tiger fern and Golpata
Crassostrea belcheri	Dead shells scattered on the sandy-muddy beach indicating its presence in nearby sea bed

(continued)

Table 15.5 (continued)

Species name	Habitat and vegetation association
Crassostrea gryphoides	Same as above, Sub tidal
Lamellidens marginalis	Freshwater area, attached to freshwater sandy pondside, euphotic zone in large number
Polymesoda bengalensis	On dead animal, '0' saline riverside area, both dead and alive on forest floor and grassland at southern Deemyrchar, Intertidal
Dosinia eudeli	On the supra and intertidal zone
Enigmonia aenigmetica	Scattered in tidal areas, especially on the creek banks
Anomia achaeus	Scattered on the supra- and intertidal sandy beach
Teredo sp.	Commonly known as shipworm, large numbers on Sundari wood, dead shell on beach and on woodblocks
Sepia officinalis	Dead shells of different sizes are common on beach area (Kichikhali).
Loligo edulis	Dead shells in and around the sea beach (Kochikhali, Deemyrchar, etc.)

[a]This species was the first citation by IUCN

to the forest campus inside Sundarbans. The common toad is widely distributed all over the Sundarbans.

Reptiles are common in Sundarbans. About 35 species of reptiles have been identified in the Sundarbans (Rashid et al. 1994). Since they have great economic potentially they are under severe threat of exploitation. Crocodiles, snakes and monitor lizards are prone to illegal pouching for their skins. The marsh crocodile once abundant has now become almost extinct. The population of estuarine crocodile is also declining. These are critically endangered species. Their population has declined so much over the past few decades that despite a significant decrease in illegal trade in skins, the population is yet to recover. Rashid and Scott (1989) estimated that only 60–70 individuals might have been left in the Sundarbans, which is probably too conservative. A general estimate of the population size of crocodiles in Sundarbans is about 2 to 300 hundred. Three species of monitor lizards are found in the Sundarbans. They are *Varanus bengalensis, V. flavascens* and *V. salvator*. The ban on export of monitor lizard skins from Bangladesh seems to have a positive impact. Their population size appears to have increased at locations. Altogether 18 species of snakes have been recorded including the king and the spectacled cobra, three vipers and ten sea snakes. There has been a decline in their numbers and sightings over the last 15 years (Rashid et al. 1994). A snake, namely *Bangarous Niger* was cited for the first time by the IUCN team in 2003. Five species of marine turtles have been recorded in the Sundarbans. They are Olive Ridley, Green, Loggerhead, Hawksbill and Leatherback. They are reported to nest on mainland shores and sandy off shore islands. The following provides a status of reptiles (Table 15.6) in Bangladesh with emphasis to Sundarbans.

Table 15.6 List of threatened reptiles of Sundarbans. (IUCN 2000)

Order	Family	Scientific name	English name	Local name	Local status	Global status	Distribution
Crocodylia	Crocodylidae	*Crocodylus porosus*	Salt water crocodile	Lonapanir kumir	Critically endangered	–	Sundarbans
Testudines	Bataguridae	*Batagur baska*	River terrapin	Baro kaitta	Critically endangered	Endangered	Sundarbans
		Geoclymis hamiltonii	Black pond turtle	Kalo kasim	Endangered	Data deficient	Widely distributed all over the country
		Hardella thurjii	Brahminy river turtle	Kali kaitta	Endangered	Lower risk	Widely distributed all over the country
		Kachuga tentoria	Median roofed turtle	Majhari kaitta	Endangered	–	Widely distributed all over the country
		Melanochelys trijuga	Indian black turtle	Kasim	Endangered	Data deficient	Widely distributed all over the country
		Morenia petersi	Yellow turtle	Haldey kaitta	Vulnerable	Low risk	Widely distributed all over the country
	Trionychidae	*Aspideretes gangeticus*	Ganges soft shelled turtle	Khalua kasim	Endangered	–	Widely distributed all over the country
		Aspideretes hurum	Peacock soft shelled turtle	Dhum kasim	Endangered	–	Widely distributed all over the country
		Lissemys punctata	Flap shell turtle	Shundhi kasim	Vulnerable	–	Widely distributed all over the country
Lacertilia	Gekkonidae	*Gekko gecko*	Wall lizard	Shanda	Vulnerable	–	Widely distributed all over the country
	Varanidae	*Varanus bengalensis*	Bengal monitor	Gui shap	Vulnerable	–	Widely distributed all over the country
		Varanus flavescens	Yellow monitor	Sona gui	Endangered	–	Widely distributed all over the country

(continued)

Table 15.6 (continued)

Order	Family	Scientific name	English name	Local name	Local status	Global status	Distribution
		Varanus salvator	Ring lizard	Ram godi	Endangered	–	Sundarbans, mixed ever green forests
Serpentes	Boidae	*Python molurus*	Rock python	Ajagar	Endangered	Low risk	Sundarbans, mixed ever green forests
	Colubridae	*Ahaetulla nasutus*	Vine snake	Sutanoli shap	Vulnerable	–	Widely distributed all over the country
		Cerberus rhynchops	Dog-faced Water Snake	Jalbora Shap	Vulnerable	–	Coast
		Coluber mucosus	Rat snake	Daraj	Vulnerable	–	Widely distributed all over the country
		Chrysopelea ornata	Ornate flying snake	Kalnagin	Endangered	–	Widely distributed all over the country
		Dendrelaphis tristis	Tree snake	Gechho shap	Vulnerable	–	Widely distributed all over the country
		Elaphe radiata	Copper head trinket snake	Dudhraj	Endangered	–	Widely distributed all over the country
		Lycodon aulicus	Common wolf snake	Gharginni shap	Vulnerable	–	Widely distributed all over the country
		Lycodon fasciatus	Banaded wolf snake	Gharginni shap	Vulnerable	–	Widely distributed all over the country
		Lycodon jara	Yellow speckled wolf snake	Gharginni shap	Vulnerable	–	Widely distributed all over the country
		Xenochrophis cerasogaster	Dark bellied marsh snake	Kalo mete dhora shap	Vulnerable	–	Marshes
	Elapidae	*Bungarus caeruleus*	Common krait	Kal keotey	Endangered	–	Widely distributed all over the country

		Bungarus fasciatus	Banded krait	Shakini shap	Endangered	–	Widely distributed all over the country
		Naja kaouthia	Bengal cobra	Gokhra shap	Vulnerable	–	Widely distributed all over the country
		Naja naja	Spectacled cobra	Naga gokhra	Endangered	–	Widely distributed all over the country
		Ophiophagus hannah	King cobra	Raj gokhra	Endangered	–	Sundarbans, mixed ever green forests
	Viperidae	*Trimeresurus erythrurus*	Spot tailed pit viper	Viper shap	Endangered	–	Sundarbans, mixed ever green forests
		Vipera russellii	Russell's viper	Bora	Critically endangered	–	Widely distributed all over the country

About 42 species of mammals are found in the Sundarbans (Rashid et al. 1994). As many as 15 bat species, seven rodent species including one species of squirrel, one species of porcupine, and five species of rats and mice are estimated to be present in the Sundarbans although the exact number of species is not known. A few of the prominent mammal species include the Royal Bengal tiger, spotted deer, macaque monkey, wild boar, jackal, jungle and Indian fishing cats, small and large civets, small mongoose, common and smooth coated otter, Indian false vampire, common flying fox, irrawaddy squirrel, crestless malay porcupine, larger bandicoot rat, and others.

At least 315 species of birds, representing 36% of the birds of Bangladesh, are found in Sundarbans (Rashid et al. 1994). Of these 315 species, 117 are waterfowls, 31 birds of prey, 2 phasianids, and 165 other birds. All eight Kingfisher species of Bangladesh are found in Sundarbans. Nest of one species of shore bird, namely *Esacus recurvirostris* was first time cited by the IUCN team in 2003. Twenty-eight new species have been added between 1987 and 1990 to the national list (IRMP 1998). Rashid and Scott (1989) noted nine species of waders in Sundarbans for the first time. Notables among these are the Grey-headed fish eagle, Palla's fishing eagle, masked finfoot, certain migratory waders, gulls and terns. The Red jungle fowl, Green pigeon and parakeets are common but beautiful birds of Sundarbans. The table below gives the list of threatened bird species of Sundarbans (Table 15.7).

15.5 Trend of Changes in Composition of Biodiversity in Sundarbans

Over the last decade increased environmental stress resulted in a decline of biodiversity in Sundarbans. It appears that the forest has entered to a premature transitional stage to shift its floral and faunal composition; it is the result of reduction of fresh water from upstream and intrusion of saline water from downstream directions. Over-exploitation of the forest resources has exacerbated this situation. These impacts would be exacerbated by climate change and sea level rise estimated at 60 cm over 50 years. By 2050 the following may happen:

1. *Freshwater mangroves are totally replaced by saline water mangroves*
2. *Decrease in total area under true mangroves*
3. *Increase of the area with mesophytic vegetation*
4. *Major loss of biodiversity through changes in communities*
5. *Major decline in timber production*
6. *Increase of use of non-timber forest products (NTFPs)*

Most of the climate change predictions indicate that with the climate change, the following events will take place.

- The sea level will rise.
- The total rainfall will decrease.

Table 15.7 List of threatened resident birds of Sundarbans. (IUCN 2000)

Order	Family	Scientific Name	English Name	Local Name	Local Status	Global Status	Distribution
Anceriformes	Anatidae	Sarkidiornis melanotos	Comb Duck	Buncha Hans	Critically Endangered	–	Widely distributed
Coraciiformes	Alcedinidae	*Alcedo hercules*	Blyth's Kingfisher	Maachranga	Endangered	Vulnerable	Sundarbans, Mixed ever-green forest
	Halcyonidae	*Halcyon coromandra*	Ruddy Kingfisher	Lal Maachranga	Vulnerable	–	Sundarbans
Strigiformes	Strigidae	Ketupa zeylonensis	Brown Fish Owl	Pencha	Endangered	Vulnerable	Widely distributed
	Caprimulgidae	Caprimulgus indicus	Grey Nightjar	Dinkana	Endangered	–	Widely distributed
Gruiformes	Heliornithidae	*Heliopais personata*	Masked finfoot	Goilo Hansh	Endangered	Vulnerable	Sundarbans
Ciconiiformes	Charadridae	Vanellus duvaucelii	River Lapwing	Hot-titi	Endangered	–	Padma, coast
	Laridae	Rynchops albicollis	Indian Skimmer	Panikata	Endangered	Vulnerable	Coast, large rivers
		Sterna acuticauda	Black-bellied Tern	Gangchil	Endangered	Vulnerable	Widely distributed
	Accipitridae	*Haliaeetus leucogaster*	White-bellied Sea Eagle	Sada Eagle	Endangered	–	Coast, Sundarbans
		Haliaeetus leucoryphus	Pallas's Fish Eagle	Kura	Critically Endangered	Vulnerable	Widely distributed
	Anhingidae	Anhinga melanogaster	Darter	Goyer	Vulnerable	Lower risk	Widely distributed
	Ardeidae	Gorcachius melanolophus	Malayan Night Heron	Bagha Bok	Critically Endangered	–	Widely distributed

(continued)

Table 15.7 (continued)

Order	Family	Scientific Name	English Name	Local Name	Local Status	Global Status	Distribution
	Threskiornithidae	Platalea leucorodia	Eurasian Spoonbill	Kodali Bok	Critically Endangered	–	Coast, padma
	Ciconiidae	Leptoptilos dubius	Greater Adjutant	Hargila	Critically Endangered	Endangered	Wetlands
		Leptoptilos javanicus	Lesser Adjutant	Modontak	Endangered	Vulnerable	Widely distributed
		Mycteria leucocephala	Painted Stork	Shonajongha	Critically Endangered	Lower Risk	Coast, Sundarbans

- Monsoon rainfall will become higher.
- There will be incessant and very heavy downpours during monsoon.
- The drought periods will be severe.
- Intensity of cyclones will increase.
- Frequency of cyclone will increase.
- Tide fluctuations will be higher.
- Salinity intrusions will be far landward.

Some such symptoms have already started. Global mean sea level is rising. For the twentieth century, the average rate of sea level rise was 1.7 ± 0.5 mm per year. The Fourth Assessment Report on Climate Change has indicated that the average rate of sea level rise was 1.8 ± 0.5 mm per year between 1961 and 2003. Shams Uddin (2011) quoting from World Bank (2000) provided the scenario of the Sundarbans under various sea level rises, which are as under.

- 10 cm SLR will inundate 15% of the Sundarbans
- 25 cm SLR will inundate 40% of the Sundarbans
- 45 cm SLR will inundate 75% of the Sundarbans
- 60 cm SLR will inundate the whole Sundarbans

A possible 45 cm sea level rise by the year 2050 will inundate 75% of the Sundarbans.

CEGIS analyses of Hiron Point data over the period 1977–2002 indicate that sea level is rising at the rate of 53 mm per year. The fig is given below (Fig. 15.8).

Species like (*Heritiera fomes)*, main economic species in the Sundarbans, would be replaced by less valuable species such as goran (*Ceriops decandra*), Gewa (*Excoecaria agallocha*), etc.

Choudhury (2009) summarized impact of climate change as follows:

(a) The average temperature has already climbed by more than 1.0 °C since 1880 and much of this in recent decades. It has been established that the rate of warming is increasing. The twentieth century's last two decades were the hottest in last 400 years. The conservative prediction of IPCC has clearly stated that the

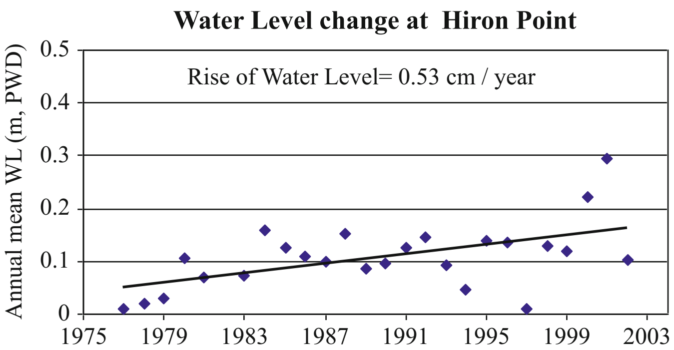

Fig. 15.8 Sea level rise at Hiron Point

sea level will rise by 7–23 inches by the end of the century. Glaciers are melting resulting in sea level rise. Coral reefs, which are highly sensitive to small changes in water temperature and acidity of water, suffered the most and many succumbed to death. An upsurge in the number and intensity of extreme weather events, such as forest fires, heat waves, cyclones, floods, etc. has become established. Many of the experts have cautioned that up to 30% of animal and plant species could be wiped out by a global temperature rise of 2.7–4.5 °C

(b) Under such change the nature will adjust (i.e. adaptation). It is already visible that some species that love low saline condition, such as Sundri (*Heritierra fomes*), Shingra (*Cynometra ramiflora*), etc. have started to die in Sundarbans, while Passur (*Xylocarpus* spp) has become almost rare now. More salt tolerant species, such as Goran (*Ceriops roxburgii*), Jhana (*Rhizophora mucronata*), etc. will come to occupy these sites. Similar impact is seen on aquatic fauna as well.

Choudhury (2009) predicted a future matrix of species for Sundarbans depending on salinity, inundation and soil texture; which is given below (Table 15.8).

The data (Table 15.9) broadly summarizes the probable major changes and resultant floral and faunal species composition that may surface in future (may be by 2050), if the climate change continues at its existing pace.

Ultimately both flora and fauna will be affected. Under the climate change impact, tall Sundri trees will be lost, which will be aggravated further because of the establishment of coal fired power plant on the north of Sundarbans and the Sundarbans will probably become a scrub forest. In the long run, because of the impact of climate change, very roughly, the major species will change from Sundri (*Heritierra fomes*) to Goran (*Ceriops roxburghii*). The name “Sundarbans” derived from ‘forests of Sundri trees’ will lose its significance. Since Goran is likely to be more abundant, the nomenclature may have to be changed to “Goranban” meaning ‘forests of Goran trees’.

15.6 Conclusions

Climate change will have severe impact on Sundarbans and its surroundings. Sea level rise will push the coastline further inward. If the sea level rise is about 1 m, the coast line will come near Mongla. The saline front will intrude further north. The whole of Sundarbans will become saline. The species composition of Sundarbans will change significantly. Sundari trees from which the name of the forest was derived may disappear totally; to be replaced by Goran species.

Table 15.8 Predicted future species matrix for Sundarbans Mangrove. (Choudhury 2009)

Salinity	Inundation	Soil Texture	Species
High	High	Clayey	Jhana to Bain
High	High	Loam	Bain to Goran
High	High	Sandy	Goran to Hental
High	Medium	Clayey	Jhana to Goran
High	Medium	Loam	Goran to Bain
High	Medium	Sandy	Bain to Hental
High	Low	Clayey	Bain to Goran
High	Low	Loam	Goran to Bain
High	Low	Sandy	Goran to Hental
Medium	High	Clayey	Keora to Jhana
Medium	High	Loam	Jhana to Kakra
Medium	High	Sandy	Kakra to Hental
Medium	Medium	Clayey	Passur to Doondool
Medium	Medium	Loam	Doondool to Gewa
Medium	Medium	Sandy	Gewa to Hental
Medium	Low	Clayey	Goran to Bain
Medium	Low	Loam	Bain to Kakra
Medium	Low	Sandy	Kakra to Hental
Low	High	Clayey	Doondool to Passur
Low	High	Loam	Passur to Sundri
Low	High	Sandy	Sundri to Hental
Low	Medium	Clayey	Sundri to Kakra
Low	Medium	Loam	Kakra to Passur
Low	Medium	Sandy	Passure to Hental
Low	Low	Clayey	Sundri to Passur
Low	Low	Loam	Sundri to Kakra
Low	Low	Sandy	Sundri to Hental

With the climate change impact, the fresh water availability in the Sundarbans Impact Zone will further decline and ultimately will get devoid of any fresh water, both surface and ground water. The cyclonic storms and tidal surges will gradually get enhanced and ultimately get very severe, which will cause a mass migration of population of the SIZ area to further north.

Under such anticipated devastating predictions, a close and intensive monitoring on a regular basis, is essential to generate some sort of 'early warning' to avoid colossal devastations. A single contiguous patch of mangrove, in a small country like Bangladesh, represents about 40% of the global diversity of mangroves, at least with respect to species (Siddiqi 2001). This needs to be recognized globally and conserved with due emphasis.

Table 15.9 Impact of climate change on future floral and faunal species composition by 2050

Biotic component	Species	Predicted situation by 2050	Remarks
Flora	Passur	Very likely to be extinct from Sundarbanss	This species has been endangered since 2005
	Sundri	All tall Sundri trees are likely to die off. Some dwarf Sundri trees are likely to remain	
	Kakra	Most of the good kakra growths will get replaced by dwarf kakra	
	Keora	Keora population is likely to march further north	
	Gewa	Many of the existing Kakra and Sundri patches are likely to be replaced by Gewa	
	Goran	This specie will occupy most of the existing Sundarbanss	
	Kholshi	This species is likely to march North and North-East and may increase in number	
	Bolla	Very likely to decline	
	Shingra	Very likely to decline, may even get seriously endangered	
	Luxuriant Nypa	Luxuriant nypa growths are very likely to disappear	
	Chullia Kata	Population is very likely to increase	
	Orchids	Most of the orchid species that are found in Sundarbanss are very likely to be endangered	
Fauna	Dragonfly	Dragonfly since live in and around very low saline environment, is likely to get extinct as the salinity increases	
	Honey bees	With increased population of Goran and Kholshi the bee population is likely to increase	
	Other insects	With the shrinking diversity of floral species many of the insect species and their population is likely to decline	
	Vultures	The vultures will seriously decline since the tall Sundri trees will die away	Vulture nests on tall Sundri trees.
	Green pigeon	Green pigeons are common in low saline areas of Sundarbans. With the shrinkage of this zone	

(continued)

Table 15.9 (continued)

Biotic component	Species	Predicted situation by 2050	Remarks
		the population of green pigeon will also shrink seriously	
	Jungle fowl	With shrinkage of dry areas, the population of jungle fowl will decline.	
	Amphibians	Some of the low saline zone loving amphibians such as *Bufo melanostictus* and *Hoplobatrachus tigerinus* will seriously decline	
	Dolphins	The population of the existing low saline water loving dolphins will decline, while new species that prefer high saline water will intrude	Already high saline water species of dolphin such as *Sausa chinensis* has been cited in 2003 in Sundarbans
	Crocodiles	The population of the existing low saline water loving species will decline	
	Deer	With shrinkage of dry area and fresh water holes, the deer population will decline	
	Tiger	With shrinkage of dry area and its prey the tiger population will decline. With the short fall of prey the man-eaters may increase	
	Other terrestrial wildlife	With shrinkage of dry area their population is likely to decline	
	Hilsha and other low saline water loving fish species	Their population will decline	

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Storm impact (Courtesy WWF-India, photo Chiranjib Chakrborty)

Chapter 16
Climate Change-Induced Environmental Hazards and *Aila* Relief Measures Undertaken to Sundarbans in Bangladesh and India

Bimal Kanti Paul and Subarna Chatterjee

Abstract Environmental degradation induced by climate change has affected lives and livelihoods of the residents of the Sundarbans in both India and Bangladesh. The Sundarbans has been severely affected by sea level rise, salinity intrusion, increasing sea surface temperature, rainfall variability, storm surges, increased frequency of river flood, storms, over- siltation of the rivers, soil erosion, and island subsidence. In addition, the Bay of Bengal coast is a breeding place of tropical cyclones in the World. This chapter is primarily an extensive literature review on the climate change-induced environmental hazards and their impact on the ecosystem and human livelihoods in the Sundarbans of India and Bangladesh. In addition, this chapter also provides a detailed account of the recent cyclonic storm *Aila* that had hit the Bay of Bengal coast in 2009, the loss suffered, and the emergency relief operations that were undertaken. Finally, the structural and non-structural adaptation measures to environmental degradation and sudden onset disasters like storms, as well as, some cyclone mitigation strategies to reduce life loss and damage from future cyclones have been suggested in this chapter.

Keywords Climate change · Environmental degradation · Tropical cyclone · Emergency relief operation · Adaptation

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16.1 Introduction

The Sundarbans, which expands over Bangladesh and India, is the world's largest coastal wetland, a delta formed by alluvial deposition of three major rivers of South Asia– Ganges, Brahmaputra, and Meghna. This mangrove forest region is home to numerous threatened species. It is one of the hotspots of global climate change and has potential to be severely affected by climate change-induced environmental hazards, such as sea level rise (SLR), salinity intrusion, rainfall variability, increases in frequency and magnitude of storms, storm surges and river floods, temperature rise, and coastal erosion, land accretion and subsidence (Hazra et al. 2002; Raha et al. 2013; Rashid and Paul 2014; Ghosh et al. 2015; Paul and Rashid 2017). These changes will seriously affect many livelihood sectors, including agriculture, fisheries, livestock, and forestry. These changes will slow development process and alleviation of poverty in the coastal region, which, in turn, will aggravate both social and environmental conditions of the region (Haldar and Debnath 2014).

Given the region's significance, its vulnerability to potential climate change-induced environmental hazards warrants careful attention, which this chapter provides. Based primarily on published sources of information, the first part presents potential climate change-induced hazards for the Sundarbans region of both Bangladesh and India, and their impacts on livelihoods of the people of the region and its natural environment. This will be followed by a description of emergency relief operations undertaken after the region was hit by Cyclone *Aila,* for example, in 2009. In light of the widespread damage caused by the cyclone, several adaptation measures are recommended to reduce damage and loss of lives from future cyclones. This specific cyclone has been selected because it made landfall on the Sundarbans coast and severely affected both Bangladesh and Indian parts of the Sundarbans in recent times.

16.2 Climate Change: Induced Hazards

16.2.1 Sea Level Rise

Sea level rise (SLR) is an important indicator of climate change. With average elevation of approximately 2 m (6.6 ft) above mean sea level, the Sundarbans in both Bangladesh and India is under threat from inundation and subsequent wetland loss. However, the relative threat from SLR for the Sundarbans remains unclear (Payo et al. 2016). According to the Intergovernmental Panel on Climate Change (IPCC) (2007) SLR of 45 cm (1.5 ft) can inundate 75% of the Sundarbans and that of 1 m (3.28 ft.) can inundate the entirety. Recent satellite altimeter data analyzed by Hazra et al. (2016) revealed an accelerated coastal retreat. The Geological Survey of India claims at least 210 km^2 (81 sq miles) of coastline on the Indian part of Sundarbans has eroded in the last few decades (Daigle 2015). Of the 102 islands in Indian Sundarbans, 54 are inhabited and the remaining is covered with mangrove forests (Das 2011). Of the inhabited islands, at least four are currently underwater due to sea level rise: Lohachara, Suparibhanga, Jambu Dwip, and New Moore Island (Ghosh et al. 2003, Shapiro 2016). The New Moore Island, also called South Talpatti Island in Bangladesh, was a disputed island along the India-Bangladesh international boundary and it was submerged under water by March 2010 (Rahman et al. 1993). The island, which emerged along the shallow continental shelf of the Bay of Bengal, was claimed by the Government of Bangladesh under its jurisdiction. The local SLR of the Sagar Islands of the Indian Sundarbans has been reported to be 5.22 mm per year (0.22 inch per year), which is much higher compared to the global average SLR of 1.88 mm per year (0.08 inch per year) (Unnikrishnan and Shankar 2007).

The Bengal delta in India and Bangladesh has witnessed a dramatic rate of population growth in the last few decades (Ericson et al. 2006). This has led to over-extraction of ground water from the shallow and deep wells resulting in an accelerated rate of land subsidence (Shearman et al. 2013). Thus, the SLR experienced by the Bengal delta is partially due to the Global Eustatic SLR and partially from land subsidence. Ericson et al. (2006) reported that Sea Level Rise will have the largest potential effect on the Bengal delta and an estimated 3.4 million people are feared to be affected by this. Syvitski et al. (2009) has categorized the Bengal delta among those that are suffering from accelerated compaction of the deltaic surface coupled with reduced aggradation, thus overwhelming the rates of global SLR. Local subsidence varies regionally. According to the recent projections by the IPCC, sea level in the northern Bay of Bengal will possibly rise 0.3 m (1 foot) to 0.6 m (2 feet) by 2100, but due to differential rates of local subsidence, this is projected to differ regionally (Kay et al. 2015).[1] Based on tide gauge data for Hiron Point in Bangladesh, Paul and Rashid (2017) estimated that net sea level rise at this station was 3.39 mm per year (0.13 inch per year) during 1980–2000. Hiron Point is located beside Kunga river on the southern coast of Bangladesh's Sundarbans and it is the only sea level rise gauge station in this part of Sundarbans. Another study by Singh (2001) estimated sea level rise at Hiron Point as 4 mm per year (0.16 inch per year), which is higher than Paul and Rashid's estimate as well as the estimates of Church et al. (2004) and Unnikrishnan and Shankar (2007). Singh (2001) claims that the monsoon season (June to September) means of tidal levels along the Bangladesh coast showed an upward trend both spatially and temporally. He explained this trend in terms of an increase in summer monsoon rainfall with a corresponding increase in freshwater contributions to the Bay of Bengal from the Ganges-Brahmaputra-Meghna basin.

[1] Also see Erosion, Accretion, and Subsidence section.

Table 16.1 Erosion and land loss (in km^2) in selected islands of the Indian Sundarbans

Island	Year		Land loss in km^2 (%)	Erosion direction	Accretion direction
	1979	2011			
Lohachar	3.42	0.0	3.42 (100)	N, S	SE
Ghoramara	7.40	4.41	2.99 (40)	NW, SW, NE, SE	
Bhangaduani	40.18	25.0	15.18 (38)	S	
Bulchery	32.20	21.2	11.0 (34)	S	
Jambudwdeep	7.34	5.0	2.4 (33)	S, W, N	E
Dalhousie	76.51	60.32	16.19 (21)	S	
Chulkati	44.00	38.3	5.7 (13)	S	
Mausuni	30.81	26.9	3.9 (13)	NW, N, W	
Dhanchi	36.68	33.56	3.12 (9)	S	NNE
Surendranagar	36.02	33.36	2.66 (7)	S, SE, SW	W
Namkhana	151.63	145.00	6.63 (4)	NW, S, W	E
Sagar	242.07	234.72	7.35 (3)	S, SW	SE, N
Lothian	35.03	34.56	0.46 (1)	W	E, S, N

Source: Chatterjee et al. (2015)

16.2.2 *Morphological Changes*

Ericson et al. (2006) have estimated an Effective Sea Level Rise (ESLR) of >10 mm per year (4 inch per year) in the Bengal delta, one of the highest in the world (25 cm per year or 10 inch per year in the Sundarbans region). ESLR is defined as the relative rate of sea level change to the delta surface. For an individual delta, ESLR is the eustatic SLR coupled with the natural rates of fluvial deposition and subsidence (due to groundwater and hydrocarbon extraction). Shearman et al. (2013) have studied changes in the deltaic coasts of the Asia Pacific region and argued that the western part of the Sundarbans suffers from higher rates of land loss compared to the other deltaic regions. Half of this loss was at the extreme southern end of the Sundarbans and was attributed to almost no compensating progradation due to sea level rise and anthropogenic impacts. Morphological changes in the Sundarbans are more pronounced in the active delta and erosion is more concentrated along the banks of the major rivers and along the Bay of Bengal coast.

Chatterjee et al. (2015) have studied the changes in the shoreline pattern of 14 islands of the Indian Sundarbans. This study found that with the exception of Nayachar Island, almost all other islands have been facing the threats of SLR, erosion, and subsidence, and this resulted in a loss of more than 31 sq miles (80 km^2) over the last 32 years (Table 16.1). The area of Nayachar land has doubled between 1979 and 2011 due to land accretion (Chatterjee et al. 2015). Shearman et al. (2013) maintain that the eastern islands of the Indian Sundarbans have been facing much higher rate of land erosion compared to the western islands. The study has further suggested that the long shore currant patterns, abnormal tide heights, unusual SLR (3.14–5.22 mm or 0.2–0.3 inch), and sub-surface geomorphology (tilting towards east and localized subsidence) appear to be responsible for variable patterns of shoreline erosion in different islands in Indian Sundarbans. In addition, several anthropogenic activities, such as deforestation of mangroves, and infrastructure development to provide better opportunities to the pilgrims of the Sagar Islands in the western parts of the Indian Sundarbans, have aggravated the erosion of islands. Unlike the Indian Sundarbans, there are no large islands off the coast of the Bangladesh's Sundarbans. Islands located south of Bangladesh's Sundarbans are small in size and few in number, and these islands lack permanent settlement (Rashid and Paul 2014).

16.2.3 Forest Ecosystem

Sea level rise may submerge coastal forests and settlements, resulting in climate refugees. These forests provide significant protection from cyclones and cyclone-associated storm surges by retarding their flow and reducing the wind speed. The forest stands also increase in sediment accretion, thus building the forest floor (Rashid and Paul 2014). However, in winter, low water flow will increase the salinity of the forest soil and coastal waters. These conditions will adversely affect freshwater dependent floral and faunal species, as well as forest productivity and biodiversity. This, in turn, will lead to a shift in the character of forest boundaries and vegetation as the species that provide dense canopy cover will be replaced by non-woody shrubs and bushes. However, forest ecosystems are generally able to tolerate some level of climate change, at least in the short-term. A time series analysis from 1924 to 2008 had indicated that the growth of mangrove vegetation in the Sundarbans has been most severely affected by the changes in the level of water salinity, mostly regulated by the inflow of the volume of freshwater from upstream (Raha et al. 2012). The same study also revealed that the growth of dominant mangrove species is more in the Western sector of the Indian Sundarbans compared to the Central sector. This is because the level of salinity in the Central sector of the Indian Sundarbans is more when compared with that of the Western Sector. However, the impact of salinity on mangrove has been species specific. Increased level of salinity could result in a stunted growth in some species while not affecting the others. This is primarily due to the levels of anatomical and physiological adaptation which varies from one species to another (Cintron et al. 1978).

16.2.4 Erosion, Accretion, and Subsidence

The sea level rise will make the coastal profile steeper and thus increase erosion. It will also cause a shoaling effect in rivers, leading to reduced sediment deposition in the coastal region. This means these sediments will not be available to compensate for erosion in the region (Paul and Rashid 2017). Investigators (e.g., Allison 1998; Brammer 2014a) maintain that coastal landform changes due to erosion, accretion, and land subsidence are generally small or undetectable in the Sundarbans coast relative to rest of the coast of Bangladesh and India. Because of withdrawal of water from the Ganges after the construction of the Farakka Barrage in India near the Bangladesh-India border in 1975the flow of water from the Ganges River to the coastal rivers of Bangladesh has slowed remarkably. This has decreased the rate of sediment accretion in the Sundarbans region of Bangladesh, and unlike other coastal zones, land accretion is almost nonexistent in the coast of the Sundarbans in Bangladesh. However, the central coastal zone of Bangladesh has been experiencing accretion (Paul and Rashid 2017).[2] Information presented in Table 16.1 suggests that several islands of the Indian Sundarbans have been experiencing both erosion and accretion. However, land lost due to erosion over 1979–2011 was much higher than the land gained due to accretion.

With the reduced rate of sediment deposition, it is more likely that the subsidence rate has increased in the Sundarbans of Bangladesh since the early 1960s with the introduction of coastal embankments and polders to prevent the intrusion of saltwater from the sea and tidal channels into enclosed interstream areas (Rashid and Mallick 1993). However, there is no reliable information either on the historical or current subsidence rate in the Indian Sundarbans region (Brammer 2014b). Measurements of plinth levels of a 400-year-old Hindu temple in the Sundarbans of Bangladesh, and two other old structures in the vicinity of the Sundarbans suggest that long-term subsidence rates have not exceeded 1–2.5 mm (0.05–0.1 inch per year) (Sarker et al. 2013). Other available studies (e.g., Hanebuth et al. 2013) confirm the evidence that subsidence in the Bangladesh's Sundarbans is occurring, but at a low rate.

16.2.5 Salinity Intrusion

There are many reasons for salinity intrusion from the coast of Sundarbans to inland areas. Some reasons are common, while others differ between two parts of Sundarbans. Both parts are affected by diurnal tides twice a day, which bring saline water inland through the network of tidal inlets and creeks, channels, and rivers. Storm surges associated with tropical cyclones also bring saline water from the sea and contaminate surface water sources by breaching coastal embankments and/or overtopping such embankments. These surges damage crops, create waterlogging problems, and increase long-term soil salinity in Sundarbans. As indicated, climate

[2]Based on ecological and physiographic characteristics, coastal Bangladesh is divided into three coastal zones: western, central, and eastern. The Sundarbans is a part of the western zone and in the past this zone was a part of the active Ganges delta. Currently, the zone is undergoing a process of transition from active to semi-moribund delta. For more details, see Paul and Rashid (2017).

change is likely to increase the frequency and height of storm surges since higher sea levels are likely to extend storm surge impacts further inland. Shrimp cultivation, which has been practised in the Bangladesh part of the Sundarbans since the early 1990s, also increases soil salinity. In both parts of the Sundarbans, the level of salinity in the coastal rivers much depends upon fresh water discharge from upland (Paul and Rashid 2017).

Although an increase of soil salinity is not a concern for most of the salt resistant species of the Sundarbans forest, salinization of surface and ground water, and soil in the villages of both Sundarbans has resulted in a severe shortage of drinking and irrigation water and the loss of habitat and income for the residents, especially the agricultural community (Hazra et al. 2016; Paul and Rashid 2017). The level of salinity differs spatially not only within the Sundarbans, but also by season. High soil and water salinity is found along the coast and the level decreases away from the coast. During the dry season (November–February), salinity increases, and it decreases in the summer season due to rainfall, which removes salts from soils.

However, the residents of both Sundarbans have responded to the climate change-induced salinity intrusion with both short-term in-situ and ex-situ adaptation measures such as changes in the agricultural practices, income diversification through off-farm employment, and migration. It should be mentioned here that salinization is also occurring in the Bangladesh Sundarbans for two other reasons as well: expansion of shrimp cultivation, and inadequate/poorly maintained infrastructures (e.g., roads, embankments, polders or enclosed dikes, and sluice gates) (Paul and Rashid 2017). Between two parts of the Sundarbans, salinity seems to be higher in the Bangladesh portion compared to the Indian portion primarily because of differences in freshwater inflows from the Transboundary Rivers. After the construction of the Farakka Barrage, the flow of water from the Ganges River to the rivers of the Sundarbans in Bangladesh has remarkably reduced, which has resulted in increases of high salinity in the coast of Bangladesh, particularly in the Sundarbans region. Diversion of the Ganges water also resulted in falling water tables in the region. In contrast, the diversion increases the amount of the Ganges water into the Indian Sundarbans region (Islam and Gnauck 2011). The reduced inflow of water from upstream also increased siltation in the rivers of the Bangladesh Sundarbans and degraded river waters, causing loss of biodiversity and threatening coastal food security.

16.2.6 Climate Refugees

Human migration is caused by the interactions of many interrelated factors. Among these factors, environmental factors are widely considered to be an important driver of migration, particularly in the context of climate change-induced sea level rise and other related factors. Although there is disagreement regarding the use of the term "climate refugees," we used the term in a general sense and acknowledge that the legal definition of "refugees" does not appropriately fit our purpose (Paul 2011;

Rashid and Paul 2014). Some researchers (e.g., Shamsuddoha and Chowdhury 2007; Seltz 2010; Salauddin and Ashikuzzaman 2011; Mallick and Etzold 2015) have already observed evidence of rising sea levels in the Sundarbans region of both Bangladesh and India and as a consequence they believe that the process of forced relocation has already started. Two major climate change-related documents (GoB 2005 and 2009) of the Bangladesh government have provided evidence of climate change-induced migration in the country. In contrast, other researchers (e.g., Paul 2011; Rashid and Paul 2014) maintain that climate migration is looming on the horizon.

A 2010 survey carried out in the Sundarbans region and other coastal regions in Bangladesh by over 200 community-based organizations and coordinated by the efforts of the Association of Climate Refugees found that 6.5 million citizens have already been displaced by the effects of climate change (Leckie et al. 2011). Though not to the extent of coastal Bangladesh, similar migration has also been reported in the Indian Sundarbans region. As noted earlier, submergence of four islands of Indian Sundarbans has forced out-migration of their residents. Mistri (2013) claims that 74% of the families from the Indian Sundarbans have at least one of their members out-migrated in search of an alternative livelihood. Hazra et al. (2002) predict a large-scale migration from the Indian Sundarbans in future. Guha and Roy (2016) reported that about 71% of households from the Indian Sundarbans have migrated from one village/block to another with the intention of settling permanently within the state. In contrast, scholar such as Hugh Brammer (2014a, b), however, maintains that there are no climate refugees in Bangladesh. Brammer acknowledges that there are refugees from coastal areas due to land erosion in Meghna estuary but maintains that this has gone for decades and probably for centuries. He further claims that there are three other reasons for migration from coastal Bangladesh. One is rapid population increase that means more people that need to move out. Another is the conversion of land from rice cultivation to shrimp farming, particularly in the southwestern coastal zone. Bangladesh's Sundarbans constitutes the western part of this zone. A third factor is people leaving to find better employment in urban areas (and overseas) – young people, in particular, are likely to get a better and safer way of life than exists in remote and dangerous coastal regions.[3] A similar observation was not reported for the Indian Sundarbans.

Available literature suggests that the two Sundarbans are not similar with respect to migration patterns. However, it seems that 12 million (4.5 million in India and 7.5 million in Bangladesh) residents of the Sundarbans face the grim prospect of large-scale inundation and permanent displacement in the near or distant future. The number of people displaced will depend on the extent of sea level rise and rate of population increase.

Where will the potential displaced persons be resettled? There are many possibilities. In the short run with a relatively small increase in sea levels, perhaps up to 2050, it may be possible to live with rising sea levels by using both indigenous and

[3]Personal communication with Hugh Brammer.

scientific *in situ* adaptation measures, such as elevating coastal embankments, raising foundations of homes, and changing agricultural practices (Lal and Aggarwal 2000; Datta et al 2011; Paul and Rashid 2017). Farmers in coastal areas have already started to cultivate salt tolerant fish, crops, vegetables, and fruits. They are using gypsum and potash to reduce soil salinity and growing crops in floating devices such as boats in Bangladesh's Sundarbans. In the face of sea level rise, permanent and temporary migrations are also options for residents of Sundarbans (Bera 2013; Mistri 2013). After cyclone *Aila* in 2009, which affected both parts of Sundarbans, people from this ecological zone have migrated to cities in search of jobs (Aulakh 2013). Some of them have been seasonal migrants; they were working in urban areas and came back to Sundarbans at harvest (Guha and Roy 2016).

People generally prefer outmigration as a last option (Penning-Roswell et al. 2011). Rahman et al. (2015) stated that migration is the last straw and takes place under conditions of extreme deprivation, when all other adaptation options have failed. Many factors discouraged outmigration from a hazardous landscape like the Sundarbans, such as lack of financial resources, uncertainty and completion in the destinations, leaving family behind, difficulty in adjustment to destination, and inability to earn enough money to send home and maintain two households (Paul 2011; Penning-Roswell et al. 2011).

Interestingly, Kartiki (2011) reported that as male members migrate to the cities, more vulnerable females and children often find themselves trapped in the hazard prone areas and become even more at risk. This results in relative immobility (Castles 2002; De Haas 2012). In addition, as the poorest of the population were the worst affected by environmental degradation, they often lack resources to migrate (Afifi and Warner 2008). However, when sea level rise completely inundates their homes, residents of both Sundarbans will probably settle in their immediate vicinity on higher grounds. It is widely believed that a large number of displaced people will migrate to urban areas.

Foregoing discussion suggests that different events that are associated with climate change have not yet been visible in the Sundarbans regions of both Bangladesh and India. However, it is a matter of time before impacts of these events will be clearly observed. For this reason, these potential events are called hazards. When potential events turn into actual events and affect (harm) people, they are called disasters (Paul 2011; Rashid and Paul 2014). Tropical cyclone, currently a hazard but which frequently becomes a disaster in the coastal areas of Bangladesh and east coast of India, is the subject of second part of this chapter. More specifically, this part presents the extent and nature of relief operations undertaken in the Sundarbans region in the immediate aftermath of a recent tropical cyclone.

16.3 Cyclone *Aila* and Relief Efforts

The Bay of Bengal is one of the leading breeding grounds in the world for tropical cyclones. Historical records show that on average, 4.29 cyclones originated annually in the Bay of Bengal, constituting only 5–6% of the global total (Alam and Dominey-Howes 2014; Paul and Rashid 2017). However, they are the deadliest of all the cyclones (Paul 2009). The cyclones that originate in the Bay of Bengal make landfall on the eastern coasts of India and Sri Lanka, southern coast of Bangladesh, or western coast of Myanmar, either in the pre-monsoon months of April–June or the post-monsoon months of October–December (Hossain et al 2008). Not all cyclones that strike Bangladesh coast make landfall along the coast of the Sundarbans. Similarly, only a few cyclones that strike the eastern coast of India make landfall in the Indian portion of the Sundarbans. In the recent past, only two cyclones made landfall along the coast of Sundarbans – Cyclone *Aila* in 2009 and Cyclone *Sidr* in 2007. The latter cyclone made landfall on the western coast of Bangladesh – just at the easternmost part of the Bangladesh portion of the Sundarbans. *Aila*, on the other hand, made landfall along the coast of the Indian Sundarbans – not very far from the coast of Bangladesh's Sundarbans. Thus, it caused widespread destruction to both Sundarbans and the adjacent areas. Most of the affected areas have no experience with an *Aila* type of cyclone in the last 30–50 years (Gupta 2009). For this reason, relief efforts undertaken immediately after *Aila* are discussed here. As background information, some of the salient features of the cyclone are presented first.

16.3.1 Salient Features

Cyclone *Aila* made landfall on the Sundarbans coast on May 25, 2009 (Fig. 16.1). It occurred at high tide and resulted in tidal surges of up to 22 ft. (6.7 m) (International Agencies 2009). The surge of saline water breached and destroyed large sections of coastal embankments in the affected regions of both Bangladesh and India. This caused an inundation of vast areas of land with salt water and some areas remained under water for months (Walton-Ellery 2009). The cyclone caused widespread damage to property, ecosystem, and infrastructure, including coastal embankments. Surges associated with the cyclone brought saline water to large tracts of agricultural fields in both parts of the Sundarbans. Many of the affected areas have still been recovering from the effects of this cyclone. Cyclone *Aila* hit 14 districts of the west coast of Bangladesh and 18 districts of West Bengal, India. Among the worst affected districts were Satkhira and Khulna in Bangladesh and North and South 24 Paragana districts of West Bengal, (Bhattacharyya et al. 2010). The cyclone killed a total of 327 people – 190 in Bangladesh and 137 in India (Gupta 2009; Saha 2015). Most of the deaths were caused by drowning, collapsing of houses, and falling of trees. Some elderly died while going to public cyclone shelters by boat (Gupta 2009).

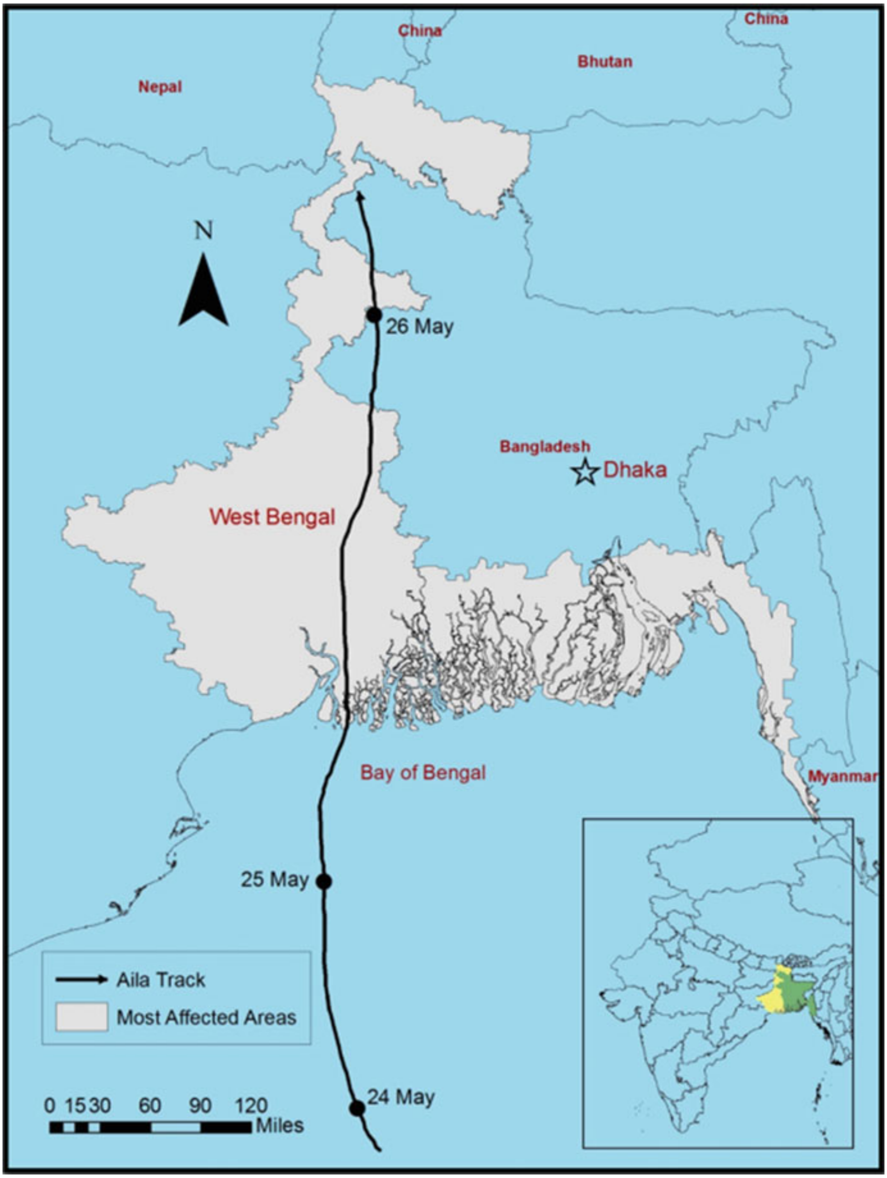

Fig. 16.1 Track of Cyclone *Aila.* (Source- Based on Relief-Web 2009)

Cyclone *Aila* destroyed 243,000 houses in Bangladesh and affected a total of about 4.8 million people in 11 coastal districts (Mallick et al. 2017). It made an approximate 375,000 people homeless, many of them having sought refuge on elevated roads and embankments. It completely damaged 68,385 acres (27,675 ha) of crop land, and another 239,212 acres (96,808 ha) were partially damaged. It also damaged 4000 miles (6000 km) of roads, more than 11,300 miles (17,000 km) of embankments and sources of drinking water, and left many areas waterlogged. This cyclone killed over 100,000 livestock and destroyed many shrimp farms (Mallick and Vogt 2014). Because of permanent waterlogged conditions in the affected areas, it also generated massive migration from such areas to the adjacent non-affected cities for alternative livelihoods (Mallick et al. 2017). Nearly 7 million people were affected by Cyclone *Aila* in the entire state of West Bengal. Over 724,552 houses were damaged in the state. The estimated cropped area damaged was 1.1 million acres (447,000 ha) (Gupta 2009). The total length of embankments severely affected was 415 miles (622 km), mostly in the coastal parts of the Sundarbans (Mukhopadhyay 2009).

Damage to about 125 sluice gates in South 24 Paragana, West Bengal, resulted in salt water flooding and salinity ingression. According to the Irrigation and Waterways Department of the Government of West Bengal, about 259,640 acres (105,075 ha) of the total area of South 24 Paragana was inundated by saline water ingression. Due to the inundation and waterlogging of agricultural fields for months after the cyclone, some rice fields in the Sundarbans were rendered infertile for agriculture. Failure to grow even high salinity tolerant rice varieties was blamed on increasing levels of surface water salinity in different parts of the affected areas and increased acidification of the land mainly due to decomposition of biomass in the waterlogged agricultural fields for months after the cyclone (Halder and Debnath 2014). Fisheries were also badly affected due to waterlogging of the individual ponds (Mukhopadhyay 2009).

16.3.2 Relief Measures

Relief and rescue operations were immediately started in both of the affected areas of India and Bangladesh after *Aila* by government, NGOs, and other humanitarian agencies. The Government of India sanctioned more than $200 million for *Aila* relief measures, while the Government of West Bengal spent nearly $100 million on *Aila* relief (Gupta 2009). Most of the government funds were spent in rescue, evacuation, relief and recovery operations. The relief measures included distribution of makeshift tents, dry cereals (including rice), clothing, baby food, gas cylinders, kerosene oil, cooking oil, water, clothes, medicine, and bleaching powder. Local officials were mobilized for immediate disaster relief after Aila (Mukhopadhyay 2009). In addition, many international, national, regional, and local NGOs also actively participated in the relief activities. Most of these humanitarian agencies also directed their attention to repairing and rebuilding damaged embankments, desalinization of ponds and other water sources, and the reconstruction of houses for the homeless (Mukhopadhyay 2009).

The West Bengal government opened 765 relief camps in the most affected districts. This number was not sufficient to provide shelter for all affected people.

As a result, many people spent many below open sky. In addition, the government set up 84 medical camps in most affected districts of West Bengal (Relief-Web 2009). UNICEF partnered with many voluntary organizations participating in the disaster relief efforts. In addition, the Indian Red Cross Society, West Bengal Red Cross Society, Sphere India New Delhi, and other organizations contributed to rescue operations, the distribution of relief items, and the provision of medical services to the *Aila* survivors.

Das (2011) reported that in his study area, relief items reached cyclone-affected people after 4 days of *Aila*. They urgently needed food as the saline water into the agricultural fields destroyed their standing crops. The arrival of relief items from both governmental and non-governmental sources was significantly delayed. The government agencies disbursed food items, tarpaulin, and medicine, while safe drinking water was supplied mostly by non-governmental sources. Because of transportation problems, residents of islands received emergency materials relatively late compared to non-island residents (Das 2011). However, relief and house building materials that had been supplied were not in sufficient quantity. There was a serious shortage of drinking water because tube wells were inundated with saline water brought inland by either breaching or overtopping of coastal embankments. Non-availability of pure drinking water resulted in an outbreak of water borne diseases and a considerable number of deaths in the affected areas (Bhunia and Ghosh 2011).

Although the Bangladesh government did not formally appeal for help for the Cyclone *Aila* survivors, the International Federation of Red Cross and Red Crescent Society (IFRC) made an emergency appeal on 24 June 2009of US$ 2.2 million for nine months to assist 36,800 families (or 184,000 beneficiaries) (IFRC 2010). Within hours of the natural disaster, as part of emergency relief, Bangladesh Red Crescent Society (BDRCS) distributed cash to its respective units to purchase dry foods. Additionally, BDRCS, in a joint effort with the IFRC, mobilized assessment teams for further emergency response. These two organizations together also distributed plastic sheets, water jerry cans, and hygiene parcels. These were despatched from pre-positioned stock and distributed to 10,000 households. The BDRCS and IFRC collaborated with Save the Children and Oxfam and provided 11,000 water jerry cans to collect clean drinking water from the water treatment plants set up by Save the Children and Oxfam in the affected areas (IFRC 2010). Many other multinational, international (e.g., UNDP, the World Bank, and the Islamic Bank), and national humanitarian organizations, including Bangladesh Rural Advancement Committee (BRAC) also participated in Cyclone *Aila* relief operations in Bangladesh.

Like in the Indian part of the Sundarbans, relief in the affected areas was inadequate. In the remote areas the situation was much worse. Water-trapped people did not receive any relief even after a week of the disaster. The public authorities in Bangladesh confirmed that about 90% of the government relief had been converted to 'food for work' by the Upazila officials[4,5] The affected people had access to this relief if they worked in the embankment repairing program undertaken by the government. But by the end of September, the government issued only 89,098 Viability Gap Funding (VGF) cards to repair the embankment and, in return, participants could receive 22 lbs (10 kg) rice a day. People also had the option of participating in cash for work schemes undertaken by different NGO's. The Bangladesh government also started employment schemes for poor people (International Agencies 2009).

By the end of June 2009, many NGOs failed to reach the remote affected areas to distribute relief (Roy et al. 2009). Even the government agencies, including military, who were already in the affected areas, were unable to deliver food, water, and emergency shelters to cyclone survivors. This was partly because of weather conditions. Cyclone *Aila* hit near monsoon season, and this hampered the relief and recovery work taken by NGO's and the government in both parts of the Sundarbans. Many local initiatives to repair embankments were not successful, as the monsoon created high tides and rains (International Agencies 2009). The affected people were required to provide their own food and shelter security until the winter season, which was 3–4 months away, while extended relief assistance was needed in some of the worst affected areas. Emergency assistance was also required for the vulnerable people of remote areas who were still surrounded by water and could be reached only by boat (IFRC 2010). The expansion of safety nets for relief and an early start up of public work schemes were necessary to generate employment opportunities and hence household income in the affected area.

Apart from inadequacy and delayed disbursement due to remoteness and inaccessibility, relief distribution efforts suffered from mismanagement and corruption, particularly in the Bangladesh part of the Sundarbans. The local elected official was supposed to distribute 22 lbs. (10 kg) of rice per head as government relief, but instead the official distributed 13 lbs. (6 kg) per head. In Khulna and Satkhira districts, affected people were concerned about the contribution of the shrimp *ghers*[6] to embankment breaches. Both of these created social unrest and chaos in the affected areas (Roy et al. 2009). There was also a shortage of medicines and scarcity of pure drinking water in the affected areas. Like in the Indian part, diarrhoea broke out in coastal areas of Khulna, Bangladesh. Roy et al. (2009) reported that at least 95% of the affected and waterlogged areas were out of the safe sanitation coverage.

As the water stayed well over ankle height for several months in most of the areas, toilets, bathrooms and other sanitary structures remained submerged. Most of the

[4]District is the top-tier official administrative unit of local governments in Bangladesh. On an average, each district contains slightly over 2 million people.

[5]*Upazila* (sub-district) is a territorial unit nested within district. A district is generally comprised of 10–15 *upazilas*.

[6]Gher is a pond that is dug into a rice field to use primarily for shrimp farming. The dug out soil is used to create dykes around the pond for growing vegetables.

safety tanks were overflowing and leaching out to the surface water. People taking refuge on the embankments were forced to defecate in open water and used the polluted saline water for household use. During the emergency phase, the government and NGOs constructed latrines at the temporary shelters on the embankments in Bangladesh, but latrine coverage was inadequate. On average, ten families were sharing a common latrine, and this resulted in operation and maintenance challenges (International Agencies 2009). This created inconvenience particularly for women and young girls. Security and the privacy were a major concern among the women living on and around the embankments.

Like in the Indian part, there was a lack of coordination and communication among the relief workers in the Bangladesh part of the Sundarbans. Therefore, up-to-date information of relief being distributed was either unavailable or confusing. Lack of access to relief and/or shortage of relief dragged many adults to leave the affected areas to nearby cities. This was also observed in the Indian part of the Sundarbans. Other reasons for migration were: lack of dry places in the affected areas, high unemployment rate, lack of household income, and no place to live.

16.4 Conclusions

Although this section provides recommendations based on Cyclone *Aila*, these recommendations have direct relevance for climate change-induced sea level rise in the Sundarbans region of both Bangladesh and India. Impacts of Cyclone *Aila* were similar in both parts of the Sundarbans. This was because of two reasons. The infrastructure was similar, and the livelihood patterns and poverty level among the residents were also similar in both Sundarbans. The cyclone caused significant damage to water sources. Before *Aila*, people of both Sundarbans used surface water sources (mainly ponds), tube well water, and rainwater as their primary sources for drinking water. Many ponds and tube wells were contaminated with saline water. In the Bangladesh part of the Sundarbans, 90% of the tube wells were submerged with salt water (International Agencies 2009). Immediately after *Aila*, people were dependent on water trucking by the government and NGOs. Some people started harvesting rainwater by taking advantage of monsoon rains. Given the scale of damage to water infrastructure caused by the cyclone, affected people were forced to drink unsafe water, leading to the outbreak of water borne diseases in both parts of the Sundarbans.

Cyclone *Aila* proved that a low magnitude cyclone of category 1 could have devastating and long-lasting impacts to the impoverished coastal residents of the affected areas. Such impacts were unexpected by the governments of both Bangladesh and India. They were also not well prepared for this event. For example, a sample survey (Das 2011) conducted in the Indian part of the Sundarbans reported that only 5% people had knowledge about Cyclone *Aila* before it made landfall (also see Gupta 2009). This implies that the cyclone forecasting and warning systems either were deployed in an untimely manner or failed to reach the coastal residents. On the other hand, the Government of Bangladesh downplayed the impacts of *Aila* by not declaring an official emergency in its immediate aftermath and not requesting external assistance (Roy et al. 2009; Walton-Ellery 2009).

As indicated, this low magnitude cyclone damaged more than half the coastal embankments in the affected areas of both parts of the Sundarbans. This supports the argument that public cyclone preparedness was not adequate to protect these embankments. Issues like illegal shrimp culture and related activities around the embankments in the Bangladesh part of the Sundarbans, lack of awareness in protecting the embankments, and negligence of proper maintenance of the embankments in both parts deserve high priority to protect coastal residents from future tropical cyclones. For these events, there is also the need to closely monitor the path of any tropical cyclone or depression originating in the northern Bay of Bengal and timely issuance of cyclone warnings for future events. Further emphasis should be placed on investigating the causes of this mass destruction from a relatively weak cyclone and proper action must be taken to reduce future risks. Given the imminent threat of climate change in the Sundarbans region, the disaster response and preparedness system need to be reviewed to prevent the loss and damage of properties due to future extreme events.

Aila seriously affected five areas: shelter, food security, drinking water, sanitation, and health. Even after 1 year of cyclone *Aila*, thousands of affected people in Bangladesh were still living in temporary shelters on damaged embankments with a scarcity of drinking water, a lack of sanitation facilities, and insufficient resources to resume normal life. Building homes on elevated tracts of lands above the rising sea level and surge height can be one important adaptation in the shelter sector. Rural homes in coastal areas are usually made of thatched materials and hence not very strong against tropical cyclones. These houses need significant strengthening to withstand impacts of cyclones and storm surges. Potential improvements of thatched or *kutcha* houses are: elevate homesteads and plinth levels, improve different features of frame, standardize door and window locations, and anchored roofs to the wall.

It is worth mentioning that Aggarwal (2007) has outlined improved designs of cyclone-prone homes that may be applicable in any cyclone zone, including the Sundarbans region. To minimize wind impact, which is the main threat to house stability in cyclone zones, houses should be built behind a mound or behind a shelter belt of trees. To avoid damage to the house from falling trees, houses should be built at a distance from the belt of trees. The foundation of houses should be based on soil characteristics of the zone. In alluvial and clay soils, pile foundation is the ideal foundation. Different shapes of houses are found in the coastal region. However, the square shape is the preferred design since wind moves around a square building relatively easy. Similarly, hip roofs are more cyclone resistant than gable roofs or flat roofs. With changing the design of existing houses, these houses can be made more cyclone resistant. The government and NGOs should promote building this type of houses, along with providing financial assistance for constructing such houses (Paul and Rashid 2017).[7]

[7] For more see, Paul and Rashid (2017).

Availability of pure drinking water has always been a serious problem in the coastal region, including the Sundarbans region of both India and Bangladesh. This problem becomes even worse after a tropical cyclone, which brings saline water inland and contaminates all water sources. More effective adaptations are needed to protect these sources, such as putting tube wells on higher ground so that they do not submerge in saline surge water and raising the height of embankments around ponds. Also, public efforts to popularize harvesting rainwater, which has been practised in some coastal areas, needs to be emphasized. As a short-term solution, cyclone-affected coastal residents should use water purifying tablets in the aftermath of a cyclone for drinking water, or boil floodwater before use. Repairing and disinfecting damaged water sources through community participation should be encouraged.

Like water sources, the sanitation situation in the coastal region is different from other parts of the country. In addition to destruction of sanitation facilities, these facilities seriously suffer from inundation and fill-up with water. Because most of the toilets in the coastal region become unusable after a cyclone, people should adapt to minimize the problem. Such adaptations include increasing the base height of the toilet using more than one sanitary ring and installing toilet far away from water sources (also see Chakraborty et al. 2016).

Lack of proper sanitation facilities, drinking water, and awareness about hygiene lead to various types of health risks after a cyclone. Suffering from illnesses is aggravated in a post-cyclone period due to inaccessibility of health facilities and non-availability of appropriate medicines. For such a period, health adaptations include drinking of pure drinking water, storing of emergency medicine, such as oral saline, painkillers and first aid, and keeping sanitation systems clean. Adaptations of the recommended measures will save many lives and properties from future disasters in the coastal region, including the Sundarbans of both Bangladesh and India.

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Erosion and embankment collapse (Courtesy A. A. Danda)

Chapter 17
Dynamics of the Sundarbans Forested Islands in the Context of Erosion-Accretion and Sea Level Rise

Anirban Mukhopadhyay and Tuhin Ghosh

Abstract The low-lying coastal areas of Sundarbans mostly covered by mangrove forests is threatened by erosion. This study attempts to address the issues of erosion and sea level rise in the mangrove forested islands of entire Sundarbans covering India and Bangladesh. From the multi-temporal satellite imageries (LANDSAT year TM1990 and OLI 2017) the total erosion of these island system has been estimated using a combined rule-based and object-oriented classification system. Near about 325 km^2 of land area has been eroded during this period over nearly three decades (1990–2017). The total Sundarbans (India and Bangladesh) has been divided into three zones – eastern, middle and western – to understand the spatial pattern and dynamics. The erosion dominates mainly in western and middle zones of the Sundarbans and decreases towards eastern zone. The rate of sea level rise has been estimated using tide gauge data and satellite altimetry data (Topex Poseidon Jason). The tide gauge data show a steady relative sea level rise in this region, which might be an important factor for the erosion. The scenario is seriously seeking bilateral management initiatives across the border to protect the pristine ecosystem and its services for futuristic benefits.

Keywords Sundarbans · Mangrove forested area · Erosion · Accretion · Sea level rise

17.1 Introduction

The Sundarbans encompasses the world's biggest chunk of mangrove forest situated in the lower part of the Ganges-Brahmaputra-Meghna (GBM) delta. Sundarbans is shared between India (~4000 km^2) and Bangladesh (~6000 km^2) (Ali 1994). Thriving with numerous creeks and islands with a continuous flow of sediment-laden

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water from several rivers of India and Bangladesh, the Sundarbans has evolved into one of the most dynamic geomorphic areas of the world. Being the largest mangrove forest area Sundarbans provides a bulk of ecosystem services. Sundarbans, with its rich mangrove ecosystems, is the only mangrove tiger land of the world. Mangroves are very much important from both the ecological and economical point of view.

The loss of mangrove area is a great concern, 35% has been observed since 1980 from a global study. In Indian scenario, degradation of the Sundarbans mangrove forest started since 1770 during British India (Mandal et al. 2010). Later in 1947, during the partition of India, a huge influx of refugee was settled in the Indian part of Sundarbans, and concern for the conservation of this mangrove forest was raised. Nevertheless, degradation of the forest was continued by illegal encroachment and this process continued up to 1981due to population pressure (Mandal et al. 2010). The average rate of mangrove area loss is about 2.1% per year, globally it shows a maximum rate up to 3.6% in America (Valiela et al. 2001). Thus, the significant reason behind this loss in the context of India is anthropogenic pressure due to unwise exploitation for multiple uses like food, fodder, fuel, charcoal, etc. (Upadhyay et al. 2002). In addition to this, conversion of the forest area to aquaculture and agricultural land, construction of infrastructures like schools, health centers, jetties and harbours meet the need of the increasing population (Blasco and Aizpuru 1997; Naskar 2004; Upadhyay et al. 2002).

An increased sea level may further significantly result in the loss of the mangrove (Valiela et al. 2001) areas, although accretion in the mangrove forest may be sufficient to compensate the loss due to rising sea level (Field 1995). In the projected scenario of accelerated sea level rise mangrove forests in different parts of the world are at high risk of substantial reduction. Although the global average annual rate of mangrove loss is about ~2% till date in response to relative sea level rise, as high as 35–86% of the total loss has taken place in the last quarter of the century (Valiela et al. 2001; Wilkie and Fortuna 2003; Duke et al. 2007). Studies on impact of relative sea level rise on mangrove systems of Pacific Island (Gilman et al. 2008), Caribbean islands (Urrego et al. 2013), Marajo Island (Eastern Amazon) (França et al. 2012), Southern Brazil (Sanders et al. 2012), coasts of Florida (Smoak et al. 2013) have indicated that mangroves can be damaged significantly. An estimate shows 10–20% of the total reduction in regional mangrove areas may result due to relative sea level rise alone (Gilman et al. 2008). Thus, a proper assessment of coastal habitats in response to rising sea level is extremely necessary for effective management and decision-making.

As the Sundarbans has its protected status in both Bangladesh and India, the loss of mangroves due to anthropogenic status is though important, the threats from the resultant effect of climate change is possibly more important. This study investigates the loss of mangrove forested areas of the Sundarbans in Bangladesh and India since 1990–2017. Considering minimum human intervention during this period the scenario of accretion and erosion in respect of sea level rise have been analyzed.

17.2 Materials and Methods

17.2.1 Study Area

The Sundarbans is situated on the southern boundary of the Ganges-Brahmaputra-Meghna delta on the Northern coast of Bay of Bengal. It is situated between 21°30′ N–23°30′ N and N88°55′ E–89° E (Fig. 17.1). The Sundarbans progressed over the millennia due to regular sediment deposition of several rivers, while the intertidal segregation has also played a significant role. The morphology is controlled by the deltaic formation that includes innumerable creeks associated with surface and subaqueous levees, splays and tidal flats. (https://en.wikipedia.org/wiki/Sundarbans17Physiography). All through the year, the weather remains hot and humid. The monsoon extends from June to September and annual rainfall ranges from 2500 mm to 3000 mm. Maximum temperature and minimum temperature range from 25–35°C to 12–24°C, respectively. Tidal level also varies from 4 m to 6.5 m seasonally and water pH from 7.2 to 7.9 (Banerjee 2002). The micro-topography of the mangrove forest floor of western lower delta plain (west of Haringhata River mouth) is 0.9–2.1 m above MSL (Katebi and Habib 1989). The area between Haringhata and Meghna estuary shows similar elevation and geological setup. The beaches/intertidal zones are composed mostly of fine sands and/or silts backed by sand dunes. About 60% of the Sundarbans is situated in the southwestern part of Bangladesh. The total area of wetlands in Bangladesh part has been variously estimated as 7–8 million ha which is almost 50% of the total land surface of the country.

The area regularly faces several cyclonic storms. The impact of climate change especially sea level rise has its well-seen impacts on the islands (Hazra et al. 2016; Payo et al. 2016). The issues of concern are mainly erosion, storm surge, coastal flooding, salinity change, and health of mangroves.

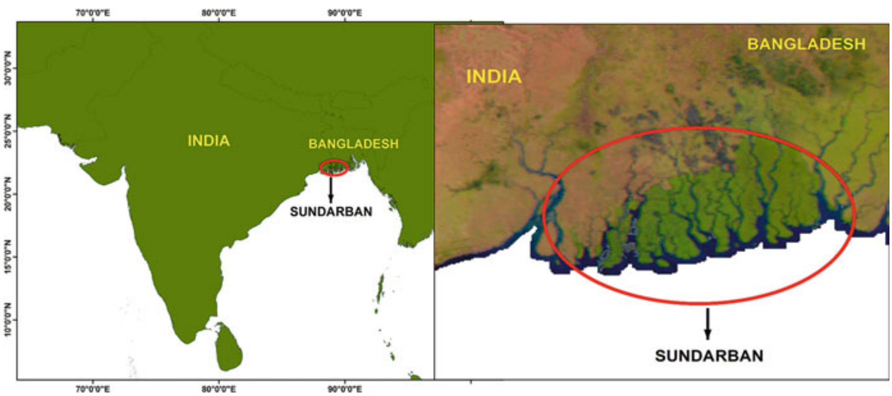

Fig. 17.1 Study area covering India and Bangladesh Sundarbans

Table 17.1 Details of the satellite data used

Date	Path-Row	Sensor	Spatial resolution (m)
1990/1/14	138–45	TM L1T	30
1989/12/22	137–45	TM L1T	30
2000/1/10	138–45	TM L1T	30
2000/1/3	137–45	TM L1T	30
2010/1/21	138–45	TM L1T	30
2010/1/30	137–45	TM L1T	30
2017/2/25	138–45	OLI TIRS L1T	30
2017/2/18	137–45	OLI TIRS L1T	30

Table 17.2 Details of the tide data from PSMSL

Station name	ID	LAT	LONG	Country	Coastline	Station no.	Duration
SAUGOR/ SAGAR	417	21.650	88.050	IND	500	111	1970–1988
HIRON POINT	1451	21.783	89.467	BGD	510	003	1983–2003

17.2.2 Data Inputs from Satellite Imageries

To assess the erosion scenarios multi-temporal satellite images of the LANDSAT have been used, the relevant details are given in Table 17.1. For the sea level analysis tide data from Permanent Service for Mean Sea Level (PSMSL) have been used; details of the data of the two stations situated within the study area are given in Table 17.2.

To estimate changes in the sea level topography in the surrounding part of Bay of Bengal Satellite data (Jason-1, Jason-2, and TOPEX/Poseidon) derived Sea Surface Height information have also been analyzed from the year 1993 to 2014 (source http://oceanmotion.org).

17.2.3 Geomorphological Analysis

Out of multi-temporal satellite images of the LANDSAT satellite TM images of the year 1990, 2000, 2010 and OLI image of the year 2017 have been used (Fig. 17.2).

The tide level during the time of acquisition of the images is very important to estimate the erosion-accretion of the islands. Unfortunately, availability of the satellite images in same tide level over these long periods is quite impossible. To overcome this ambiguity the boundaries of the islands have been estimated using the canopy cover with a logic that canopy covers are the boundary lines of the islands. Hence possible error from tidal fluctuations has been eliminated from this analysis.

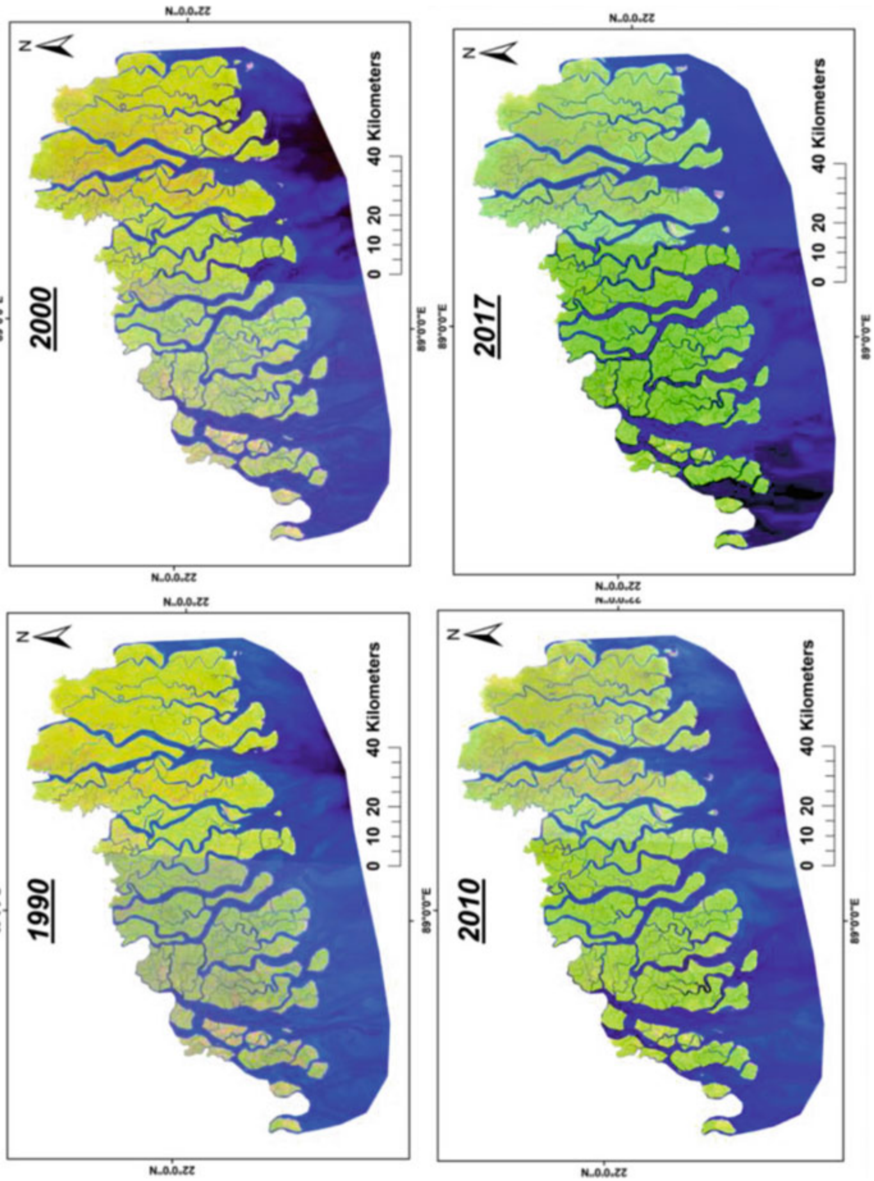

Fig. 17.2 True colour composite of the satellite images of the year 1990, 2000, 2010, 2017 of the study area

To extract the land and water extent of the images these have been classified into two-bit images. To standardize the classification and reduce the errors of the LANDSAT images radiometric standardization/atmospheric correction has been followed (Duggin and Robinove 1990; Song et al. 2001). The bands of the LANDSAT images were radiometrically calibrated. For the transformation of the DN values into the top of the atmosphere (TOA) radiance (θ_2) sensor calibration function (Eq.17.1) according to Chander et al. (2007) has been used. The radiance of the bands has been transformed to surface reflectance using atmospheric correction model (Chavez 1996) (Eq. 17.2).

$$L_{TOA} = \left(\frac{L\text{max}_{\lambda} - L\text{min}_{\lambda}}{QCAL\text{max} - QCAL\text{min}}\right) \times (DN - QCAL\text{min}) + L\text{min}_{\lambda} \qquad (17.1)$$

where, $L\text{max}_{\lambda}$ and $L\text{min}_{\lambda}$ are maximum and minimum radiance (in W/m^{-2}sr^{-1}μm^{-1}), $QCAL$max and $QCAL$min are maximum and minimum DN value possible (255/1).

$$\rho = \frac{(L_{TOA} - L_p)\pi d^2}{ESUN_{\lambda} \cos \theta_z \mathrm{T}_z} \qquad (17.2)$$

where,

ρ = surface reflectance,

d = Earth sun distance (in Astronomical Units),

$ESUN_{\lambda}$ = band pass solar irradiance at top of the atmosphere (TOA),

θ_2 = Solar zenith angle (deg),

T_Z = atmospheric transmission between ground and TOA,

The values of the T_Z for band 4 and 5 were taken as 0.85 and 0.95, respectively (Chavez 1996).

Lp = radiance resulted with the interaction aerosol and atmospheric particles, and estimated based on Chavez (1996), Song et al. (2001), Sobrino et al. (2004). The atmospheric correction was done using ATCORE Module of ERDAS Imagine software. After classification of the islands and water of the year 1990, 2000, 2010, 2017 change detection analysis has been performed to find the changes that occurred during the periods. The classified islands have been vectorized to extract the boundary of the islands as polygon layer. The multi-resolution segmentation has been done using the eCognition software. Each boundary polygon then converted into one point on centroid and that way the centroids of the islands have been extracted. Then the positional changes of the centroid have been calculated (Fig. 17.3).

For a better understanding of the scenario, the total Sundarbans have been classified into three zones West, Mid, and East according to the area. The erosion-accretion and shifting of centroid have been estimated zone wise. The flow chart of the methodology used is given in Fig. 17.4.

To analyze the sea level scenario tide data of two stations from PSMSL within the Sundarbans have been analyzed. Tide data of Sagar Island (India) from 1970 to 1988

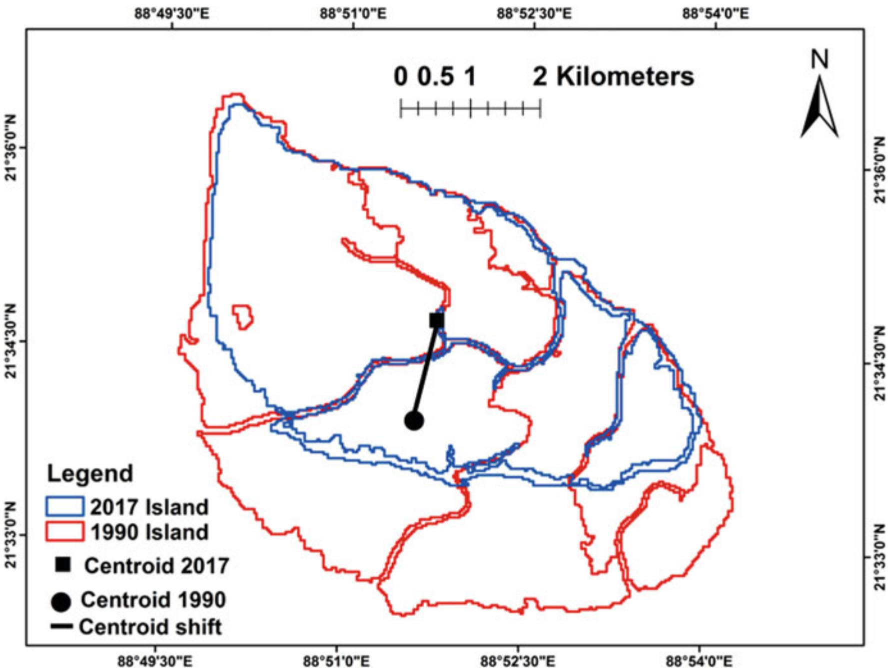

Fig. 17.3 Centroid shifting of Vangaduani Island

and Hiron Point (Bangladesh) from 1983 to 2003 have been analyzed. As available data were not enough and recent, the sea surface topography of the surrounding area has also been analyzed to understand the sea level scenario. Absolute Dynamic Sea-Level Topography for the area between 90.0E–92.0E and 20.0N–22.0N has been analyzed using Jason-1, Jason-2, and TOPEX/Poseidon derived Sea Surface Height 1993–2014 (source http://oceanmotion.org).

17.3 Results and Discussion

17.3.1 Erosion and Accretion of the Islands vis-à-vis Sea Level Rise

Eustatic sea level rise is one of the most certain outcomes of the global warming which will affect the coastal belts and may lead to coastal erosion, saline water intrusion in coastal aquifers and rivers, degradation of dunes, loss of mangroves and coastal marshes. The most recent projection of global warming ranges from 1.4 °C to 5.8 °C within the next century (Galbraith et al. 2002). During the twentieth century, the global sea level rise ranged between 12 and 22 cm (Gilman et al. 2008) and the projected rise from 1980 to 1999 to the end of twenty-first century (2090–2099)

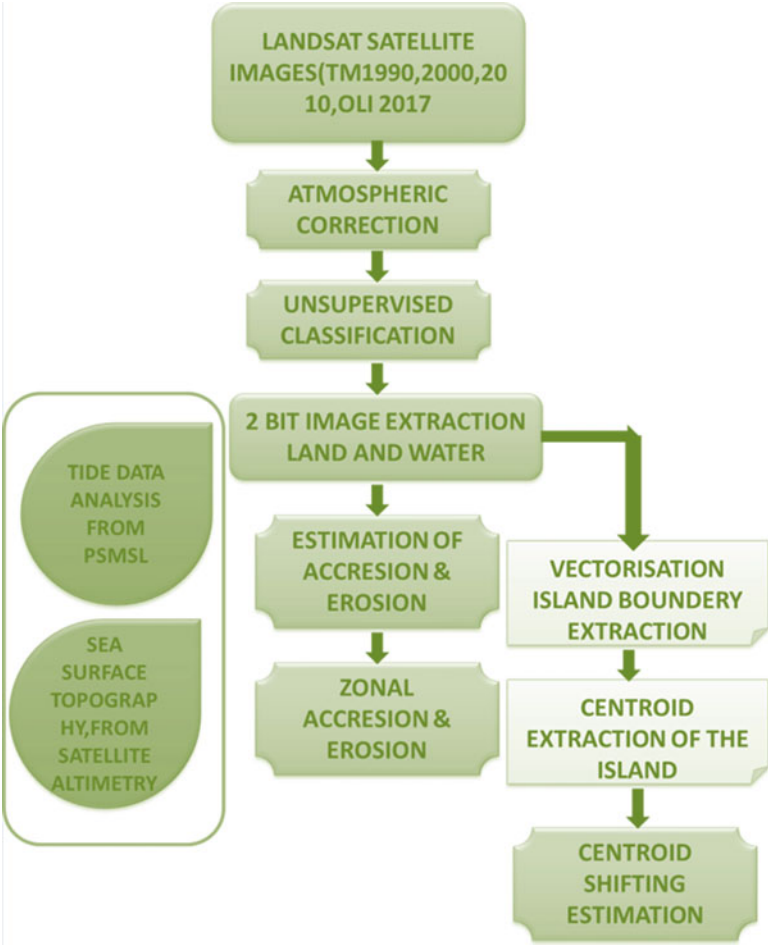

Fig. 17.4 Methodology flow chart

would range from 0.18 m to 0.59 m (Solomon et al. 2007). To assess the sea level scenario of the Sundarbans region tide data as well as satellite altimetry data have been analyzed. Both the analyses are showing a positive trend of sea level rise in and around the Sundarbans. The tide data derived from PSMSL (Fig. 17.5) of the Sagar tide station of the Indian part of Sundarbans during 1970–1988 shows a steady ~3 mm per year increase during the period. In the Bangladesh Sundarbans portion the tide data of the Hiron Point Station during the period of 1983–2003 have been analyzed. The result shows similar trend of sea level rise ~4 mm per year (Fig. 17.5). The better understanding of the sea level has been derived from the satellite altimetry. The satellite altimetry is preferable due to its larger coverage area instead of point data and also its higher temporal resolution. Absolute Dynamic Sea Level Topography of northern Bay of Bengal surrounding Sundarbans region from 90.0E–

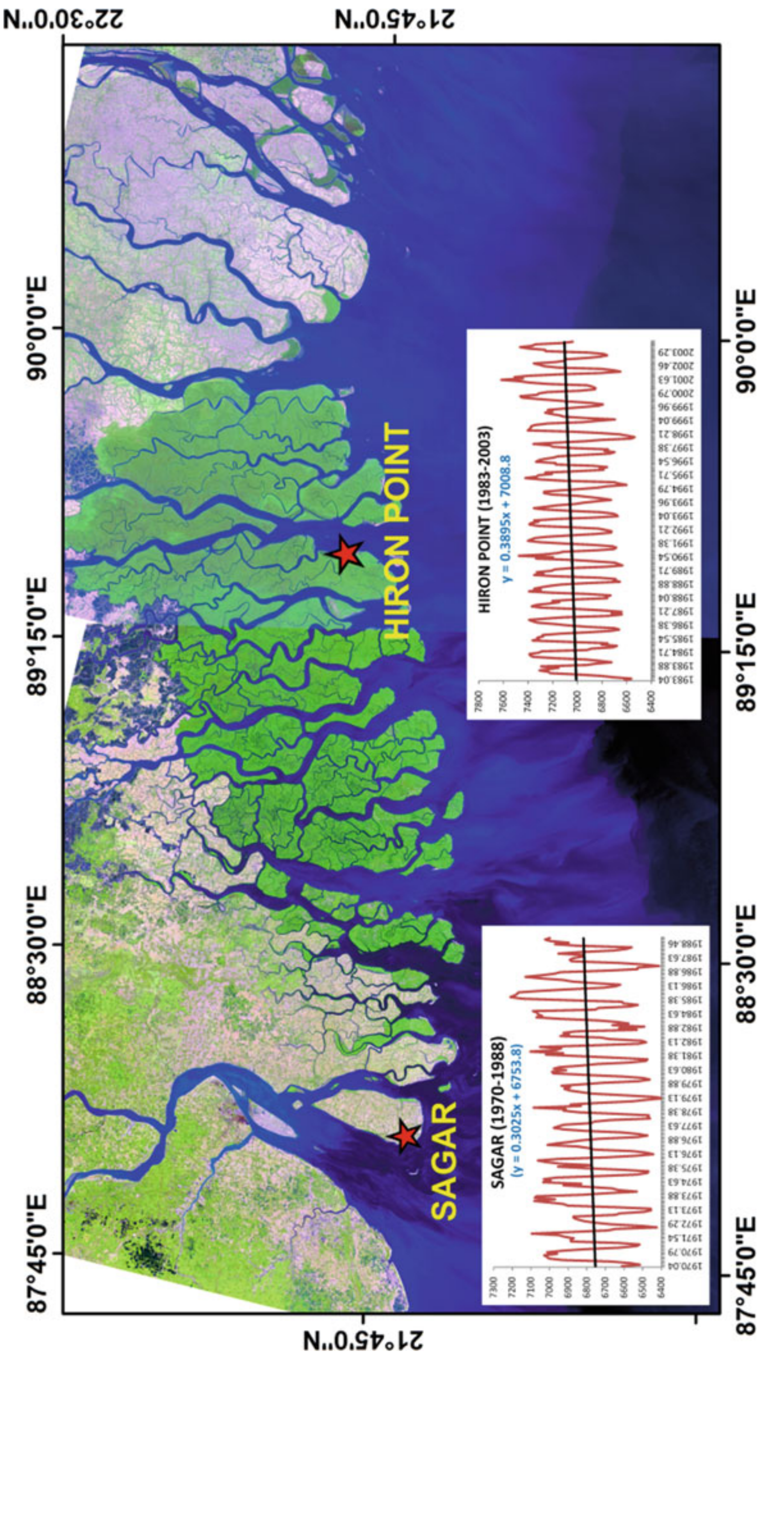

Fig. 17.5 Tide data of Sagar (1970–1988) and Hiron Point (1983–2003). (Source PSMSL)

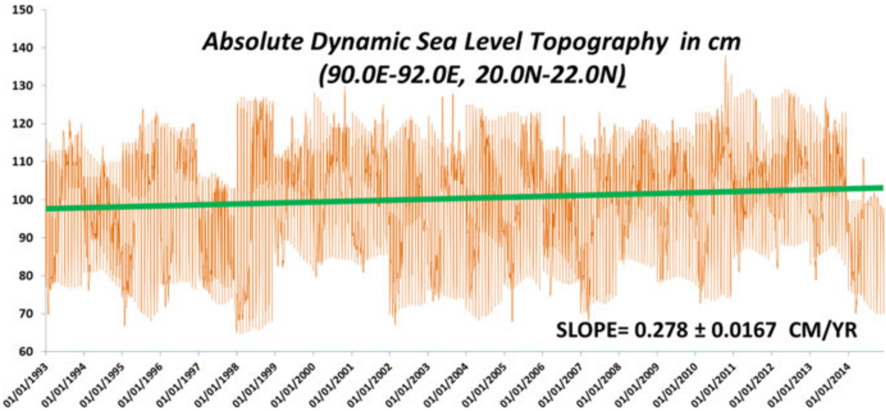

Fig. 17.6 Sea level topography of northern Bay of Bengal between1993 and 2014. (Source http://oceanmotion.org)

92.0E to 20.0N–22.0N has been analyzed from the year 1993 to 2014 using Jason-1, Jason-2, and TOPEX/Poseidon derived Sea Surface Height. The result shows the sea level topography of the entire region is increasing in a steady rate about ~0.278 ± 0.0167 cm per year (Fig. 17.6). This combined study indicates that the sea level rise is a slow onset disaster in the Sundarbans region and its consequences are inevitable.

Several assessments are addressing the impact of sea level rise on the coastal areas (Snoussi et al. 2009; Kuhn et al. 2011; França et al. 2012; Urrego et al. 2013) and the results indicate that the coastal areas are threatened by inundation and/or erosion. Mangrove systems cannot keep pace with changing sea level if there is a net lowering in sediment supply. The shoreline of Sundarbans is vulnerable to the impact of sea level rise and storm surge intensification (Warrick and Ahmad 1996; Cruz et al. 2007; Nicholls et al. 2007; Sarwar and Khan 2007; Karim and Mimura 2008), and during 1989–2009 the erosion was dominant along the seaward margin of Sundarbans possibly augmented by subsidence and tidal flow (Sarwar and Woodroffe 2013). An estimate shows that in a worst scenario of relative sea level rise and increased high intensity events, habitable land loss in Bangladesh between 1989 and 2100 could be about 36% (Ericson et al. 2006). The satellite data derived erosion-accretion study of the mangrove forested island (Fig. 17.7) show almost 2% loss of total area during the last 27 years. A total ~313 km^2 area has been lost during this period whereas ~125 km^2 new areas has been deposited and became vegetated. This leads to a total ~188 km^2 net loss of the land mass which indicates an alarming situation. The total area of erosion was maximum (~124 km^2) during the period of 1990–2000, while accretion was less ~24 km^2 when compared with the proceeding years. The erosion and accretion during 2000–2010 and 2010–2017 were almost the same, while the maximum deposition happened during the last phase 2010–2017. The pattern of the erosion and related shifting of the centroids of the islands has been analyzed zone-wise (Fig. 17.8).

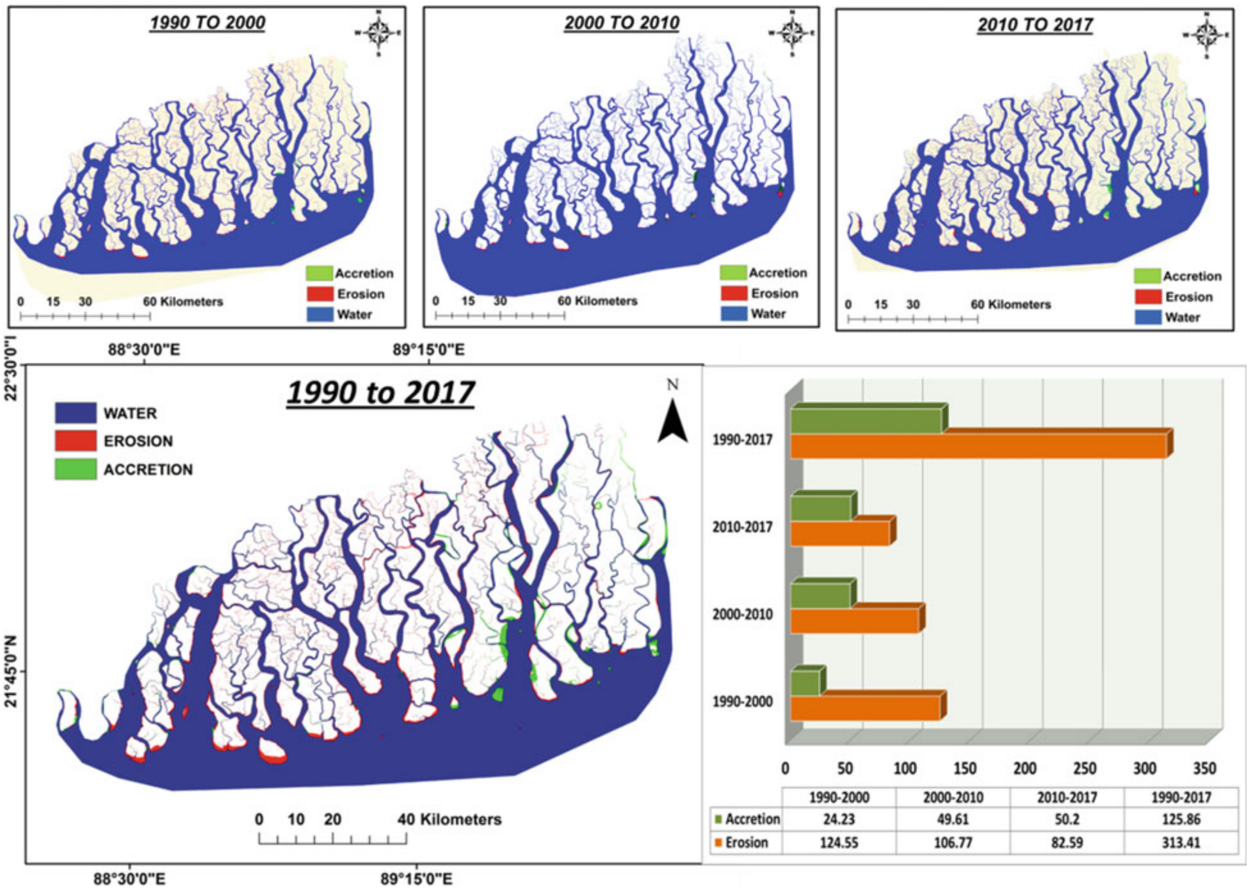

Fig. 17.7 Erosion-accretion scenario of Sundarbans from 1990 to 2017. (From LANDSAT satellite images)

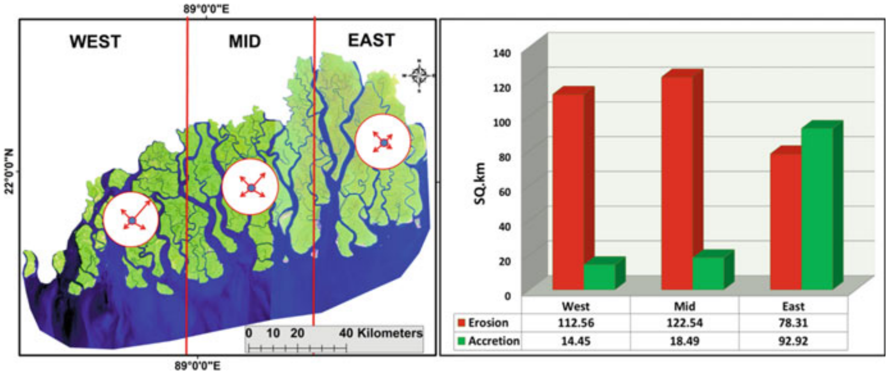

Fig. 17.8 Zone-wise erosion-accretion statistics along with directional amplitude of the erosion based on centroid shifting

17.3.2 Zone-Wise Morpho-Dynamics

While analyzing the zone-wise island dynamics it has been noticed that the western and middle zones are mainly erosion dominated while the eastern zone of Sundarbans situated within Bangladesh is showing dominant accretion. Net erosion of the western and middle zone of the Sundarbans during last three decades is almost 100 km^2 in both the zones, while in the eastern zone a net accretion of near about 15 km^2 was noticed. The shifting of the centroids of these islands also shows similar pattern- a dominant shift towards south-west direction. In the western part the direction of erosion vis-à-vis shifting of the centroid is dominating towards the north-east direction. The direction is almost opposite while approaching to the eastern zone. The main reason behind this phenomenon is probably the higher rate of sediment supply in the Bangladesh part of the Sundarbans due to higher influx from the upland rivers, while in the Indian part of the Sundarbans most of the rivers have lost upland connections and are mostly tide dominated with negligible sediment supply. Along with this, a steady rise in the sea level and subsidence is making the scenario worse leading to more erosion of the forested islands.

17.4 Conclusion

The entire Sundarbans forest (including India and Bangladesh) is facing acute erosion problem resulting in a huge loss of forested lands. The rate of erosion is gradually higher from east to west, while a steady rise of sea level and subsidence is triggering the issue. Though the erosion is occurring in entire Sundarbans seaward islands are suffering most. The loss of the fragile ecosystem and unique biodiversity is a major concern for both the countries. Hence, a bilateral cooperation and management effort are necessary between India and Bangladesh. The situation is quite alarming and urgently seeking the attentions of the policy makers and scientists across the border.

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Disaster due to cyclone (Courtesy Arjun Kumar Manna)

Chapter 18
Space Technology and its Application in Disaster Management: Case Studies on Ecological Disturbance and Landmass Changes in Sundarbans

Dibyendu Dutta, Tanumi Kumar, Libeesh Lukose, and Sourav Samanta

Abstract Sundarbans, the largest single patch of mangrove habitation of the world is prone to large number of natural disasters. There is an urgent need to protect this precious resource to maintain the natural harmony between man and environment. To show the capability of remote sensing satellites, two case studies for Sundarbans have been presented. In the first study, assessment of ecological disturbance caused by some of the major cyclones of the last decade has been carried out in which Moderate Resolution Imaging Spectroradiometer (MODIS)-derived Land Surface Temperature and Enhanced Vegetation Index have been used to calculate MODIS Global Disturbance Index (MGDI). MGDI approach was used to assess the instantaneous ecological disturbance caused by cyclones, of different intensities, striking the mangroves at different phenological stages. The second study is about the landmass change and its periodicity during 1973 to 2017 using multispectral satellite data. Overall decrease in the landmass is in the order of 329.45 km^2 during 1973 to 2017 @ 7.48 km^2 $year^{-1}$. However, the rate of erosion is highly variable over the years and varies between 1.62% (between 1973 and 1999) and as high as 4.50% (between 1973 and 2017). Based upon the net loss of landmass the islands are classified into 4 categories, viz. low (<10 ha $year^{-1}$, including Kankramari, Sikarpur and Putni Island), medium (between 10 and 20 ha $year^{-1}$, including Ghoramara, Jambudwip and Mahisani), high (between 20 and 30 ha $year^{-1}$, including Sagar and Bulcherry), and very high (>30 ha $year^{-1}$, including Dalhausi and Bangaduni).

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Keywords Sundarbans · Cyclone · Flood · Lightning · Earthquake · ICT · Ecological disturbance · Landmass change

18.1 Introduction

Among various natural disasters in Sundarbans high intensity super-cyclones, tidal flooding, salt water intrusion, and soil salinization and cloud to ground lightning during pre-monsoon and monsoon periods cause misery to the inhabitants, loss of livelihood, properties and life. The vagaries of natural disasters have serious negative implications on the economy of the region, which is already resource poor, ecologically vulnerable and constrained due to over-population. The high population pressure in the fringe areas of the biosphere reserve has made the ecosystem more fragile and vulnerable to natural disasters. There is an urgent need to protect this precious resource to maintain the natural harmony between man and environment.

With the advent of new technologies and tools, especially the information communication technology (ICT), the loss can be considerably minimized by developing suitable warning systems, effective communication, monitoring and post disaster damage assessment in near real time. The host of ICT applications including Satellite Remote Sensing, Satellite Communication, Geographic Information System (GIS), Global Positioning System (GPS), etc. are operationally being used in the planning and implementation of hazard minimization programmes, emergency preparedness, response and mitigation. Easy and affordable internet facilities help in rapid and automatic global dissemination of information through public portals, generating historical events, posting weather forecasts, cyclone tracking, rainfall estimation and crowd sourcing using mobile applications. Remote sensing data collection using multiple sensors and platforms at high spatial and temporal resolution is one of the unique ways to monitor and model the weather system. GIS helps integrating various spatial and non-spatial data to arrive at optimal decisions and in turn can improve the quality and power of analysis of natural hazard assessment. The spatial analysis tool helps in modelling, simulation, multi-theme action plan generation, and generating various scenarios for decision planning. It also helps in search and rescue operations in a more effective manner. The benefits of cellular technology are aptly being used to transmit tsunami and cyclone warnings as SMS through mobile phones based upon the information collected from weather satellites or from seismic observatories. Towards the entire framework, satellite radio plays a key role during both the disaster warning and recovery phases, especially when the normal transmission mode is affected. The formation of thunderstorm cloud, its temporal development, tracking and rainfall prediction – all are catered using multiple satellite sensors, including Geostationary and Earth Observation satellites. Complementary information from optical, thermal and microwave regions of electromagnetic (EM) spectrum are used to infer about cloud type, texture, thickness, albedo, cloud top temperature, liquid water content, and threedimensional structure of thunderclouds, which are considered to be useful for rainfall estimation.

Presently, operational precipitation products are generated using multi-sensor techniques including rain gauge and precipitation radar data at finer temporal and spatial scales. Besides prediction satellite data can be effectively used at various stages of flood management, viz. risk mapping including assessment, monitoring, analysis and modelling of flood events through distributed hydrological modelling, post-flood changes in river configuration, silt deposition and damage of embankments at local level. The satellite-based precipitation rate, moisture transport and soil wetness are vital for runoff modelling. In post-flood stage the extent of inundation is mapped using optical and radar data to monitor the spatial extent. Every year several lives are lost in the coastal region during nor'westers and monsoon months due to lightning. The geo-location and lead time of lightning discharge from cloud to ground is extremely important for lightning warning and safety applications. With the network of Lightning Detection Systems (LDS), it is now possible to detect the movement of thunderstorm cells, evolution of their charge structure in real time, location of cloud to ground discharge in sufficient lead time and consequent changes in the atmospheric chemistry.

The article presents the use of ICT at various stages of disaster management, along with predictions of ecological disturbance and temporal change of landmass due to erosion and accretion in selected islands in Sundarbans.

18.2 Geography and Salient Features of Sundarbans

Sundarbans is the world's largest deltaic patch of mangrove ecosystem formed by the fluvial deposits of 3 major rivers, viz. the Ganges, Brahmaputra and Meghna. This mangrove forest is extended over two neighbouring countries, viz. Bangladesh and India, and bounded by 21°32′ N to 22°13′ N latitude and 88°15′ E to 89°53′ E longitude (Fig. 18.1). The forest area spans over South and North 24 Parganas districts of West Bengal State (India) and Khulna, Satkhira, Bagerhat districts of Bangladesh. The larger part of the Sundarbans (about 60%) is situated in Bangladesh and about 40% in India. Baleswar River of Bangladesh forms the eastern boundary, whereas Saptamukhi River of West Bengal, India forms the western limit. The Indian part the deltaic complex consists of 106 islands of which 54 are inhabited and 52 are forested islands, whereas in Bangladesh it consists of 31 islands.

The landscape of Sundarbans is characterized by a complex network of serpentine tidal waterways/creeks, mudflats and small islands of mangrove forests. The tidal amplitude varies between 3.5 and 5 m, with the highest amplitudes observed in July–August and lowest in December–January. In 1985, Indian Sundarbans was inscribed as World Heritage site by United Nations Educational, Scientific and Cultural Organization (UNESCO), declared as a world heritage site by International Union for Conservation of Nature and Natural Resources (IUCN) in 1987 and Global Biosphere Reserve by UNESCO in 1989. The most prominent feature of the

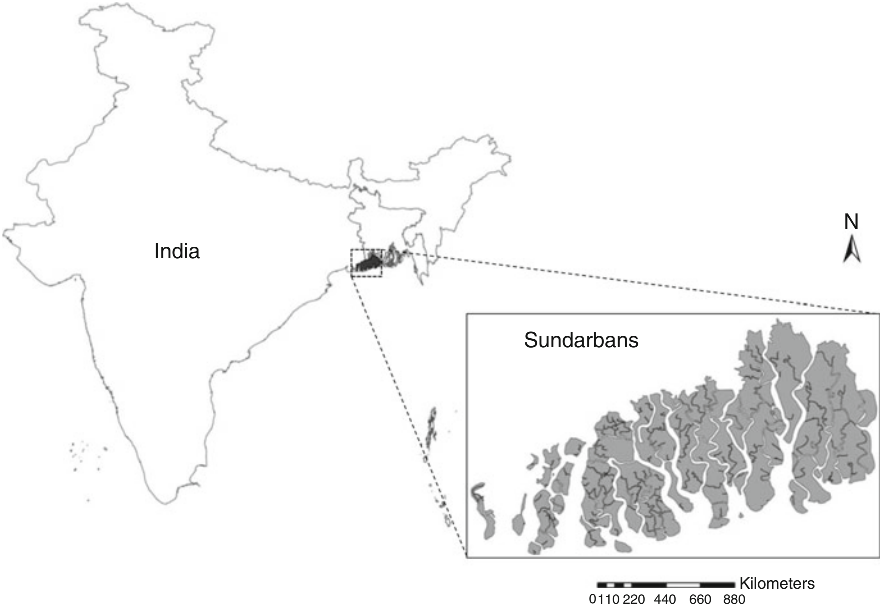

Fig. 18.1 Location map of Sundarbans forests. (Source: In-house production, not published)

Sundarbans delta is the ubiquitous mangrove ecosystem that dominates the landscape. The mangroves have unique importance because of their ecosystem services, protective functions, biological productivity and livelihood options for the large number of population living in the fringes of the Sundarbans Biosphere Reserve (Naskar and Guha Bakshi 1987). The ecosystem plays crucial role by acting as bio-shield against storm surges and thereby reducing the vulnerability to extreme climatic events, like cyclones (Kathiresan and Bingham 2001; Alongi et al. 1992). Extensive and deep-rooted system of mangroves help in protecting coastline from erosion, act as nutrient filter and nursery grounds for coastal fishes (Rahman and Asaduzzaman 2010). The long-term carbon sequestering capacity of mangrove is as high as 469.2 to 569.2 mega grams of C/ha, which is very high in comparison to other forest and agricultural ecosystems.

However, the coastal mangrove forests are highly vulnerable to frequent cyclones formed over Bay of Bengal during May–June and October–November. About one-tenth of the global tropical cyclones occur in the Bay of Bengal (Government of Bangladesh, UNDP, World Bank 1993), of which one-sixth had landfall on the Sundarbans coast. Tropical cyclones at landfall region cause extensive damage to mangroves, wildlife habitat and human settlements in the adjoining forest areas due to low and flat topography. During storm surge brackish water intrudes deep inside the forest through creeks making the land highly saline and unsuitable for forest species sensitive to soil salinity. Moreover, frequent catastrophic disturbances may lead to limited chance of recovery of mangrove vegetation due to non-availability of mangrove propagules (Rashid et al. 2009). Hence, prolonged canopy gaps in the open areas are occupied by invasive species, which alter the existing physical environment and community of organisms at a particular site (Ameen 1999; Biswas 2003) causing cryptic ecological degradation. Under climate change scenario the intensity and frequency of tropical cyclones have considerably increased (Houghton et al. 2001; IPCC 2007) which affect the delta building process. It is evident that both the process of erosion and accretion occur almost simultaneously in different parts of Sundarbans. The western part exhibits more erosion compared to deposition, which is reverse in case of central Indian Sundarbans. The phenomena of erosion and accretion are largely regulated by littoral current pattern and sediment influx from different rivers and adjacent Bay of Bengal.

18.3 Evolution and Changes in Sundarbans Delta

The evolution of Sundarbans delta is closely linked with the development of the Ganges-Brahmaputra-Meghna (GBM) delta which was formed millions of years ago when the North Eastern portion of the Indo-Australian plate fractured and sank below the sea level. The depressed basin attracted the rivers and in due course of time the depression was filled up by the sediments carried by the mighty rivers, viz. the Ganges, Brahmaputra and Meghna (Coleman 1969) to form the present Bengal basin mostly during the Holocene period (Jakia Akter et al. 2016), although initiated during the onset of Pleistocene glacial maximum. During this period the Ganges shifted incrementally from west to east primarily as a consequence of the delta building process. Conversely, the Brahmaputra switched back and forth from the east of the Madhupur block to the west. The initiation of the modern GBM delta and its evolution to the present configuration are intricately related to Holocene fluvio-dynamic processes, eustatic sea-level changes and tectonic movements. It is presumed that in the distant past the tidal swamp of Sundarbans was extended more towards the inland, i.e. at the base of the Rajmahal hills of West Bengal, than at its present location (IUCN Bangladesh 2014). It moved towards the south as the delta extended towards the Bay. The growth of the delta associated with various other geomorphological alterations and subsequent hydrological effects have resulted in the present location and condition of the forest.

During twelfth and fifteenth century AD, neo-tectonic activities (Raha et al. 2012) in the Bengal basin resulted in an easterly tilt (Morgan and McIntire 1959) of the deltaic complex, resulting in a rise of the western part of the Ganges from present Sundarbans (Sanyal et al. 1984) and brought changes in the geomorphology and biota of the Sundarbans (Junk et al. 2006). In the Bangladesh portion of Sundarbans formation of the pro-gradational sequence began prior to 4000 year BC and ended about 1800 cal years BC (Allison et al. 2003). Phase associated with the ganges - G1, G2, G3 sub-deltas (Allison et al. 2003) (Fig. 18.2) that border the Bay of Bengal have reached maturity and are no longer prograding (Allison et al. 2003). Historical data show that G1 area has retreated several km in the past 200 years (Allison 1998).

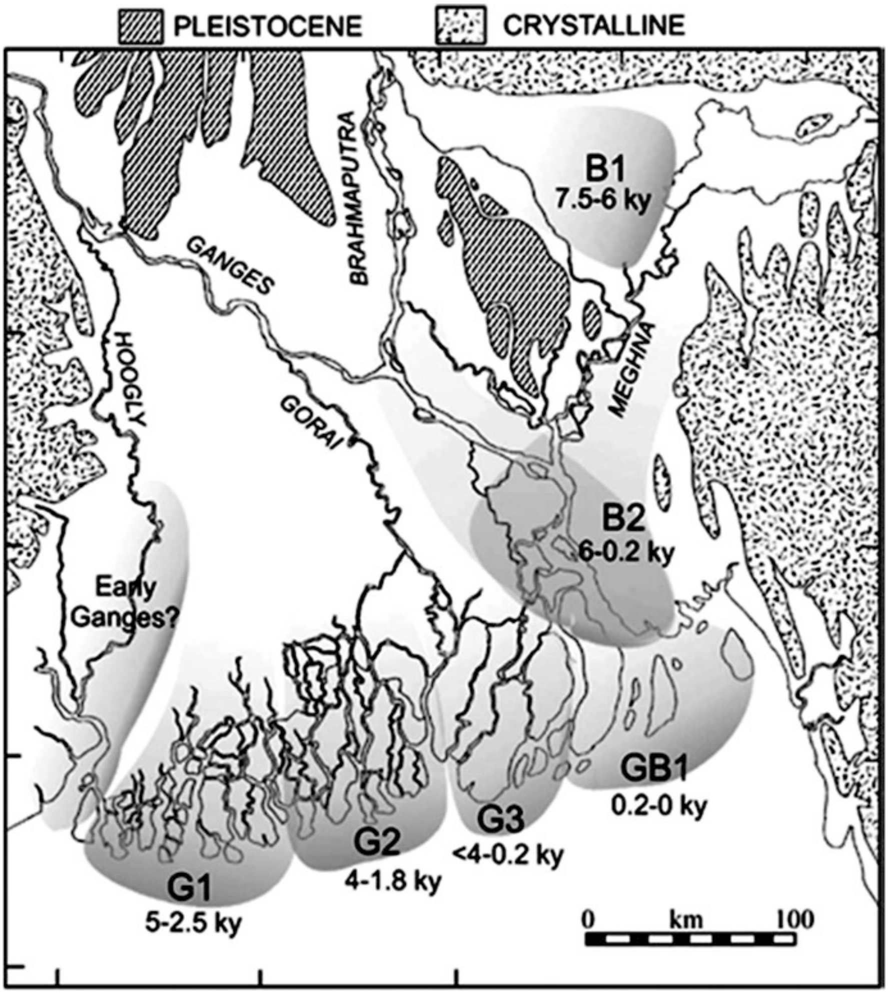

Fig. 18.2 Map of the pathways and timing of the phases of late Holocene growth of the lower delta plain associated with the Ganges (G1, G2, G3), Brahmaputra (B1, B2) and combined Ganges-Brahmaputra rivers (GB1). Ky = thousands of years before present. (Source: Allison et al. 2003)

In the sixteenth century the river Ganges changed its course to shift eastward and joined the Brahmaputra (Deb 1956; Blasco 1975; Snedaker 1991) which brought metamorphic changes in the deltaic lobe. Later in the mid eighteenth century, the combined Ganges (now Padma) and Brahmaputra again tilted eastward to empty into river Meghna (Snedaker 1991), but drastic changes in the Ganges-Brahmaputra (GB) basins were observed in the past as a result of major seismic activities (Gupta et al. 2014) resulting in change in the sedimentation pattern and freshwater flow. The 1950 Assam earthquake with a magnitude of 8.5 on the Richter scale caused huge changes in the river system and the deltaic plain. Most of the rivers, distributaries other than the Hooghly, that contributed to the formation of the Ganges delta (from west to east: Muriganga, Saptamukhi, Thakuran, Matla, Gosaba and Bidya), have lost their original connections with the Ganges because of siltation and their estuarine character is now maintained by the monsoonal runoff (Cole and Vaidyaraman 1966) and tidal actions (Mitra et al. 2009, 2011). Besides sedimentation, subsidence of unconsolidated deltaic sediments is occurring constantly in deltas as a result of compaction of deltaic deposits (van Asselen et al. 2009), tectonics and isostasy (Kooi et al. 1998). Based upon the radiocarbon dating (Umitsu 1993) it was stated that the coastal areas of Bangladesh are subsiding at a rate of about 3 mm $year^{-1}$, whereas Syvitski et al. (2009) claimed that the Bengal delta was sinking at a very high rate of 8–18 mm $year^{-1}$ (Raha et al. 2012).

18.4 Demography and Population Change

In early eighteenth century, the Sundarbans and adjoining Kolkata region was inhabited by dense jungles. In the post-independence era after the abolition of the *zamindari* system in 1950, the Irrigation Department, Government of West Bengal was bestowed with the responsibility of protecting the embankments all over the Sundarbans. Several activities, viz. construction of weak embankments, poor maintenance, filling up of marshes and ponds, changing hydrological regimes of the rivers, etc. caused by construction of canals, barrages, check dams, multi-purpose river valley projects and rapid urbanisation around Kolkata made the area vulnerable to tropical storms and other natural vagaries. In late 1970s, shrimp cultivation flourished at Kakdwip and Namkhana region, causing a new phase of land transformation, which was not only remunerative, but also provided ancillary business opportunities. This business suffered a setback in 1990s due to widespread viral disease which turned to epidemic. Following the economic setback, a new means of livelihood in terms of ecotourism business quickly picked up which further triggered environmental pollution, river bank erosion and unauthorized construction of resorts. There is about four times increase in the population in the region since 1951 when it was only 1.15 million to as high as 4.44 million in 2011 (Fig. 18.3). The exponential growth of population is one of the major reasons for forest degradation and increasing vulnerability to natural disasters. Although, the exposure to natural calamities is common for all, there is difference in terms of coping strategy across the demographic profile which is a function of asset base. Geographer David Harvey aptly pointed out that there is a dialectical relationship between nature, society and disaster that leads to environmental change with a substantial impact on marginalized communities who are forced to occupy these vulnerable places.

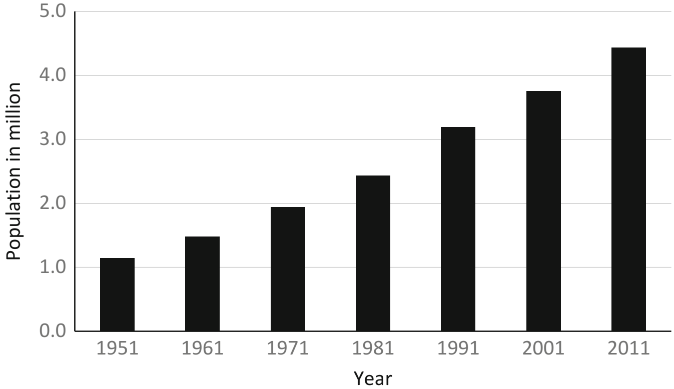

Fig. 18.3 Decadal population growth in the Indian Sundarbans during 1951 to 2011. (Source: Ghosh et al. 2015)

18.5 Common Disasters of Sundarbans

Natural disasters can be divided into five major types, viz. geological disaster (avalanche and landslide, earthquakes, sinkholes, volcanic eruptions), hydrological disaster (flood, tsunami), meteorological disaster (cyclone/tornado, drought, thunderstorm, hailstorm, heat waves, lightning), wildfires and space disasters. Out of five major types two are most common in Sundarbans region, namely meteorological, hydrological, and to a limited extent the geological disaster. The detailed description of different types of disasters relevant for the Sundarbans region is given below.

18.5.1 Meteorological Disasters

Major meteorological disasters prevalent in the coastal areas of Sundarbans include cyclone, thunderstorm and lightning. Brief account of each of the disasters is given below.

18.5.1.1 Cyclone

Cyclone is a vortex of flow by large-scale convergence of moist air in the boundary layer which forces air mass to ascent vertically upward, causing strong columns of convection and releasing large amount of latent heat due to condensation. The probabilities of genesis of tropical cyclone is calculated by a Dvorak current intensity (CI) number. Whenever a convective cloud mass develops over the ocean and sustain for a number of days without decaying there is a probability that the system may develop into a tropical cyclone. A cyclone is formed when sea surface temperature is above 26.5 °C and characterized by inward spiralling winds that rotate about a zone of low pressure. From the vast ocean surface moisture laden warm air rises quickly due to less density, creating an *updraft*, and eventually when the cloud condensation is enough, it may fall back to the ground as rain and draw cool air down which it called *downdraft*. A powerful downward current of air is usually accompanied by precipitation within a thunderstorm. When both updraft and downdraft work together a storm cell is formed. As this process continues, the cloud grows and eventually a large thunderstorm cloud is formed. When the air in the thunderstorm cloud spins horizontally it takes the shape of tropical cyclones and tornedoes. The term "tropical" refers to both the geographic origin of these systems, which form almost exclusively in tropical regions of the globe, and their dependence on Maritime Tropical air masses for formation. This process creates an intense low-pressure centre which drives air from surrounding areas with higher air pressure into the low pressure area. So long the ocean temperature remains above the threshold the warm air continues to rise and cools off to grow into large clouds. While tropical cyclones can produce extremely powerful winds and torrential rain, they are also able to produce high waves and a damaging storm surge. It is interesting to note that as many as 10% of world's cyclone develop over Indian ocean but they cause 85% of the world's cyclonic havoc (Gray 1968). From historical record it can be noted that there are two peaks in the annual distribution of the tropical cyclone formation in the Bay of Bengal (BoB), one in May and the other in November, with the peak season during April–May and October–November, respectively.

The intensity of a tropical cyclone is determined by the spiralling surface wind velocity near the centre. Once a tropical cyclone reaches maximum sustained wind speed of 74 miles per hour or higher, it is classified as a hurricane, typhoon, tropical cyclone or cyclone depending upon where the storm originates in the world. The Tropical Cyclone Severity is measured differently in the Southern and Northern hemisphere (Annex Table 2). The Northern hemisphere follows the US Saffir Simpson Categories whereas the Southern hemisphere usually follows the Australian categories (Annex Table 2).

18.5.1.2 Thunderstorm

Thunderstorms result from the rapid upward movement (updraft) of warm, moist air, sometimes along a front. As the warm, moist air rises into the atmosphere, it begins to cool. When the rising air reaches its dew point temperature, water vapour condenses into water droplets, or ice, releasing latent heat of vaporization, which allows the rising packet of air to cool more than the surrounding air. If enough instability is present in the atmosphere, this process will continue long enough for cumulonimbus clouds to form resulting in lightning and thunder. As the droplets fall, they collide with other droplets and become larger. The falling droplets create a downdraft as it pulls cold air with it, and sinking back to the ground, occasionally causing strong winds that are commonly associated with thunderstorms. The combined warm updraft and cool downdraft create a storm cell.

18.5.1.3 Lightning

Lightning can be defined as a transient, high current (typically tens of kiloamperes) electric discharge in air. The electrical discharge can take place in several ways, viz. intra-cloud discharges (ICD), cloud to ground discharges (CGD) cloud to cloud discharges (CCD), and cloud to air discharges (CAD). The most common type of discharge and consequent lightning happens due to intra-cloud discharge, in which the flash occurs entirely within the cloud. However, the most visible form of lightning is cloud to ground discharge which is most pertinent to human life. In CGD, the negatively charged base of the cloud induces a positive charge on the earth below wherein the clouds and the earth are act as two plates of a giant parallel plate capacitor.

18.5.2 Hydrological Disasters

18.5.2.1 Flood

Floods are among the most catastrophic natural disasters after cyclones in Sundarbans impacting several thousands of human lives and infrastructure. Flood may be triggered by high intensity rainfall, excessive runoff from the catchment, tropical storms, tidal surge from the estuary and from tsunamis. Due to low-lying and flat topography (0.9–2.11 m above mean sea level) and poor soil infiltration coupled with drainage obstruction the area is susceptible to frequent floods. However, ingression of saline ocean water causes more harm to this region than flood caused by rainfall. The high frequency flood events caused by excessive surface runoff is a major impediment to sustainable development of this region. For improvement of crisis management and to help response efforts, timely detection and monitoring of flood events is crucial.

18.5.2.2 Tsunami

Many of the convergent plate boundaries exist under the oceans, and when the epicentre of an earthquake occurs in these locations they may lead to tsunamis. As a result, the seabed may be displaced sufficiently and abrupt movement of large volumes of water may take place. Tsunami may also be triggered by landslide, volcanic activity, air pressure disturbance due to squall lines, asteroids and comets.

Tsunamis are long-wavelength waves wherein the waves can travel thousands of kilometers across open-ocean and create havoc on far shores hours after the earthquake that generated them. The speeds of tsunamis depend on the depth of the ocean. The intensity and damaging power increases with successive waves.

18.5.3 Geological Disasters

18.5.3.1 Earthquake

An earthquake is the result of a sudden release of energy in the Earth's lithosphere as a result of stress along dynamic plate boundaries that creates seismic waves. These plates can push together (compressional stress) or pulled apart (tensional stress). When the rocks slide past each other in opposite direction they generate significant frictional forces known as shear stress. When the frictional force exceeds a critical limit, a sudden failure occurs often at a zone of existing weakness with the rock called fault plane. When the failure at the fault plane results in a violent displacement of the earth's crust, the elastic strain energy is released and seismic waves are radiated, thus causing an earthquake.

18.6 Common Information Communication Technology (ICT) Used in Disaster Management

The natural disasters cannot be avoided completely but their impact can be minimized through hazard zonation, mass awareness, advance warning system at different temporal scales, disaster preparedness, ground intelligence, and policy intervention at appropriate level. The advanced suite of ICT such as Remote Sensing, Satellite Communication, Geographic Information System (GIS), Global Positioning System (GPS), etc. can help to a great deal in planning and implementation of hazard reduction measures. Considerable emphasis is now given on the implementation of information technology in operational forecasting, disaster preparedness and mitigation, which has ushered in a new era of natural disaster management. Some of the ICTs that are being used in disaster management are discussed below.

18.6.1 Internet

The internet provides a useful platform for disaster mitigation communications. It provides a new and potentially revolutionary option for the rapid, automatic and global dissemination of disaster information through public portal or through crowd sourcing. The internet sites and portals host plenty of information related to hazard proneness, historical events, list of organisations which are involved in disaster management activities along with their specific roles, precautions that are to be taken during disaster, public awareness to help in developing a learned society, etc. Several national and international organizations regularly post multi-temporal weather and meteorological information at high temporal resolution, weather forecasts, trajectory of cyclone and its probable location of landfall with ground rainfall intensity. Internet makes historic data available to public for analysis and modelling. Some of the disaster portals host crowd source data using mobile platform. In short, the internet facilitates the opportunities to enhance the capabilities of addressing hazard awareness and risk management practices before, during, and following emergency events.

18.6.2 Remote Sensing

Remote sensing is a mechanism of acquiring information about an object without being in physical contact. Satellite remote sensing can effectively contribute towards identification of vulnerable areas, monitoring the land surface processes, their changes on a real-time basis, and further giving early warning to many impending disasters. The advantage of remote sensing technique over conventional ground-based observation is that it can acquire synoptic information in a shortest possible time and in a repetitive manner. Hence, integration of space technology inputs into natural disaster monitoring and mitigation mechanisms is critical for hazard reduction. In recent past, India and Bangladesh have made great strides in the disaster alert systems through space-based information support, augmentation of observation networks, data simulation, introduction of high-performance computing system and professional training. The loss of lives during last three decades due to tropical cyclones has reduced to less than hundred as compared to thousands during the previous decades. Varieties of spaceborne sensors that use different regions of electromagnetic spectrum (e.g. optical, thermal and microwave) are judiciously being utilized to capture disaster relevant information at a given temporal and spatial scale. The geostationary and meteorological satellites orbiting at 36,000 km can revisit any point on the globe at 15–30 min intervals, making it possible to capture dynamic features like thunderstorms and cyclones. Communication satellites have become vital for providing emergency communication and taking timely relief measures. The navigation satellites also play a crucial role in location-based services, mobile-based mapping and crowd sourcing.

Besides geostationary and meteorological satellites, the low earth orbit (LEO) satellites observe the earth system processes from 600 km to 700 km altitude and bring out more detailed information of earth surface for local-level planning and implementation. Although, LEO earth observation satellites are constrained by their

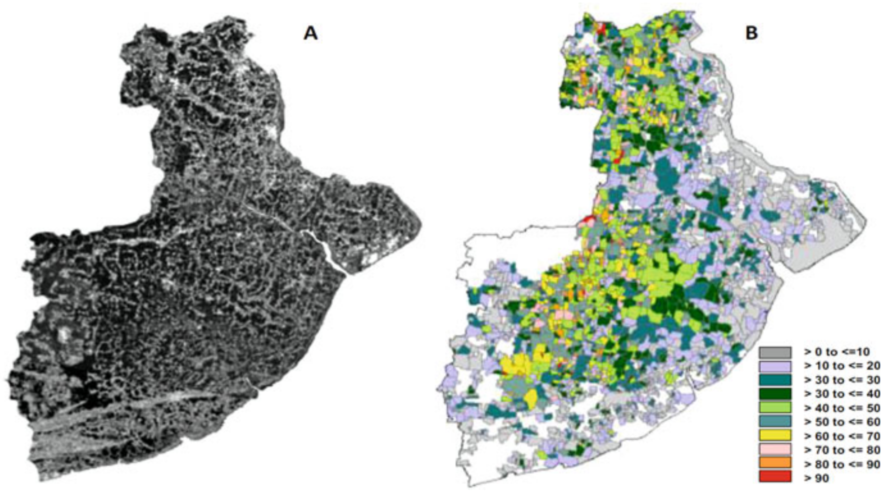

Fig. 18.4 Use of remote sensing data for inundation mapping. (**a**) Synthetic Aperture Radar data (black areas show water inundation). (**b**) Percent of village area under inundation (based on radar data and village layer). (Source: In-house data, not published)

temporal frequency requirement, the data are used for pre-disaster hazard/vulnerability mapping, post-disaster monitoring and management. During monsoon/cloud cover conditions the optical sensors are not effective but active radars (synthetic aperture radar, SAR) can penetrate through the clouds and capture the ground conditions. The extent of flood/water inundation can be precisely mapped using radar data especially during rainy season (Fig. 18.4). Under cloud-free condition high resolution optical data can be used for flood damage assessment and post-flood survey of river configuration and protection works. Based upon the natural resources information, historical data and ground-based observation, multi-hazard vulnerability map can be generated for carrying out risk analysis. The hazard vulnerability atlas may provide ready-to-use micro-level information for use by the disaster management authorities towards implementing mitigation and preventive actions.

18.6.3 Geographic Information System (GIS)

GIS provides a tool for efficient storage of historic and legacy data along with remotely sensed, other spatial and non-spatial data for scientific analysis and policy interventions. Scientific and rational decision-making needs large number of datasets to be integrated to arrive at optimal decisions and their feasible alternatives. Information received from Earth Observation (EO) satellites, navigation satellites, existing digital maps and non-spatial data in tabular format can be integrated on a common platform and analysed in GIS environment. This can improve the quality and power of analysis of

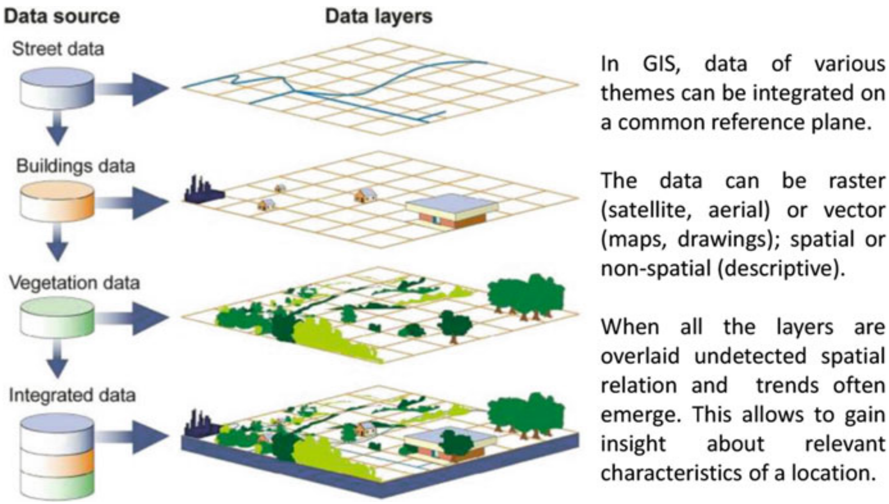

Fig. 18.5 Concept of spatial data integration in GIS. (Source: www.nationalgeographic.org/)

natural hazard assessment by taking help of contextual information (Fig. 18.5). GIS and remote sensing technology are being used for preparing seismic hazards zonation maps, micro-zonation for landslide prone areas, coastal vulnerability, risk of flood and forest fires in order to assess the exact nature of risks. As a tool, GIS can monitor the development activities and assist planners in the selection of measures and in the implementation of emergency preparedness and response action. The powerful spatial analyst tool is capable of performing various spatial analysis including multi-theme action plan generation, modelling, simulation and helps in generating various scenarios for decision planning. Besides, GIS can be used in carrying out search and rescue operations in a more effective manner by identifying areas that are disaster-prone and zoning them accordingly into risk magnitudes. Remote sensing and GIS are considered as coupled technology for data acquisition, their efficient management and analysis, especially, during disaster management.

18.6.4 Cellular Technology

Cellular phones use the ultra high frequencies, e.g. 900 MHz, 1900 MHz and 2100 MHz. In 1983, the advance mobile phone services were introduced which used 800 MHz to 900 MHz frequency band and the 30 KHz band width for each channel to enhance seamless mobile connectivity. From analogue to digital transmission of cellular technology, 2G has evolved to increase the voice capacity and limited scalability by using Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) and Global System for Mobile (GSM) technology. In comparison to FDMA, TDMA systems are able to provide 5–10 times improvement in capacity without adding new cell sites (Raith and Uddenfeldt 1991). GSM combine both TDMA and FDMA systems, which provides tele-services, bearer services and supplementary services. CDMA systems can operate with much larger interference levels because of their inherent interference-resistant properties. In this system every user is allocated with specialized unique codes and allows to transmit at the same frequency and at the same time. CDMA allows to utilize all available spectrum to support more users. Later, 3G was evolved with better and faster data connectivity and thus enable smooth mobile broad band connectivity with unlimited scalability by using CDMA, Wideband Code Division Multiple Access (WCDMA), High Speed Packet Access (HSPA), Evolution-Data Optimized (EV-DO), Time Division-Synchronous Code Division Multiple Access (TD- SCDMA) technologies. This technology supports high data rates along with high capacity to manage more end users. The 4G Long Term Evolution (LTE) is the compliment booster of 3G, using multimode network facility to provide the high speed and better data capacity for more rich content and connections.

The Ministry of Science and Technology of India has developed the world's first of its kind multilingual disaster alert system – National Disaster Information System (NDIS), that transmits tsunami and cyclone warnings as SMS through mobile phones within 30 s after receiving alert signals from India Meteorological Division (IMD), based upon information collected from weather satellites or from seismic observatories. The SMS alerts are disseminated in several languages including 14 regional languages. The SMS alerts are followed by voice alerts on the mobile phones as well as fixed phones. The NDIS server coverts the alert message received from IMD as SMS within 2 s. In the next 19 s, the software translates the alert into multiple languages and finally the SMS reaches the end-user in 30 s.

18.6.5 Satellite Radio

A satellite radio service uses satellites to broadcast its programme. In 1992, the Federal Communications Commission (FCC) allocated a satellite spectrum (the "S" band, 2.3 GHz) for the broadcasting of satellite-based digital audio radio service (DARS). As the satellites orbit the earth, programmes are beamed from broadcast stations. The satellites then transmit the signal to special antennas at homes, cars and portable radios. Terrestrial repeaters throughout the country also receive the signal and help ensure that it is transmitted to receivers, especially in areas with tall buildings that might block the signal. Satellite radio can play a key role during both the disaster warning and disaster recovery phases. Its key advantage is the ability to work even outside of areas not covered by normal radio channels. Satellite radio can also be of help when the transmission towers of the normal radio channels are damaged in a disaster.

18.6.6 Satellite Capability and Remote Sensing Applications

18.6.6.1 Optical Remote Sensing

Optical remote sensing makes use of reflected solar radiation from visible, near infrared, and shortwave-infrared regions of electromagnetic spectrum to form images of the earth's surface. Different materials reflect and absorb differently at different wavelengths resulting in characteristic spectral signatures. Optical remote sensing can be classified into 4 categories, viz. panchromatic, multispectral, superspectral and hyperspectral imaging systems. In panchromatic sensors single channel detector with broad wavelength range is used and typically produces black and white images are produced, e.g. Cartosat, IKONOS PAN, Satellite Pour I'Observation de la Terra (SPOT) High Resolution Visible (HRV) PAN. In multispectral sensors, multi-channel detectors with different spectral bands are used. Each channel is sensitive to radiation within a narrow wavelength band resulting in multilayer image that contains both the brightness and spectral information of the targets. Example of these types of sensors include Indian Remote Sensing Satellite (IRS), Landsat, SPOT, IKONOS, etc. The superspectral sensors have more number of spectral wavebands with narrower bandwidths (~ 10 nm) than the multi-spectral sensors and are capable of capturing the finer spectral characteristics of the targets, e.g. Moderate Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS). The hyperspectral image system acquires images in about a hundred or more narrow and contiguous spectral bands popularly called as imaging spectroscopy. The precise spectral information enables better characterization and identification of targets, e.g. Hyperion on EO satellite.

18.6.6.2 Thermal Remote Sensing

In thermal remote sensing, radiations emitted in the 3–14 μm wavelength region by ground objects are measured as radiant temperature which is a function of kinetic temperature and emissivity. Hence, it is complementary to other remote sensing data and help to identify surface materials and features. However, for most of the remote sensing applications 3–8 and 8–14 μm ranges are used due to absorption bands. The surface properties that affect the thermal emission depends upon albedo and emissivity of the object, i.e. capability to emit longwave radiation. Important thermal infrared sensors include Indian National Satellite System (INSAT 3D/3DR), Television Infrared Observation Satellites (TIROS), Geostationary Operational Environmental Satellite (GOES), Coastal Zone Color Scanner (CZCS), Advanced Very High Resolution Radiometer (AVHRR), Atmospheric Laboratory for Applications and Science (ATLAS), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), MODIS and Landsat-7. Thermal data are used for estimation of land surface temperature, radiation balance study, cloud top temperature, underground burning of coal mines, volcano studies, rock types, etc.

18.6.6.3 Microwave Remote Sensing

Microwave remote sensing utilizes the spectral region between 1 cm and 1 m. Relatively long wavelengths have the advantage that they can penetrate through the clouds and are independent of atmospheric scattering. Like optical sensing, microwave sensors can be either passive (non-imaging radiometers) or active (imaging SAR). The passive systems, i.e. microwave radiometers operate similarly as the thermal sensors by detecting naturally emitted microwave energy (either terrestrial or atmospheric). The passive microwave radiometers can measure the emitted spectral radiance received, called brightness temperature, which is linearly related to the kinetic temperature of the surface through emissivity. The brightness temperature (TB) is a measure of the radiance traveling upward from the top of the atmosphere to the satellite and is expressed in units of the temperature of an equivalent black body. The TBs measured at different microwave frequencies are used at remote sensing systems to derive wind, vapour, cloud liquid water, rainfall rate, soil moisture, snow water equivalent and Sea Surface Temperature (SST) products. Over the ocean, microwave emissivities of rain (0.9) and ocean (0.5) are used for estimating surface rain rate. On the other hand, over the land surface, microwave scattering by frozen hydrometeors is used as a measure of rain rate through physical or empirical models. Some of the microwave radiometers in space include Advanced Microwave Sounding Unit (AMSU), Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I), Tropical Rainfall Measuring Mission (TRMM) and Advanced Microwave Scanning Radiometer (AMSR-E).

In active radar systems the antenna transmits microwave signals towards the Earth's surface where they are backscattered and received by the receiver. The active sensors can be divided into two groups, viz. imaging and non-imaging types. Imaging radar acquires image in which each pixel contains a digital number according to the strength of the backscattered energy that is received from the ground. The energy received from each transmitted radar pulse can be expressed in terms of the physical parameters and illumination geometry. Similar to optical remote sensing, radar sensors operate with one or more wavebands. Besides amplitude, the polarization of electromagnetic wave is important in radar remote sensing. Depending upon the orientation of the transmitted and received radar wave, polarization will result in different images. Unique inference can be drawn using different polarization and wavelength combinations. In real aperture radar (RAR), spatial resolution is constrained by physical antenna size and hence the concept of SAR has been introduced. In synthetic aperture radar (SAR) synthetization is achieved by taking advantage of the forward motion of the platform. Using all the backscattered signals in which a contribution of the same object is present, a very long antenna can be synthesized. The terrain properties that affects the radar backscattering include surface roughness, complex dielectric constant, surface orientation and volume scattering. Besides amplitude and polarization, active SAR has the potential to provide accurate information about phase changes which is used for 3-dimensional mapping of the surface called interferrometric SAR (InSAR).

18.6.7 Cloud and Precipitation

Clouds have very high albedo in comparison to ground objects. Cloud albedo depends on the type, thickness and texture of the cloud. For delineation of the extent of cloud, visible images are mostly used. The optical remote sensing data from geostationary platform (e.g. INSAT 3D/3DR) can map cloud albedo consistently and reliably with high spatial and temporal resolution. Although the sensor technology varies among different sensors the commonalities include nominal resolutions of 1×1 km and 4×4 km and acquisition of images at every 30 min or 15 min interval in VNIR region. Lower layer cloud properties e.g. height, temperature, optical depth, and liquid water path are obtained from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and CloudSat data, while upper layer cloud properties are retrieved using the multilayered cloud retrieval system and validated with CALIPSO, CloudSat, MODIS and Cloud and the Earth's Radiant Energy System (CERES) observations (Yi et al. 2008). This combination of techniques provides a unique information of cloud properties and provides a strong baseline for future cloud property measurements. Recent advancement in this direction is the increase in the number of multi-instrument measurements and their interdependency. The new satellites reduce the uncertainty in cloud properties by providing self-consistency between results and have filled in the gaps between the 'conventional' clear sky and cloudy sky regimes. Normally cloud estimation is carried out using visible and thermal infrared techniques, which are indirect methods for rainfall estimation, but radar technique is more direct. The satellite-based rainfall estimation can be grouped into three types, viz. visible and infrared technique (VIS and IR), passive microwave, and active microwave technique. Different techniques for rainfall estimation are (1) Visible – Infrared, (2) Passive microwave, (3) Active microwave and (4) Multi-sensor technique.

18.6.7.1 Rainfall Products

Several gridded rainfall data products are available, generated from different satellites, at global scale and pre-defined temporal/spatial resolution grid. Normally two types of products are generated, viz. (i) high resolution product aimed at 'operational' user community requiring daily or sub-daily good spatial resolution products, and (ii) the long-term climatological datasets that necessitate greater stability, but at

Fig. 18.6 MOSDAC home page. (http://www.mosdac.gov.in)

the expense of temporal and spatial resolution. Some of the notable surface datasets include the Global Precipitation Climatology Centre (GPCC) gauge analyses, which generate monthly and daily global products using approximately 64,000 gauges. The Global Historical Climatology Network (GHCN) provides a dataset with 31,000 stations. In India, Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC) of Space Application Centre (Ahmedabad) portal (http://www.mosdac.gov.in) provides precipitation products (Fig. 18.6) at varied temporal and spatial scale using different algorithms.

18.6.7.2 Weather Radar (WR)

The ground-based weather radars can address some of the constraints of rain gauge especially by virtue of its spatial measurement rather than a point measurement. In general radar observations are very effective tool for detecting, tracking, and monitoring the growth, decay, and movement of weather systems. A weather radar transmits electromagnetic energy in the X, C and S bands through a directional antenna in all directions and in a focussed manner. A portion of the transmitted energy is absorbed by the atmosphere, some travels through the atmosphere, and a fraction of it is scattered backward by the targets and is received by the radar which is of importance for weather system analysis. The two-way travel time of the electromagnetic waves gives the range (or distance from the radar) of the target. Weather radar can detect systems upto a range of 500 km but for velocity measurements, the effective range is 250 km due to attenuation by rain and earth curvature effect. Depending upon the radar being used, it is also possible to estimate or measure the number of droplets present, their sizes, form (water or ice), speed of the target towards or away from the radar, as well as spectrum width, which indicates the wind shear and turbulence in the atmosphere.

The advanced Doppler Weather Radars (DWR) employ Doppler principle to provide information about the speed and direction of the moving objects. Doppler Radars compares the frequency of transmitted and received signals and compute the difference in frequency. When the source and the observer are in relative motion, there is change in the observed frequency (wavelength). The frequency increases when the source and the observer are moving closer and vice versa. One of the major advantages of Doppler radar is real time weather monitoring, understanding about the structure of thunderstorms, cyclones, and other precipitating cloud systems. One disadvantage is that the backscatter radiation is dependent upon the drop size distribution, which can vary considerably across the range of precipitation regimes. Moreover, range effect may induce undetected precipitation. Hence, radar data should be used with much care as signal is influenced by atmosphere, earth curvature, blockage of radar beam by permanent structures, radar resolution, etc. which may lead to erroneous conclusions. IMD has installed 33 weather radars across the country for real time information and monitoring of severe weather systems out of which 22 are Doppler radars (Fig. 18.7) (www.imd.gov.in).

18.6.8 Flood Assessment

Satellite data has been an integral part of all the phases of flood management. In the *preparedness phase* detailed risk mapping can be performed using time series space-

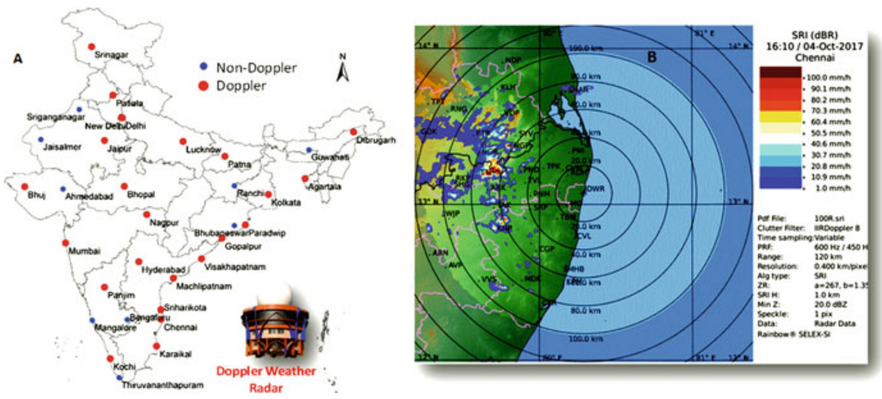

Fig. 18.7 (**a**) Location of the IMD weather radars. (**b**) Surface rainfall intensity map from weather radar. (www.imd.gov.in)

based inputs which contribute towards hazard and vulnerability assessment. Different flood condition factors, viz. slope, distance to channels, drainage, texture, geology, and land cover can be used in conjunction with distributed hydrological models and can serve as a supplement to *in situ* observations which is also cost-effective. Development and implementation of distributed hydrological models can fully exploit remotely sensed data towards forecasting and simulation of stream flow (Leconte and Pultz 1990; Jobin and Pultz 1996). Implementation of a flood predicting system can potentially help mitigate flood-induced hazards.

In the *flood prevention phase* services of meteorological satellites are used to detect various aspects of hydrological cycle, especially cloud type, precipitation rate, moisture transport, and surface soil wetness (Scofield and Achutuni 1996). Monitoring of intensity, movement, and propagation of the precipitation system in near real time using NOAA AVHRR and 'Nowcasting' for next 3 h has been demonstrated (Domenikiotis et al. 2003). As a vital input to runoff modelling soil wetness derived from AMSR-E can provide distributed spatial information. Medium to high resolution satellite data, viz. Landsat, IRS, SPOT, etc. is operationally being used to determine flood extent under cloud-free sky condition. The precipitable water (PW) products are generated operationally for assessing the state of the atmosphere and moisture transport from combination of GOES, SSM/I and model data (Scofield et al. 1995, 1996). Model predictions of potential flood extent can help emergency managers to develop contingency plans well in advance of an actual event to help facilitate a more efficient and effective response. Quantitative Precipitation Estimates (QPE) and Forecasts (QPF) use satellite data as a source of information to facilitate flood forecasts. A substantial improvement in rainfall spatial distribution has been achieved by integrating radar, rain gauges and remote sensing techniques to improve real time flood forecasting (Vicente et al. 1998). Wave run-up simulations can help planners to determine the degree of coastal inundation to be expected under different user-specified storm conditions.

In the *response phase*, also called relief phase, damage assessment is carried out using satellite data. The medium resolution data can establish the extent of flood damages, whereas the high-resolution data are suitable for pinpointing the location and degree of damages. Indian remote sensing data from geostationary platform (INSAT 3D/3DR) provide rapid information on cloud characteristics. The SAR data from Scatsat-1 are used for flood situation over Indian sub-continent. Merging of backscattering and brightness temperature data can help to delineate the flooded, partially submerged area, and also the soil wetness.

18.6.9 Cyclone Tracking

The formation, growth and intensity of the depression till its conversion to tropical cyclone can be monitored at short time intervals (15–30 min) using images acquired from weather satellites positioned at geostationary orbit. The appearance of a well-formed eye is a definite indicator of where the storm is located. In absence of an eye, it is still possible to obtain a reasonable estimate of the centre location by tracing the spiral rainbands of the storm or by studying the relative motion of cloud features near its centre. A similar approach can be used to locate the centre of a tropical cyclone if it comes within the effective range of the weather radar of a land station. Tropical cyclone track forecasting relies on interpretation of past and current weather situations and requires skill and experience on the part of the forecasters. Climatology and statistics are used for forecasting the track of a tropical cyclone. The end products are normally some kind of average, probability, extrapolation, nomograms, or correlation formulae. Apart from the behaviour of the storm itself, these methods can also provide helpful indications to the probable local wind and weather conditions. The science of tropical cyclone forecasting is by no means perfect. The multitude of contributing factors are so complex that they are as yet not entirely understood in various forecast schemes. The volatile nature of tropical cyclones, with their inherent fluctuation in both motion and intensity, is also partly responsible. Further uncertainty arises from the problem of identifying the initial position of the tropical cyclone, which many experts regard as a major source of error in forecasting. Some of the cyclones do not even have spiral bandings to give clues to the possible circulation centre. In poorly organized storms, there can be strong asymmetry and irregularity in the horizontal structure as well as distortion in the vertical alignment.

Using space-based input and appropriate models ISRO is supporting the efforts of India Meteorological Department to predict the tropical cyclone track intensity and landfall. These experimental track predictions are regularly posted on Space Application Centre (ISRO) web portal (http://www.mosdac.gov.in/scorpio/). Using the wind pattern generated by the Oceansat-2 Scatterometer, data models have been developed for predicting the formation of a cyclone even before the depression turns into a cyclone.

18.6.10 Lightning Detection

Besides ground-based system, lightning detection sensors are also available onboard several earth orbiting satellites. The satellite sensors detect the light scattered by the volume of cloud that produces the lightning, and hence its location accuracy cannot be better than 10 km which is equivalent to the diameter of thunderstorm cloud. Additionally, satellite-based sensors cannot distinguish between cloud and ground discharges. The Optical Transient Detector (OTD) aboard the OrbView-1 satellite, launched on April 3, 1995, and the subsequent Lightning Imaging Sensor (LIS) aboard TRMM, launched on November 28, 1997 are the two mostly used satellite sensor for lightning detection.

18.7 Framework for Disaster Management

Disaster management includes several vital activities to take control over the disaster and provide a framework to help, avoid or recover from their impact. The integral components of disaster management include prevention, mitigation, preparedness, response, recovery and rehabilitation. In this endeavour, governmental, non-governmental, and community-based organisations – all play crucial role before, during and after disaster. Pre-disaster planning, vulnerability zonation, organizational planning, training/awareness, information dissemination, emergency management, and preparedness play crucial role before the occurrence of the disaster. As a cyclic process (Fig. 18.8) the key phases are as follows:

18.7.1 Mitigation

It includes any activity that prevents a disaster, reduce or eliminate the impacts and risks of hazards through proactive measures taken before and after the disaster in order to reduce the loss of life and property. Effective mitigation requires understanding the local risks, address the hard choices, and invest in long-term community well-being. Mitigation strategies address prevention, property protection, natural resource protection, structural projects, emergency services, public education and awareness. Mitigation goals include (i) developing plans and studies that will support the implementation of techniques which will aid in the mitigation of natural

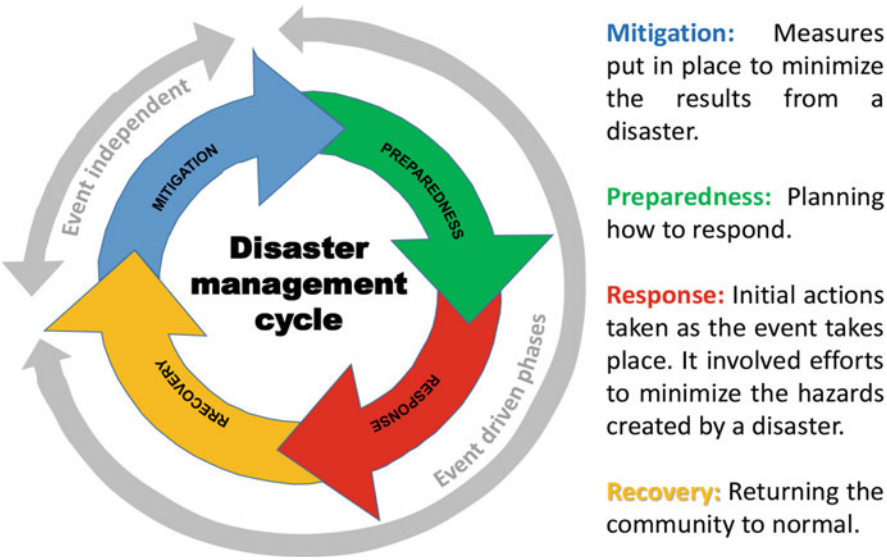

Fig. 18.8 Different phases of disaster management. (Source: Blaikie et al. 2004)

hazards in the region, (ii) conduct public education, outreach and awareness programmes to help local citizens better understand hazard mitigation, and ways to protect lives and property from the impact of natural hazards, (iii) to undertake cost-beneficial structural projects across the region that will be beneficial to reducing the impact of natural hazards when they occur, and (iv) implement sound hazard mitigation policies into the framework of local government operations across the region.

18.7.2 Preparedness

Preparedness includes plans or preparations that is made to reduce the effects of disasters, save lives or property, and help the response and rescue service operations. In other words, preparedness refers to a research-based set of actions that are taken as precautionary measures in the advent of potential disasters. The actions include both physical preparations (e.g. emergency supplies, cyclone shelters, and so on) and trainings for emergency action. In general preparedness measures include generation of plan, emergency exercises/training, warning systems, emergency communications systems, evacuation plans and training, resources inventory, personal/contact list, mutual aid agreements, and public information/education. Preparedness has both short and long-term perspectives. In short-term plan the components are capacity building, education and training, community-based disaster management, and networking/awareness. In mid-term plan major work components include (i) creation of core group of master trainers at district level, (ii) strengthening public-private partnership in research and development, and (iii) formation of national resources inventory and distance learning courses for sensitization across various stakeholders.

18.7.3 Response

This phase includes actions taken to save lives and prevent property damage, and to preserve the environment during emergencies or disasters. The aim of emergency response is to provide immediate assistance to maintain life, improve health, and support the morale of the affected population. It consists of a number of elements, e.g. warning/evacuation, search and rescue, providing immediate assistance, assessing damage, continuing assistance, and the immediate restoration of infrastructure. The focus in the response phase is on meeting the basic needs of the people until more permanent and sustainable solutions can be found. The main responsibility to address these needs and response to a disaster lies with the government or the administrative body in whose territory the disaster has occurred. In addition, humanitarian organizations are often strongly present in this phase of the disaster management cycle.

18.7.4 Recovery

It is the fourth phase of disaster wherein actions are taken for restoration of all aspects of the disaster's impact on a community and the return of the local economy to a sense of normalcy after a disaster. The recovery phase of disaster can be divided into two parts, viz. (i) short-term phase which typically lasts from 6 months to at least 1 year, and involves delivering immediate services, and (ii) long-term phase, which can range up to decades, requires thoughtful strategic planning and action to address more serious or permanent impacts of a disaster. Investment in economic development and capacity building becomes essential to foster economic diversification, attain new resources, build new partnerships, and implement effective recovery strategies and tactics. Communities must access and deploy a range of public and private resources to enable long-term economic recovery. However, all these four phases usually overlap.

18.8 Early Warning System (EWS) towards Disaster Forecasting

The objective of early warning systems is to empower individuals and communities threatened by hazards to act in advance and in an appropriate manner to reduce the possibility of personal injury, loss of life, and damage to property and the environment (United Nations International Strategy for Disaster Reduction, UN-ISDR 2006). Four pre-requisites for effective early warning system include (i) communication and dissemination systems tailored to the needs to individual communities, (ii) warning communication technologies to reach the entire population, (iii) procurement of appropriate instrument, and (iv) multiple communication mechanism for warning dissemination. A EWS system follows a distributed architecture in which communication infrastructure forms the backbone, viz. internet, sensor communication, as well as, satellite communication. Design and implementation of a communication system that employs multiple communication channels, i.e. both terrestrial and satellite communication link, to connect the sensors to the central warning centre and to ensure that maximum number of persons receive the warning message. The message being communicated has to be clear and simple with useful information and geographically specific to ensure that warning is targeted to those at risk only (UN-ISDR 2006).

Several international organisations do provide disaster warning forecast. Some of the major organisations are given below.

- *The Indian Tsunami Early Warning System (ITEWS, India)* has the responsibility to provide tsunami advisories to Indian Mainland and the Island regions. Acting as one of the Regional Tsunami Advisory service Providers (RTSPs) for the

Indian Ocean Region, ITEWS also provides tsunami advisories to the Indian Ocean rim countries along with Australia & Indonesia.

- *National Remote Sensing Centre (Hyderabad, India*): The Centre is responsible for remote sensing satellite data acquisition and processing, value addition, dissemination of information, low altitude aerial survey, and decision- support for disaster management. The National Database for Emergency Management (NDEM) hosted at NRSC is conceived as a GIS based repository of data to support disaster/emergency management in India. The database enables development of decision support system in the form of customized user interface with necessary security mechanism.
- *Space Application Centre (Ahmedabad, India*): Using appropriate models and satellite data, SAC is supporting the efforts of India Meteorological Department (IMD) to predict the tropical cyclone track, intensity and landfall. Satellite observations are used to continuously monitor cyclogenesis over North Indian Ocean.The information generated are regularly posted on web portal (http://www.mosdac.gov.in/scorpio/).
- *International Research Institute for Climate Prediction (IRICP, Columbia University, USA):* The organisation performs seasonal climate forecast from a variety of climate prediction tools, including dynamical models of the atmosphere, statistical models of climate variability related to sea surface temperature variability and knowledge of the current state of the climate system.
- *Interactive Weather Information Network (IWIN, NOAA-USA):* It obtains raw data from a telecommunications gateway, satellite and other multi-layered redundant links.
- *Cooperative Institute for Meteorological Satellite Studies (University of Wisconsin-Madison, USA)* : Repository of satellite derived winds and analyses of storm related data.
- *National Hurricane Centre (Florida International University, NOAA, USA):* The mission is to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts, and analyses of hazardous tropical weather for increasing understanding of these hazards.
- *Canadian Hurricane Centre (Canada):* Provides information on genesis, and sequences along with precautions to be taken for the Hurricanes.
- *Hurricane and Tropical Storm Info, Southern Regional Climate Centre, Louisiana State University (USA)*: Provides latest data of tropical storm imagery, observations, satellite data, and predictions based on the trajectory.
- *Hurricane Hunters Association (Department of Defence USA):* Flying aircraft into the eye of cyclone since 1944.
- *National Weather Service (USA)*: The National Weather Service (NWS) is an agency of the United States federal government that is tasked with providing weather forecasts, warnings of hazardous weather, and other weather-related products to organizations and the public for the purposes of protection, safety, and general information. It is a part of the National Oceanic and Atmospheric Administration (NOAA).

- *Purdue University Hurricane and Tropical Data (USA)*: Provides access to a wealth of Hurricane information including charts on the track of the storm plus a text-based table of tracking information. The information includes geographic location, maximum sustained wind speed and centre pressure in millibar.
- *World Wide Earthquake Locator (WWEL, University of Edinburgh, UK):* Develops earthquake analysis system using dynamically obtained data over the internet.
- *World Earthquake Information from USGS National Earthquake Information Centre (USGS-NEIC, USA,):* Repository of World Data Centre for Earthquake Information and Observation station.
- *European Mediterranean Seismological Centre (EMSC, France):* Earthquake Alert System for potentially damaging earthquakes in the Euro-Med region which consists of the rapid determination of the epicentre and the dissemination of the seismic alert message within the hour following the occurrence of the earthquake.

18.9 Sundarbans Case Studies

18.9.1 Satellite-Based Assessment of Ecological Disturbance in Sundarbans

Sundarbans are prone to frequent natural disasters which cause considerable degradation to natural ecosystem. As the area is protected and often inaccessible, it is difficult to assess the biodiversity loss and disturbance caused by natural disasters, especially cyclones and floods, by conventional means. Periodic and reliable estimation of disturbance regime to this fragile ecosystem is a must for better forest management plan. Earth observation satellite remote sensing helps in tracking changes in mangrove ecosystem and can assess performance (Kerr and Ostrovsky 2003). MODIS sensor onboard Earth Observation satellites like Terra/Aqua is capable of synoptic viewing of inaccessible and protected areas for monitoring land surface processes with high temporal resolution. Mildrexler et al. (2009) proposed an index called MODIS Global Disturbance Index (MGDI) for assessment of large scale ecological disturbance in woody ecosystem of North America. The concept of MGDI is based upon the fact that surface temperature decreases with an increase in vegetation density (Nemani and Running 1989). Besides, the two input variables, viz. land surface temperature (LST) from thermal sensor and enhanced vegetation index (EVI) from optical sensor respond to different biophysical processes, thereby enriching the information content of indices (Lambin and Ehrlich 1995). MGDI approach can be used to assess the instantaneous ecological disturbance caused by cyclones of different intensities striking the mangrove at different phenological stages. The time-series satellite data, pre- and post-disturbance, can be utilized to develop the MGDI-based thresholds for disturbed area identification and island-wise disturbance intensity maps to aid in forest management. The instantaneous disturbance caused by cyclone can be calculated using MGDI, the formula of which is given below:

$$\mathrm{MGDI_{inst}} = \frac{\left(\mathrm{LST_{max}}/\mathrm{EVI_{max-post}}\right)_{\mathrm{current\ year(y)}}}{\left(\mathrm{LST_{max}}/\mathrm{EVI_{max-post}}\right)_{\mathrm{multi-year\ mean\ (y-1)}}} \tag{18.1}$$

where, LST_{max} is the maximum value of LST (°C) for each pixel in a given year, $EVI_{max\text{-}post}$ is the maximum value of EVI following the LST_{max} within the same year, current year (y) is the year being evaluated for disturbance, and multi-year mean ($y - 1$) is the mean value considering all the years together excluding the current year. Enhanced vegetation index (EVI) used in MGDI enables improved sensitivity under high biomass condition by effectively de-coupling the canopy background signal and reducing atmospheric influences. The equation for computing EVI is given below:

$$\mathrm{EVI} = \frac{G \times (R_{\mathrm{NIR}} - R_{\mathrm{RED}})}{(R_{\mathrm{NIR}} + C_1 R_{\mathrm{RED}} - C_2 R_{\mathrm{BLUE}} + L)} \tag{18.2}$$

where, R_{NIR} and R_{RED} are atmospherically corrected surface reflectance in the near-infrared and red bands, L is the canopy background adjustment that addresses non-linear, differential NIR and red radiant transfer through a canopy, and C_1, C_2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band. It is critical to determine the threshold value for discriminating the disturbed areas caused by natural calamities. To achieve this the time-series MGDI values are converted to the '% change in MGDI' (% $MGDI_{change}$) in order to normalize the data at spatio-temporal scale. The % change in instantaneous MGDI for each pixel was calculated using the Eq. 18.3,

$$\%\mathrm{change\ in\ MGDI_{current\ year(y)}} = \frac{\mathrm{MGDI_{current\ year(y)}}}{\mathrm{Multi-year\ mean\ MGDI_{(y-1)}}} \times 100 \tag{18.3}$$

In the second step, threshold is decided by comparing spatially varying 'percent change MGDI' image with surface manifestation on high-resolution multi-spectral data co-located in time and space both before and after the cyclones. Cyclone affected pixels in the high-resolution data are identified and the corresponding values of the $\%MGDI_{change}$ are extracted to generate cluster mean values. The inter-cluster mean value plus one standard deviation (to consider the inter-cluster and intra-cluster variability) of the $\%MGDI_{change}$ is generally considered to be the threshold for discrimination of the disturbed pixels to accommodate spatial variability within different parts of the Sundarbans. However, it may vary depending upon the region and type of disturbance. The pixels having $\%MGDI_{change}$ greater than the given threshold of the temporal mean is considered as the disturbed pixels. Finally, the

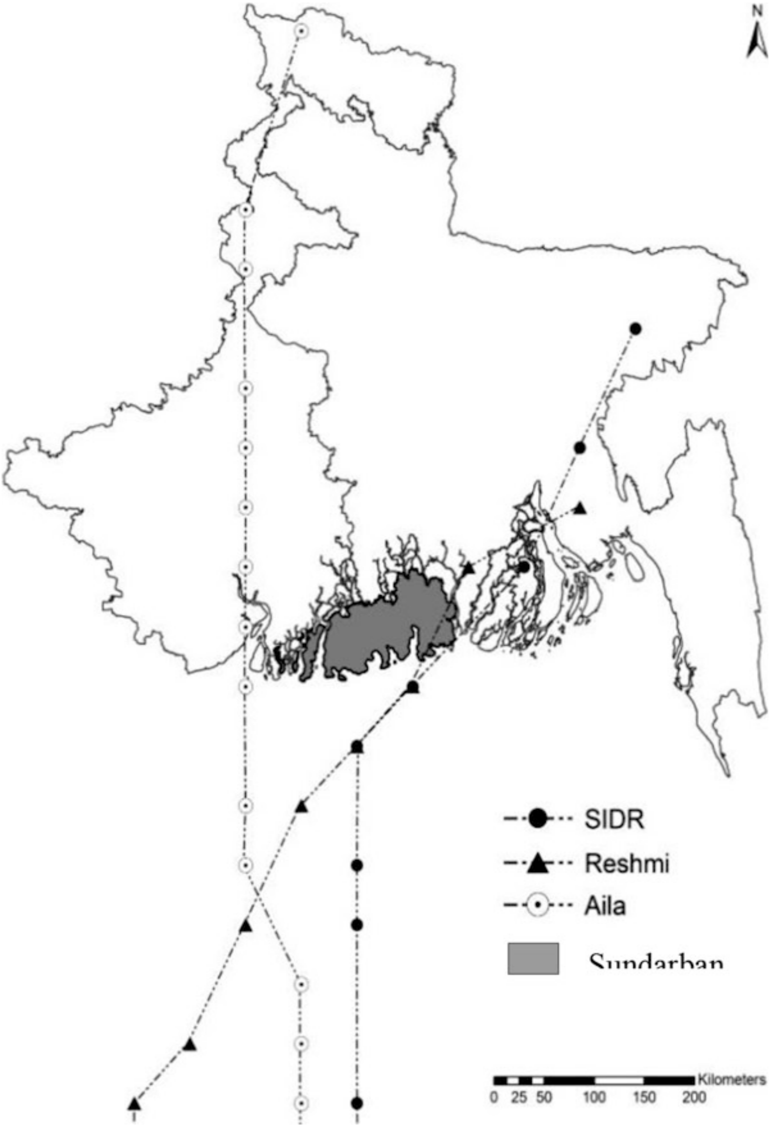

Fig. 18.9 Trajectory of the cyclones. (Source: Dutta et al. 2015)

percentage of disturbed area under each of the islands are computed and mapped to generate actionable output.

Ecological disturbance caused by SIDR (2007), Rashmi (2008) and Aila (2009) were studied by Dutta et al. (2015) using satellite data. The SIDR made landfall at the extreme south-east of Bangladesh Sundarbans (Fig. 18.9). A large decrease in the EVI was observed during post-cyclone period but not captured in the $EVI_{max\text{-}post}$, as at the time of SIDR the mangrove vegetation was almost at the helm of peak growth (EVI > 0.7). Hence the MGDI could not capture the post-cyclone ecological disturbance during 2007.

The 'Rashmi' had landfall at the southern part of Bangladesh. Overall the % $MGDI_{change}$ was less, except in eastern part of the Sundarbans (Bangladesh) where very high %$MGDI_{change}$ (>15) was recorded. It was interesting to notice that similar spatial pattern was observed in the %EVI_{change} caused by the cyclone 'SIDR' in the 2007. The MGDI during 2007 was unable to capture the impact of SIDR, whereas it was apparent in case of 'Rashmi' (2008), as a result of reduced vegetation vigour and increased surface temperature in the post SIDR period, i.e. 2008.

The Aila super-cyclone caused extensive damage and inundation in both India and Bangladesh portion of Sundarbans. Due to sustained high velocity, about 6.1 m high tidal surges lashed the Sundarbans forest which remained submerged under 2.4 m water for several days. Analysis of satellite derived EVI time composite pre- and post-cyclone data depict that almost entire Sundarbans region was affected by 'Aila' except in few pockets (Fig. 18.10c). Unlike other two preceding cyclones, i.e. 'SIDR' and 'Rashmi' (Fig. 18.10a, b), the impact was not geographically confined to any specific region, but appeared to be uniformly distributed throughout the study area, signifying widespread impact of 'Aila' over mangrove ecosystem. The impact of 'Aila' on the mangrove ecosystem was clearly evident by the increased values of MGDI, distributed across the whole Sundarbans region (Fig. 18.10c). The % MGDI change values varied between 0% and 20%, based upon the severity of the damage. As the occurrence of 'Aila' was during the fall season of the mangrove, the negative changes of the EVI in post- 'Aila' period can be considered as combined effect of cyclone and normal phenological changes of mangrove. Unlike 'SIDR' and 'Rashmi', the 'Aila' occurred during the mid of the year coinciding with the highest surface temperature whereas peak vegetation vigour was achieved in the post-cyclonic period only. Hence the MGDI during 2009 could successfully capture the disturbance regime of the Sundarbans caused by 'Aila'.

The island-wise percent disturbed area is given in Fig. 18.11a–c, where the extent of disturbance is mostly between 10% and 30%. However, in some of the islands the % disturbed area is as high as 60–80% (Fig. 18.11a–c).

18.9.2 Changes in the Land Mass of Sundarbans: Remote Sensing Perspective

With the advent and operationalization of high-resolution earth observation satellites spatially explicit information about deforestation and degradation of the mangrove forest of Sundarbans (Koedsin and Vaiphasa 2013) is possible to obtain. Several studies have been carried out in Sundarbans using satellite remote sensing data (Giri et al. 2007; Islam et al. 1997; Dwivedi et al. 1999; Blasco et al. 2001; Nayak et al. 2001) on mapping of

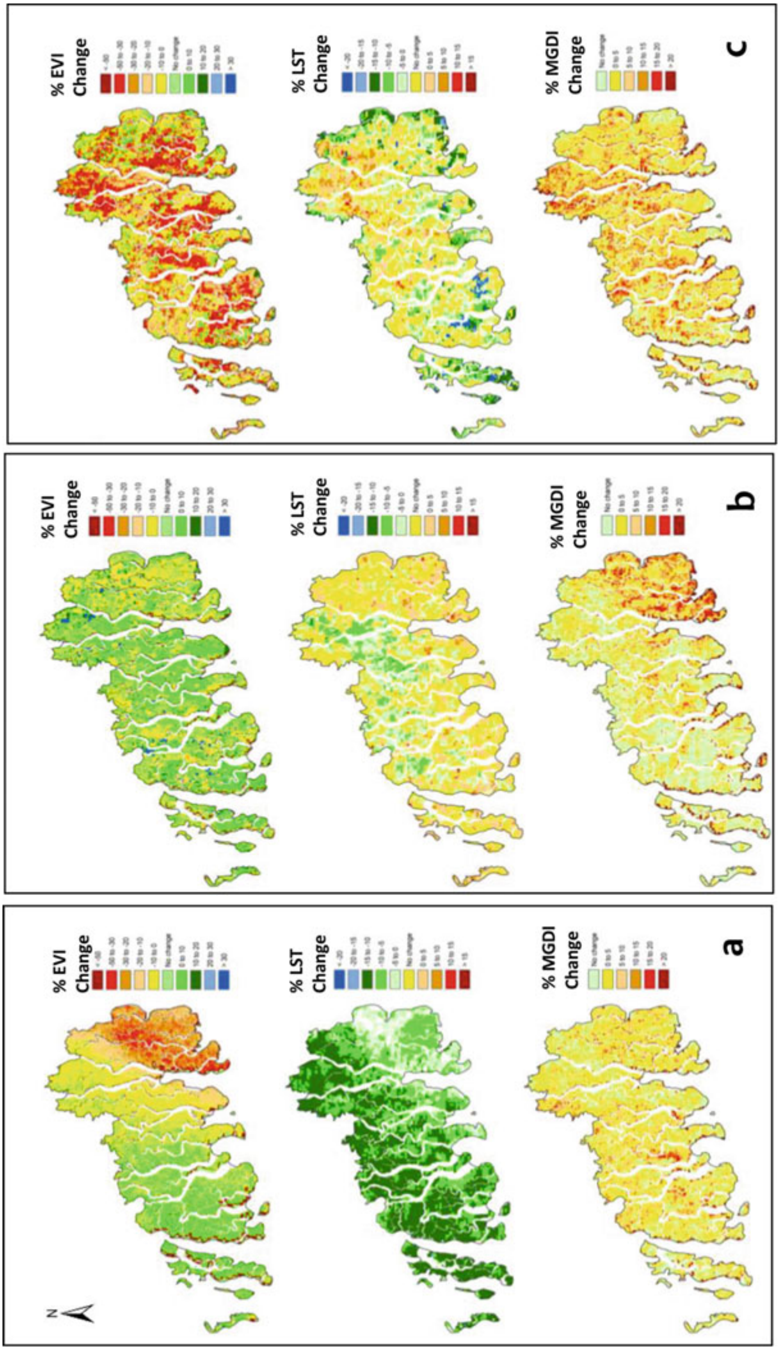

Fig. 18.10 Percent change in EVI, LST and MGDI in (**a**) SiDR (**b**) Rashmi and (**c**) Aila. (Source: Dutta et al. 2015)

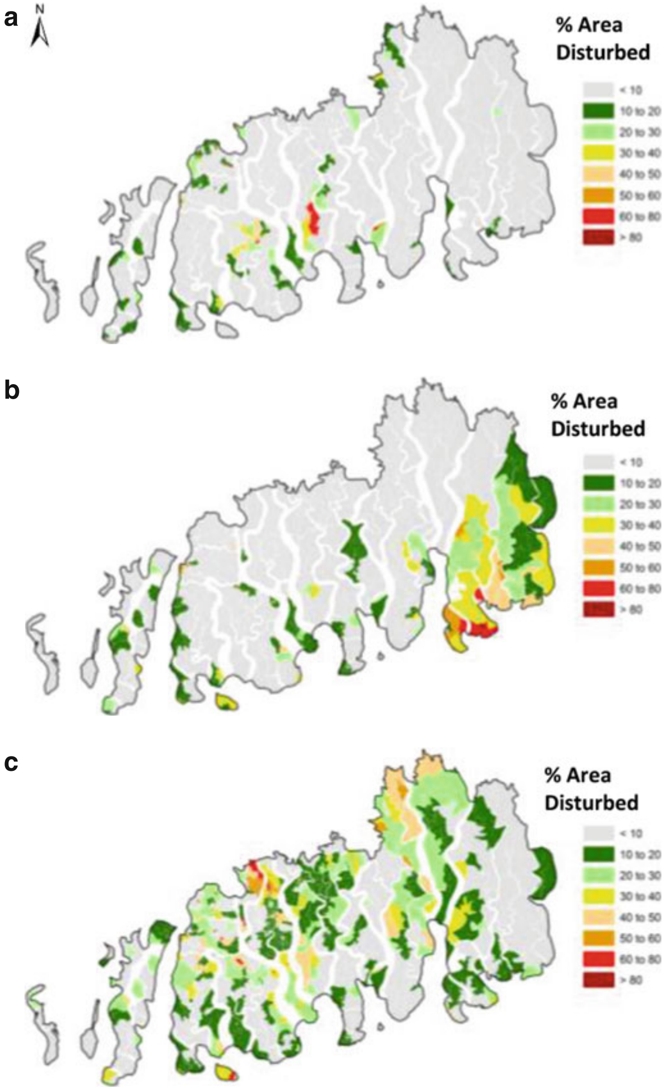

Fig. 18.11 Percent disturbed area of the islands (**a**) SiDR (**b**) Rashmi and (**c**) Aila. (Source: Dutta et al. 2015)

mangrove areas, but most of them are lacking a holistic view of the whole forest and limited to either Indian or Bangladesh Sundarbans. Studies reveal that in Indian Sundarbans region erosion and accretion occur almost simultaneously (Raha et al. 2012). The western part of Indian Sundarbans exhibits more erosion compared to deposition, which is reverse in case of central part of Indian Sundarbans. The net result, however, is inclined towards erosion as the total area eroded is almost 283.58 km^2, whereas total area of accretion is 83.97 km^2 (Ganguly et al. 2006). The phenomena of erosion and accretion are largely regulated by littoral current pattern and sediment influx from different rivers and adjacent Bay of Bengal. Severe bank erosion in southern tips of Sagar Island and Jambu Island is due to high flood velocity and meandering nature of the river course. Along the Sundarbans coastline, retreat is evident everywhere, but large areas of erosion have been observed in south and south-eastern parts. In contrast small islands are forming at the mouth of Baleshwar, Bhanba and Haringhata rivers. The highest coastal erosion was observed around the Mayadwip, Bulcherry and Bhangaduani Islands (Giri et al. 2014). Besides erosion land aggradation is also taking place to partly offset a large part of the erosion loss. Giri et al. (2014) has reported that approximately half of the mangrove forest was lost at the extreme southern edge of the Sundarbans where almost no compensating aggradation took place. Their study revealed about 13.27% of mangrove was lost in 1990 with respect to 1970s and also the mangrove receded by 1 km to the east by 2000. Only a ring of mangrove at the shoreline remained. Zilla forest area was almost degraded in 1975 but got re-vegetated by 1989.

Several studies carried out at Bangladesh reveals that 85 km^2 of land is lost over 20 year and about 200 km^2 over 70 years (Rahman 2012). Recent study using Landsat data over 2000–2014 reported that net total erosion of 48.56 km^2 and 93.5 km^2 for Bangladesh Sundarbans (BS) and entire Sundarbans, respectively. The erosion-accretion scenario of 4 islands of Bangladesh Sundarbans, viz. Bhola, Hatiya, Sandwip and Manpura along with Bangladesh Sundarbans between 1960 and 1984 was analyzed by SPARRSO (1987). All the islands showed significant erosion and less accretion with highest value of erosion for Bhola island (360.76 km^2) and lowest for Manpura island (99.30 km^2). Siddiqui (1988) carried out land mass change studies over different islands of Bangladesh in two spells from 1940–1963 to 1963–1982, wherein it was reported that the erosion at the northern tip of Hatiya Island is at the rate of 400 m $year^{-1}$ during 1963–1982, however during 1940–1963 the landmass remained stable. According to Sarwar and Woodroffe (2013), Hatiya is one of the rapidly changing islands especially at its northern end. Between 1989 and 2009, the net land loss was 15 km^2, with 65.9 km^2 erosion and 50.9 km^2 accretion. During the same period, Kudubdia island decreased to 68.7 km^2 from 72.9 km^2. The land loss at Manpura island was reported to be 20 km^2, however, Sandwip island gained 12.3 km^2 of land.

It is apparent from the literature that most of the change studies were carried out separately for the Indian and Bangladesh part of the Sundarbans, although there was lack of consolidated study using remote sensing data of similar sensors. Towards a holistic assessment time series Landsat MSS, TM, OLI data of winter season for the period of 1973 to 2017 and Army Map Service (1951) were used for change dynamics of integrated Sundarbans.

The change study was carried out separately for the main landmass of Sundarbans and the islands located in the Hooghly estuary and north of Bay of Bengal. For clarity the Sundarbans region has been presented in 3 parts, zone 1 covers exclusively the Indian Sundarbans, zone 2 is comprised of both Indian and Bangladesh Sundarbans, and zone 3 is exclusively the Bangladesh Sundarbans. Overall changes in the landmass over the years is given in Table 18.1 and Fig. 18.12.

Table 18.1 Changes in the area of landmass in Sundarbans

Year	Zone 1 (km^2)	Zone 2 (km^2)	Zone 3 (km^2)	Total area (km^2)
1973	1408.85	2837.37	3097.61	7343.83
1979	1345.95 (−4.46)	2816.13 (−9.75)	3102.08 (0.14)	7264.16 (−1.08)
1989	1366.05 (−3.04)	2686.29 (−5.32)	3041.25 (−1.82)	7093.58 (−3.41)
1999	1447.54 (2.75)	2736.46 (−3.56)	3040.93 (−1.83)	7224.93 (−1.62)
2010	1401.53 (−0.52)	2648.82 (−6.65)	3023.89 (−2.38)	7074.23 (−3.67)
2017	1361.19 (−3.38)	2580.70 (−9.05)	3071.82 (−0.83)	7013.71 (−4.50)

Source: In-house study
Figure in the parenthesis represents % change with respect to 1973

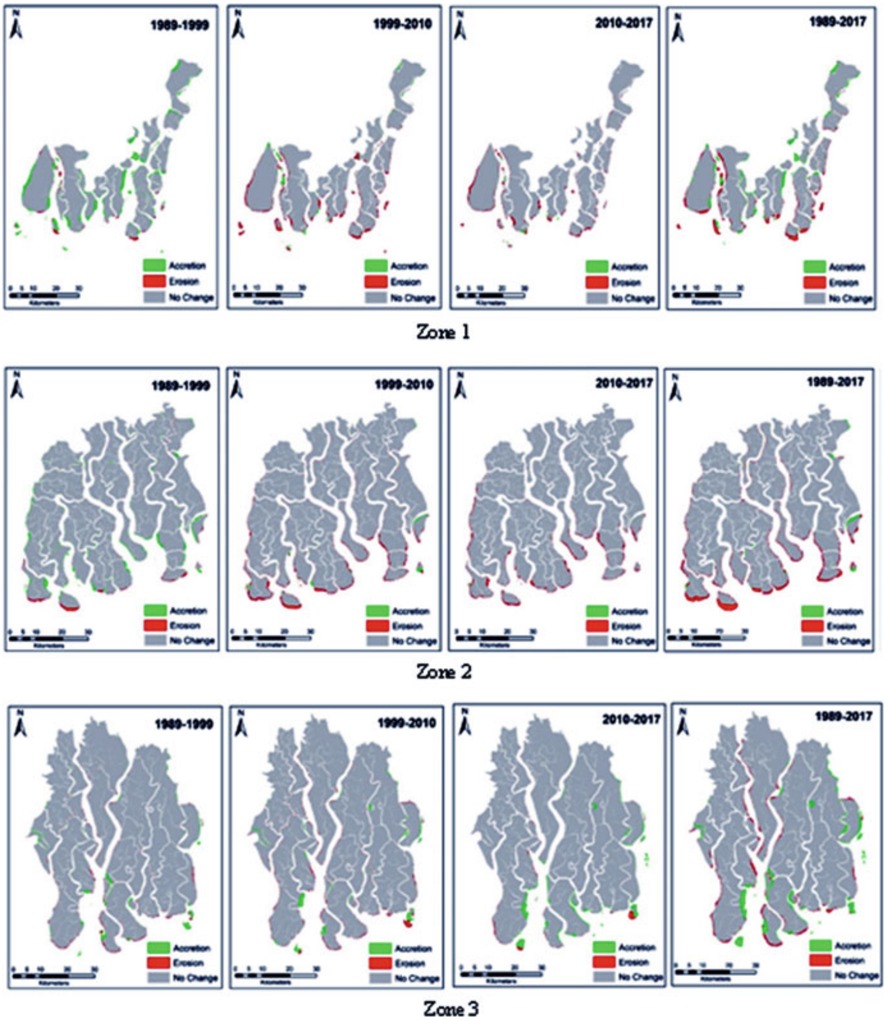

Fig. 18.12 Erosion and accretion over the years. (Source: In house production, not published)

From Table 18.1 there is overall decrease in the landmass between 1973 and 2017 to the order of 329.45 km^2 @ 7.48 km^2 $year^{-1}$. Most of the erosion took place in zone 2 (consists of both Indian and Bangladesh portion), where the land loss was 256.67 km^2, and minimum was found in zone 3 (Bangladesh Sundarbans). The rate of erosion is highly variable over the observation years (Table 18.1) and varies between 1.62% (between 1999 and 1973) and 4.50% (between 2017 and 1973). The rate of erosion is consistently higher since 2010 in zone 1 and 2 but significantly less in zone 3. Both the process of accretion and erosion is active in the coastal region but there is a net loss of land since 1999, except during 1989–1999, when there was gain of 98.05 km^2. The overall erosion/accretion of the Sundarbans land mass at different temporal intervals and their rate is given in Annex Table 3.

Ten of the islands located in the Indian part of Sundarbans were also analysed for temporal changes (Table 18.2). Among all the islands studied, Sagar is the largest one (24,743.5 ha) and Kankramari is the smallest (210.8 ha). Large variability in the rate of erosion was also observed among the islands ranging from 1.21 ha $year^{-1}$ in Putni island to 48.50 ha $year^{-1}$ in Bangaduni island between 1973 and 2017. Based upon the net loss of landmass the islands can be classified into 4 categories, viz. low (<10 ha $year^{-1}$, including Kankramari, Sikarpur and Putni island), medium (between 10 and 20 ha $year^{-1}$, including Ghoramara, Jambudwip and Mahisani), high (between 20 and 30 ha $year^{-1}$, including Sagar and Bucherry), and very high (>30 ha $year^{-1}$, including Dalhausi and Bangaduni) (Table 18.2). The changes in the landmass boundaries of the islands is given in Fig. 18.13. The temporal change of landmass of the mainland and all the zones show cyclic pattern (Fig. 18.14) especially for the zones 1 and 2. For zone 1 the difference between maxima and minima is 19 years, whereas for zone 1, it is 14 years. Considering all the zones the observed periodicity is 15 years.

18.10 Conclusion

The vulnerability of the mangrove habitation has increased due to anthropogenic interventions caused by ever increasing population pressure compounded with climate change. Although the disaster cannot be averted completely the impact and loss of life can be minimized by effective implementation of frontier technologies like Information Communication Technology (ICT) through advance warning, last mile communication, preparedness, monitoring, and damage assessment. The advanced suite of ICT such as Remote Sensing, Satellite Communication, Geographic Information System (GIS), location-based services using Global Positioning System (GPS), etc. can help to a great deal in hazard vulnerability analysis, forewarning, preparedness and post-disaster monitoring.

The internet has enabled wider access of information related to advance weather forecasting and bulletin, warning messages, hosting crowd source data using mobile applications, and many more. Satellite data products are used in pre-disaster planning, which includes vulnerability zonation. In the flood prevention phase services of meteorological satellites can be used to detect various aspects of hydrological

Table 18.2 Changes in the area of the islands over the years

Island/year	1973	1979	1989	1999	2010	2017	Change (1973~2017)	Av rate of change (ha/year)
Ghoramara	875.5	757.7	643.2	570.2	481.7	400.8	−474.7	−10.79
Sagar	24,743.5	23,694.7	24,025.8	25,029.0	24,705.8	23,747.9	−995.6	−22.63
Jambudwip	1063.3	828.9	780.3	960.3	584.5	444.5	−618.8	−14.06
Kankramari	210.8	154.2	95.7	77.4	29.9	13.3	−197.5	−4.49
Mahisani	3399.2	3296.1	3141.7	3124.1	2924.9	2754.3	−644.9	−14.66
Sikarpur	224.1	177.2	98.3	52.7	16.7	4.5	−219.6	−4.99
Bulcherry	3235.0	3023.6	2859.9	2737.4	2365.3	2157.5	−1077.5	−24.49
Dalhausi	8249.2	7903.4	7497.6	7635.1	6830.7	6175.5	−2073.3	−47.13
Bangaduni	4456.7	4253.9	3921.7	3439.5	2736.9	2322.5	−2134.2	−48.50
Putni island	490.3	450.5	377.8	516.7	552.1	437.2	−53.1	−1.21

Source: In-house study

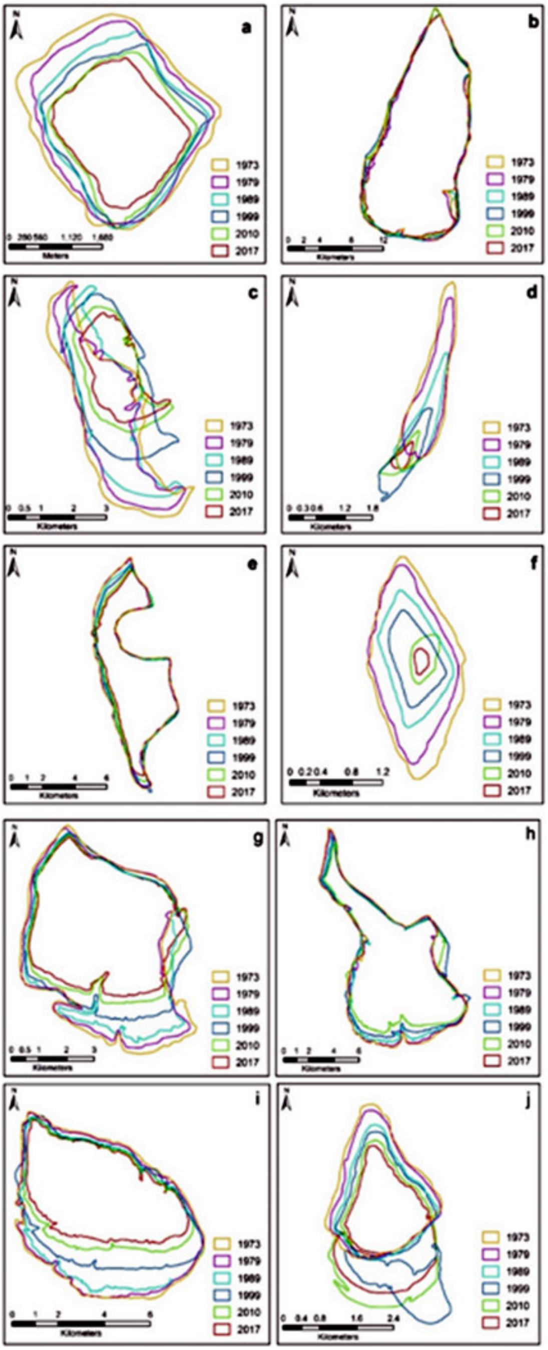

Fig. 18.13 Changes in the landmass boundary during 1973–2017 (**a**) Ghoramara (**b**) Sagar (**c**) Jambudwip (**d**) Kankamari (**e**) Mahisani (**f**) Sikarpur (**g**) Bulcherry (**h**) Dalhousi (**i**) Bangaduni (**j**) Putney island. (Source: In house production, not published)

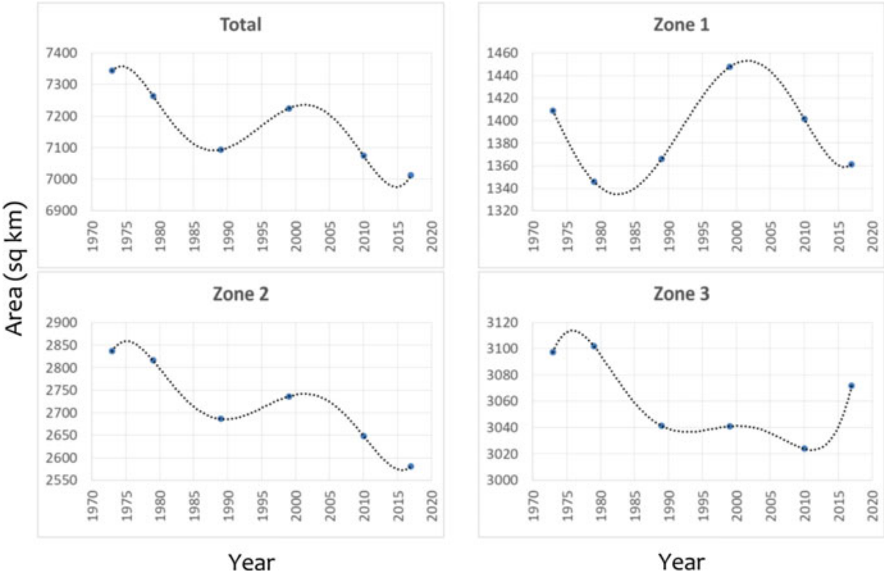

Fig. 18.14 Periodicity of land mass changes in the Sundarbans. (Source: In house product, not published)

cycle especially cloud type, precipitation rate, moisture transport, and surface soil wetness which is a vital input for runoff modelling. Flood extent is determined from moderate to high resolution remote sensing satellite, viz. IRS, Landsat, Spot, etc. Large number of blended operational products are generated integrating various sensors data and ground measurements which can readily be used in different models. The model-derived potential flood extent can help emergency managers to develop contingency plans well in advance. In response phase of disaster mitigation, remote sensing data are used for damage assessment. The two case studies applied to Sundarbans showed application of the remote sensing technologies to monitor ecological disturbances following cyclones, and land mass change due to accretion and erosion, the latter causing change in the boundary of islands, a dynamic phenomenon, often not accessible physically due to remoteness, particularly during post-hazards period.

It is prudent, therefore, that although both countries made individual efforts to make such studies using advanced technologies to cope up with hazards being essentially of trans-boundary in nature, a combined approach using similar sensors and data sharing, could be more effective in the preparation and implementation of policy framework for developing early warning systems, preparedness, monitoring, and mitigating loss due to hazards, including rehabilitation.

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Part VII
Mainstreaming Engineering Interventions to Climate Change

Endangered earthen embankment and *jetty* ghat due to caving of soil frequently encountered in the flood-prone areas (Courtsey D. Burman)

Chapter 19
Mainstreaming Climate Change Adaptation into Policies in the Sundarbans Region

M. Monirul Qader Mirza, Mir Ahsan A. Talpur, and Ainun Nishat

Abstract The Sundarbans, the single largest mangroves forest in the World is shared by Bangladesh and India. It is situated in the delta of the Ganges, Brahmaputra and the Meghna rivers. The Sundarbans ecosystem interacts with the coastal processes of the Bay of Bengal and the Ganges River and its distributaries. The mangrove forest is sensitive to sea surface and surface temperatures, precipitation, fresh water flows, saline water intrusion and sedimentation. The value of the ecosystem services of the Sundarbans is enormous. Salinity intrusion due to reduced flow of the Ganges since the commissioning of the Farakka Barrage in 1975 has been affecting the Bangladesh part of the Sundarbans. The Sundarbans is also vulnerable to frequent occurrences of cyclones and associated storm surges. Livelihoods of the people living in and around Sundarbans are also affected by the changes that are taking place there. Future climate change and sea level rise together with human interventions on the upstream water flows may affect the Sundarbans ecosystem significantly. The possible impacts can be reduced by mainstreaming adaptation in the national policies and programmes of the departments/institutions involved with the management of the Sundarbans. However, many challenges are associated with the mainstream process which need to be addressed. India and Bangladesh can work together for the sustenance of the Sundarbans ecosystem and to safeguard livelihoods of millions of people.

Keywords Sundarbans · Mangroves · Climate change · Sea level rise · Salinity · Adaptation · Mainstreaming · Policy

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19.1 Introduction

The ‘Sundarbans’ (Fig. 19.1) is the single largest tract of mangrove forest in the World located in the delta of the Ganges, Brahmaputra and Meghna (GBM) rivers. The area of Sundarbans is approximately one million hectare, of which 62% lies within Bangladesh and 38% in India (Ghosh et al. 2015). The Sundarbans is characterized by subtropical climate with hot, humid summers and mild winters. Climate is slightly different in the Bangladesh part of the Sundarbans than the Indian part. Mean annual temperature of the Bangladesh part of the Sundarbans is ~23 °C. Annual rainfall range is 1600–1800 mm (Ghosh et al. 2015). Average temperature in the Indian part of the Sundarbans is 25 °C. The average annual rainfall is ~1662 mm (Gopal and Chauhan 2006). The forest is vulnerable to cyclonic storms and associated surges. Cyclone ‘Sidr” was the most devastating cyclone that hit the Sundarbans in November 2007. An approximately 2500 km^2 or 25% biomass cover of the Sundarbans was damaged by strong wind and tidal surge (CEGIS 2007).

The Sundarbans ecosystem in Bangladesh is a linked landscape with the Ganges River and its distributaries on the land side and coastal processes along the Bay of Bengal. The interaction of components and the ecological variables of the Sundarbans and the linked system is quite complex. Functioning of the ecosystem is governed by the intermixing of upstream freshwater flow and marine tidal water (Karim 2004). Since the commissioning of the Farakka Barrage on the Ganges River in 1975 by India in the upstream, freshwater flows to the Sundarbans in Bangladesh drastically reduced (Mirza 2004; Gopal and Chauhan 2006). Impacts of reduced freshwater flows has been further accentuated by the impacts of climate change manifested through sea level rise. As a result, salinity level has increased significantly. The impact of such increase in salinity on the Sundarbans ecosystem is well documented (Karim 2004). The estuarine network of Indian Sundarbans is comprised of seven major estuaries. Excessive siltation resulted in loss of connection of five of the seven estuaries with the flow of the Ganges. Runoff in the monsoon was the only source of water that maintained their estuarine characteristics (Cole and Vaidyaraman 1966). In the western part of the Indian Sundarbans, delta building processes through sedimentation almost ceased (Cole and Vaidyaraman 1966). On the other hand, the process has accelerated in the eastern part. The distribution of biota followed the west to east gradients of salinity and freshwater occurrence across the Sundarbans (Gopal and Chauhan 2006).

Climate variability and change affect mangroves many ways. Variability of temperature declines leaf formation rates, cause thermal stress, affects photosynthesis severely, etc. Cyclonic storm and associated surges cause damage to mangroves as well as wildlife. Increased salinity due to reduced precipitation and runoff decrease productivity, growth and survival of seedlings. Migration of mangrove species could occur due to rise of sea level.

The impacts of climate change will also be felt on the livelihoods of the people that are dependent on the Sundarbans. Some 3 million people live in the areas around the Bangladesh Sundarbans. An estimated 4.4 million people live at the edge of the

Fig. 19.1 Sundarbans in Bangladesh and India. (https://www.pinterest.co.uk/pin/308144799480768186/)

Indian Sundarbans (World Bank 2014). For many generations, they lived in harmony with the nature as well as earned their livelihoods as woodcutters, honey collectors, fishermen and subsistence farmers. Climate change could emerge as a threat to their livelihoods in the future.

Impacts of climate change on the Sundarbans region could be minimized through adaptation. This Chapter is particularly focusing on mainstreaming of climate change adaptation specific to the Sundarbans region. Srinivasan (2007) listed several benefits of mainstreaming: to ensure that current projects are no longer at risk from climate change or no longer contribute to the vulnerability of its recipients; to ensure that future projects are consciously aimed at reducing vulnerability by incorporating priorities that are critical to successful adaptation, such as ensuring water rights to social groups are exposed to water stress during droughts; to use resources efficiently and effectively; to avoid mal-adaptations; and to ensure consistency between the needs of poverty eradication and adaptation. This Sect. 19.1 introduced the necessity of mainstreaming of climate change adaptation for the Sundarbans. Section 19.2 discusses the concept of mainstreaming of climate change adaptation and applications. Approaches to mainstreaming are discussed in Sect. 19.3. Mainstreaming of entry points are examined in Sect. 19.4. Section 19.5 focuses on implementation challenges. Concluding remarks are presented in Sect. 19.6.

19.2 The Concept of Mainstreaming and Applications in the Sundarbans Region

In the last two decades, we have witnessed an increasing research, action plans, and policy development on adaptation and it's mainstreaming in four stages. *First*, a large pool of literature on the adaptation options appeared especially since the publication of the IPCC's Third Assessment Report (2001). IPCC's Fourth Assessment Report (AR4) (2007) synthesized the options available for various key economic sectors. *Second*, with the launching of NAPA (National Adaptation Programme of Action) by the UNFCCC in early 2000 for the least developed countries, actions plans/programmes started formally taking shape. *Third*, policy documents on climate change officially formulated and adopted in many least developed and developing countries including Bangladesh, India and Nepal (see Chap. 20). *Fourth*, recent initiatives include a momentum of academic research on mainstreaming and integrating it into development plans and programmes by the government and concerned public agencies, international funding/donor agencies, private sector stakeholders and civil society.

The concept of "mainstreaming" evolved significantly from the dictionary definition to its practical applications to climate change. The term "mainstream" can be defined either as a "noun" or an "adjective" (Guzman 2016). As a noun, the Mariam-Webster Dictionary defines it "The ideas, attitudes, or activities that are shared by most people and regarded as normal or conventional". As an adjective, it is

“Belonging to or characteristic of the mainstream”. Other definitions of “mainstream” are also available as an adjective. For example, as per Dictionary by Farlex (2018), “mainstream” is “Representing the prevalent attitudes, values and practices of a society or group”. As a concept, the term “mainstreaming” is quite comprehensive. It comprises of political, sectoral, spatial, economic, social, knowledge, institutional and equity dimensions. Gupta and van der Grijp (2010, p. 67) denote that mainstreaming “is a concept that brings marginal, sectorial issues into the center of discussions, thereby attracting more political attention, economic resources and intellectual capacities”. Regarding environmental problem, mainstreaming is “The informed inclusion of relevant environmental concerns into the decisions of institutions that drive national, local and sectoral development policy, rules, plans, investment and action” (Dalal-Clayton and Bass 2009, p. 11). With regard to gender equality in the society, the UN Economic and Social Council (ECOSOC) (1997, p. 27) defines it as “. . .a strategy for making women’s as well as men’s concerns and experiences an integral dimension of the design, implementation, monitoring and evaluation of policies and programmes in all political, economic and societal spheres so that women and men benefit equally and inequality is not perpetuated”. In terms of institutions involved in development activities, Ayers et al. (2014, p. 295) states that mainstreaming is “integrating an issue into existing (usually development) institutions and decision-making”. In the last few decades, mainstream concept has been widely applied in environmental degradation (Dalal-Clayton and Bass 2009), natural hazards and disaster risk reduction (Benson 2009), poverty alleviation (Lobb 2005), gender equality (Manyire and Apekey 2013), HIV/AIDS (Elsey et al. 2007) and climate change (Rauken et al. 2014).

Literature on the application of mainstreaming concept in the countries related to the Sundarbans region is limited. Most of this literature focuses broadly on the development, which is being affected by climate variability (including extremes) and change. Bangladesh was ranked sixth among the countries worst affected by extreme weather events from 1996–2015 and the cumulative estimated loss was ~US$ (PPP) 2284 million (German Watch 2016). Mirza (2003) argued that adaptation measures could significantly reduce damages from extreme weather events and therefore could facilitate development if the adaptation was made a part of the investment policies. Ayers et al. (2014) examined mainstreaming of climate information, policies and measures with development in Bangladesh. They found that in terms of resource uses, it was more efficient to integrate climate policies with development rather than addressing them separately. They also noted that mainstreaming was not a linear process in Bangladesh as many government and non-government stakeholders were involved in the process. India is another country highly vulnerable to climate change. Losses from annual extreme weather events in India were estimated at US$ 9–-10 billion and 80% of the losses were not insured (ESG 2016). Ravindranath et al. (2014) argued that there were sufficient knowledge available in India to commence implementation of adaptation measures. They also presented a four step-strategy recommended by the UNFCCC (2011) for mainstreaming adaptation in the planning process. Bisht and Shaikh (undated) analyzed issues involving mainstreaming of climate change adaptation in policy planning in the Bundelkhand region in Madhaya

Pradesh, India. Despite several gaps in the mainstreaming process, they opined presence of enough scope for implementing climate adaptive planning successfully in the decision-making procedure. Sharma and Tomar (2010) discussed mainstreaming climate change adaptation in India specific to the urban context. They listed a few challenges that include importantly inadequate understanding of potential climate change impacts in urban areas and absence of capacity to integrate climate change in the local government institutions.

Huq et al. (2017) discussed mainstreaming of ecosystem services-based climate change adaptation (EbA) in Bangladesh. They examined 'ecosystem services (ESS)' at strategic level (vertical mainstreaming) and policy formulation and implementation stage (horizontal mainstreaming). The contribution of ecosystem services to human-wellbeing is immense (MA 2005, Costanza et al. 2014). For Bangladesh, Hossain et al. (2016) assessed the role of ESS for poverty alleviation and found a significant reduction ($\sim -17\%$) in poverty level since 1980 contributed by increased food and inland fish production. On the other hand, non-food ecosystem services such as water availability, water quality and land stability experienced deterioration. The area of the Sundarbans in Bangladesh and the production of timber were found stable. In contrast, tree density and volume reduced perhaps due to increased exploitation or fragmentation. Abdullah-Al-Mamun et al. (2017) evaluated direct and indirect ecosystem services by the Sundarbans mangrove forest using an economic framework. They found that ecosystem services of the Sundarbans decreased by reduced fresh water flow from the upstream, overharvesting of resources, sea level rise, salinity increase, poaching and climate change. They concluded that the services (provisioning, supporting, regulating and cultural) being provided by the Sundarbans are far greater than its economic valuation. While the value of ESS is very significant, at the strategic level of mainstreaming, it merely received a marginal attention in Bangladesh. In terms of policy formation and implementation level of mainstreaming, priority was given to structural adaptation solutions instead of ESS (Huq et al. 2017).

19.3 Approaches to Mainstream Climate Change Adaptation

UNFCCC (2011) outlines a four-step approaches for mainstreaming. They are: assessment of climate impacts and vulnerability; planning for adaptation; implementation of adaptation measures; and monitoring and evaluation of adaptation actions. Huq and Iyers (2008) proposed a four-tier activity: awareness raising, targeted information, pilot activities and mainstreaming to build national capacity. In this section, we will mainly focus on the UNFCCC approaches to mainstream climate change adaptation in the Sundarbans region.

19.3.1 Assessment of Vulnerability and Impacts

There are three components of climate change vulnerability and impact assessment. The IPCC (1992) and UNDP (2004) published the relevant guidelines. The first component is the construction of climate change scenarios. Scenarios can be constructed from the outputs of the global climate models (GCMs) or by downscaling with the aid of Regional Climate Models (RCMs). Specific climate change scenarios for the Sundarbans have so far been not constructed.

Along the Indian coasts, sea surface temperature is projected to increase by 2.0–2.5 °C by the end of the present century under Special Report on Emissions Scenarios' (SRES) A2 scenario (Vivekanandan 2013). Using 1975–2005 baseline, precipitation in West Bengal is projected to increase by 11.5% and 2.5% by 2050s and 2100 under SRES A1B scenario (Bal et al. 2016). The historical sea level rise in the Sundarbans was found to be higher than the average of the Indian coasts. The rate of sea level change from 1952–2013 in two tidal gauge stations nearest to the Sundarbans was found about 4.67 ± 0.68 mm per year in Diamond Harbour and 2.59 ± 1.00 mm per year in Haldia (Pramanik 2016). By the end of 2100, the median projection of sea level rise at Haldia under Representative Concentration Pathways (RCP) 2.6, RCP 6.0 and RCP 8.5 scenarios are 0.38 m, 0.48 m and 0.63 m, respectively (Kay et al. 2015).

Projection of future sea surface temperature for the Bangladesh coast is not available. Dasgupta et al. (2016) reported projected temperature and precipitation change scenarios for Bangladesh from the three global climate models forced with three IPCC SRES scenarios (A2, A1B, and B1). For temperature, the projected changes were: 2.6–8% for the A2 scenario, 3.3–8.2% for the A1b scenario, and 3.3–7.1% for the B1 scenario by 2050. The rainfall projections were also variable from model to model. The projected changes were: 30.9% decrease to 26.4% increase for the A2 scenario, 6.9% decrease to 21.9% increase for the A1B scenario, and 23.4% decrease to 21.2% increase for the B1 scenario. Dasgupta et al. (2016) applied 27–32-cm global SLR range by 2050 derived from the various scenarios of Rahmstorf (2007). By taking into account land subsidence and IPCC (2007) assessment, World Bank (2014) estimated that total relative sea level rise in the Indian part of the Sundarbans could be between 0.46 m and 1.39 m by 2100.

The second and third parts are assessment of vulnerability and impacts with the applications of scenarios. Mangroves are sensitive to changes in temperature, precipitation, CO_2 concentrations, sea-level and salinity. Mitra (2013) presented a detailed general synthesis of vulnerability to and impacts of these factors on the mangroves, a summary of which is presented in Table 19.1. Studies related to the impacts of climate change specific to the Sundarbans in Bangladesh and India are limited. Dasgupta et al. (2016) conducted a research on salinity intrusion by 2050 to the coastal zone of Bangladesh with respect to sea level rise, changes in freshwater supplies from the upstream areas, and their impacts on drinking water supply, irrigation water and ecosystems including the Sundarbans mangroves. The research adopted a five-step process. *First*, temperature and rainfall scenarios for 2050 were

Table 19.1 Vulnerability and impacts of climatic and non-climatic factors on mangroves

Climatic and Non-climatic factors	Vulnerability	Impacts
Temperatures Above 25 °C	Rate of change in leaf formation	Some species may experience a decline in leaf formation rate (Saenger and Moverly 1985).
Above 35 °C	Thermal stress	Thermal stress occurs and affects mangrove root structures and development of mangrove seedlings (UNESCO 1992).
Between 38–40 °C	Reduced growth and cellular respiration	At this range of leaf temperatures, almost no photosynthesis takes place (Clough et al. 1982; Andrews et al. 1984). Decline in food and energy for growth and cellular respiration.
Precipitation	Productivity and change in species composition	Decrease in freshwater from reduced precipitation and resulting increase in salinity. Likely to decrease mangrove productivity, growth and seedling survival. A change in species composition may occur creating a favorable environment for more salt-tolerant species (Ellison 2000, 2004).
Increased atmospheric CO_2 concentrations	–	May enhance growth of mangrove vegetation and photosynthesis (Reef et al. 2016). However, may not be enough to compensate for the adverse impacts of sea-level rise (Ellison et al. 1996).
Sea-level rise	Inundation and lateral migration	Will change the salinity distribution and inundate mangroves (IPCC 2001). Mangrove systems may tend to migrate in response to rising sea level but may not keep pace with the rate of rise (Mitra 2013).
Salinity	Reduced photosynthesis and increased mortality	Photosynthesis mechanism of mangroves is adversely affected by salinity (Lin and Sternberg 1992). It retards growth of mangrove leaves as well as increase leaf mortality rate and declines the leaf primary production (Panda et al. 2006). Hossain et al. (2014) documented decreased survival rates in *Heritiera fomes* seedlings with increased salinity in laboratory tests.

downscaled at the Bangladesh window from nine climate models for IPCC's B1, A1B and A2 scenarios. Finally, scenarios from three models were retained. *Second*, estimates on relative mean sea level rise (RMSLR) at the coastline of Bangladesh were compiled from the published literature on global sea level rise and land subsidence in the lower Bengal Delta. *Third*, the freshwater flows from upstream, surface water runoff from rainfall events, and tidal dynamics in the coastal river system were estimated by using the MIKE 11 hydrodynamic module, the DHI (Danish Hydraulic Institute) Global Tide model, the Bay of Bengal model, and the MIKE 11 advection-dispersion module. Location specific river salinity scenarios were also projected with the aid of these models. *Fourth*, the scenarios were

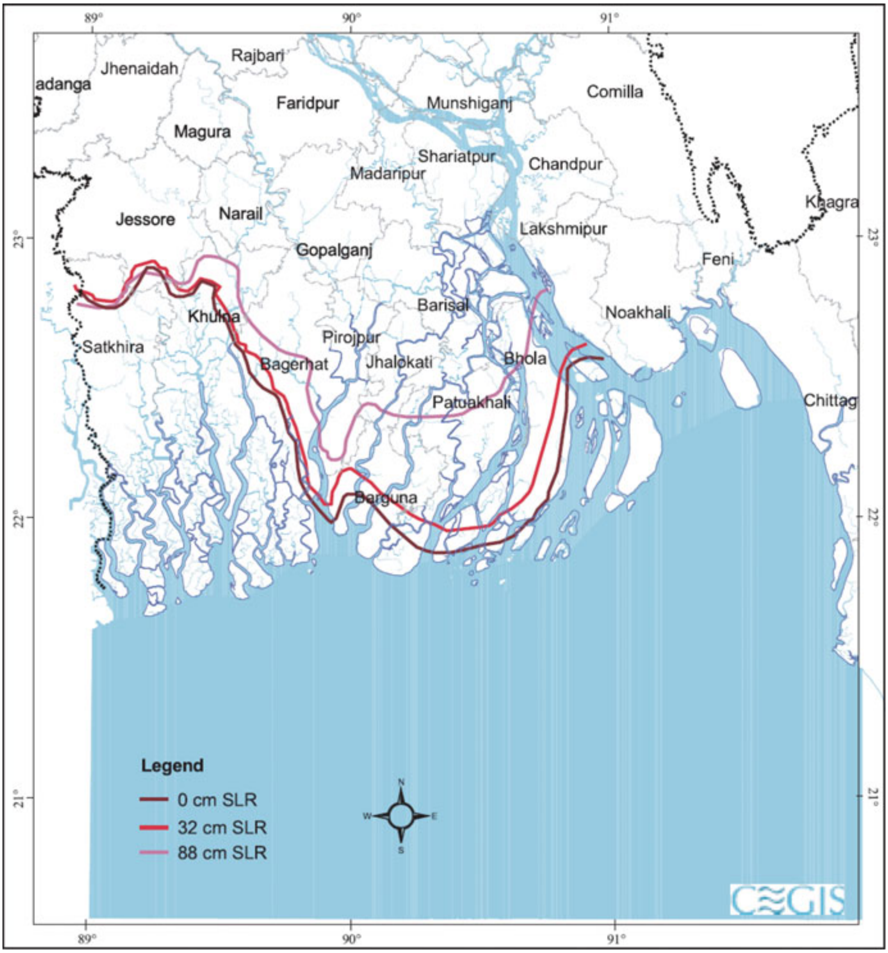

Fig. 19.2 Salinity intrusion boundaries at different sea level rise scenarios. (GoB 2009)

compared with the baseline salinity at 2012. *Fifth*, expected changes at the administrative boundaries of the coastal zone were estimated by overlaying geo-coded changes in river salinity. The research findings concluded that the southwest coastal area of Bangladesh could experience *significant* changes in river salinity by 2050. River areas under slight (<1 dSm^{-1}) and moderate (1–5 dSm^{-1}) salinity could be reduced but moderate to highly saline (5–10 dSm^{-1}) river area would be increased from 8% to 27%, and highly saline (>10 dSm^{-1}) river area could be increased from 35–40%. Figure 19.2 shows the boundary of saline water intrusion at different sea level rise scenarios. The research concluded that these changes could result in significant shortages of drinking water availability in the urban areas of the coastal region; scarcity of irrigation water for dry-season agriculture, especially for the *boro* (post-monsoon) crop; and significant changes in the coastal aquatic ecosystems as well as in the Sundarbans mangroves.

Dasgupta et al. (2016) concluded that the projected rise in salinity in response to climatic and other physical factors would introduce changes in the ecosystems in the Sundarbans in Bangladesh. This unique ecosystem- the UNESCO Heritage site is enriched with 334 recorded plant species, 270 species of birds, 42 species of mammals, 35 reptiles, eight amphibian species, and at least 150 species of commercially important fishes. The most commonly found trees in Sundarbans are Sundari (*Heritiera fomes*), Gurjan (*Dipterocarpus turbinatus*), Gewa (*Excoecaria agallocha*), Goran (*Ceriops decandra*), Keora (*Sonneratia apetala*), and Kankra (*Bruguiera sexangula) (*Scott 1991*)*. Among these common trees in the Sundarbans, Sundari is the most dominant and with the highest economic value. With the gradual increase in salinity, the trunk diameter of the Sundari tree decreases steadily and at salinity level greater than 25 ppt (~39 dSm^{-1}), the decrease is drastic (Dasgupta et al. 2016). With the increase in salinity levels under the future climate change scenarios, less salt tolerant tree species may be substituted by more salt tolerant species (e.g., Gewa and Goran). This will also alter the composition of species and loss of biodiversity in the Sundarbans (Hossain et al. 2014). Changes in the composition of species are already occurring in the Indian part of the Sundarbans (VYAS 2012).

19.3.2 Planning for Adaptation

Bangladesh launched its national climate change strategy and action plan in 2009. The plan is comprised of six pillars: Food security, social protection and health, comprehensive disaster management, infrastructure, research and knowledge management, mitigation and low carbon management, and capacity building and institutional strengthening (GoB 2009). None of these pillars or the programmes identified under them mentions Sundarbans'. It only appears at the title of a photo at page 17 demonstrating the devastation of cyclone *Sidr* that hit Bangladesh in November 2007. The Indian national action plan on climate change also does not mention Sundarbans or any other mangroves forests. However, Sundarbans has appeared many times in the 'West Bengal State Action Plan on Climate Change' being a State component report within India. In the report, the Sundarbans has been identified as one of the most vulnerable regions to climate change and stressed to address the vulnerabilities properly (GoWB 2012).

Planning for adaptation and its mainstreaming in the Sundarbans requires identification of vulnerable forest areas and species, climate change and sea level rise scenarios, fresh water supply from upstream and estimation of runoff generated internally, erosion and accretion, sediment flow, salinity intrusion phenomenon and salinity levels, livelihoods dependent on the forests and their risks from climate variability and climate change, and institutions involved in the management. In addition to these, evaluation of adequacy of currently available technologies and practices for their ability to adaptation and development of strategies based on scientific research and the participatory approach involving all stakeholders are also listed (Ravindranath et al. 2014).

19.3.3 Adaptation Options and Implementation

Because of geo-physical characteristics of the Sundarbans, the adaptation options to tackle the impacts of climate change and sea level rise are limited. Perhaps the most effective step will be to restore the fresh water supply that the south west region used to receive in pre-1975 period. Construction of a Barrage on the Ganges, just downstream of the distributaries, namely the Gorai-Modhumati, and, the Chandana-Barashia will be able to restore the flow partially. For this purpose, a collaborative action, jointly, by India and Bangladesh may be pursued to ensure proper management of the adverse impacts of climate change and fight the sea level rise-induced salinity that is likely to rise further. For the Bangladesh part of the Sundarbans, Agrawala et al. (2003) suggested that the major aim of adaptation for Sundarbans would be to modify the threats of permanent inundation from the sea level rise-induced submergence. They opined that the submergence process could not be stopped as most of the sea level rise would occur from the tectonic subsidence. One of the options is to retard the inundation process by enhancing sedimentation on the forest floor by applying guided sedimentation techniques. However, such techniques need to be piloted before formal application in the forest. The second but the most important adaptation option would be targeting to reduce the threat due to salinity intrusion as well as bringing down its concentration. This could be done through: (a) increasing freshwater flows from upstream areas; (b) resuscitation of existing river networks towards improving flow regime along the forest; and (c) artificial enhancement of existing river networks to facilitate freshwater flow regime along the rivers supplying freshwater to the western parts of the forest (Agrawala et al. 2003). Flows of water into the Bangladesh part of the Sundarbans is dependent on the flow from the Ganges through the Gorai River. Mirza (1998) recommended to maintain 240 m^3s^{-1} in the Gorai River especially in the critical month of April for natural sustenance of the mangrove forest. Dry season flow in the Gorai River was plunged into a dismal situation after commissioning of the Farakka Barrage by India on the Ganges in 1975. After signing of the Ganges Water Treaty in 1996 and rehabilitation of the Gorai River through massive dredging, the water supply situation had slightly improved (Agrawala et al. 2003). Building hydropower dams in Nepal could be an effective cross-border adaptation option for the Sundarbans. Flow of the Ganges can be doubled in the dry months by storing a small portion of monsoon flows in the Nepalese dams. Low flow augmentation could check saline water intrusion and help sustaining the Sundarbans ecosystem (Sadoff et al. 2013).

For the Indian Sundarbans, World Bank (2014) considered long- and short-term adaption options and suggested the following: (a) *estuary management* measures such as embankment realignment, mangrove restoration, and salinity management to reduce long-term threats; and (b) *disaster risk management* interventions such as early warning systems, emergency preparedness, and cyclone shelters to tackle near-term threats. However, it was stated that these measures would not provide a permanent solution but they would increase safety of the residents in the next 50-plus years. Over this long time-span, it was recommended to build human through poverty reduction and livelihood enhancement programs (World Bank 2014). Smit et al. (2001) identified economic resource as one of the key determinants of adaptive capacity. Poverty influences coping capacity of a region (Kelly and Adger 1999).

19.3.4 Implementation of Adaptation Measures

Implementation of the adaptation measures for the Sundarbans requires their mainstreaming into the development programmes and policies. The Sundarbans cannot be treated as an isolated piece of ecosystem sitting in the delta of the GBM rivers. It is already proven that development programme(s) undertaken hundreds of kilometers in the upstream of the Sundarbans affected it seriously. It has to be integrated into the broad development programmes of the countries of the GBM region. A cooperative mandate among the countries is required to implement adaptation policies and measures for the Sundarbans. In Chap. 20, we have recommended that the BBIN Sub-regional platform of the SAARC would be an appropriate platform for integration of climate change policies. Glaholt et al. (2014, p. 29) states "The impact of mangrove degradation on saltwater intrusion and loss of fisheries potential, and the responses of the Sundarbans ecosystem to climate change, are particular issues that should be included in future policy dialogues". Bangladesh and India can learn from each other's experience in the management of the Sundarbans. They can also engage in exploring possibilities for cooperative management approaches in the future. Some cooperative programmes have already been initiated between India and Bangladesh regarding the conservation of Sundarbans.

Both countries initiated a study at non-government level on the methodology to calculate environmental flow (quantity, quality and timing) requirement for the Sundarbans focusing particularly at: forest composition, fisheries, aquatic diversity, connectivity (floodplain to river system), navigation, pollution and sedimentation (Glaholt et al. 2014). Environmental flow requirement for the Sundarbans should be included in the future water negotiations between India and Bangladesh on the Ganges waters. Participation of Nepal cannot be excluded in the Ganges water sharing negotiations as it has a pivotal role in the augmentation of the Ganges flow. Inclusion of Nepal during the negotiations in the spirit of the 1977 Ganges Water Agreement will be beneficial for both parties.

Bangladesh and India signed a Memorandum of Understanding (MoU) on the conservation of the Sundarbans in September 2011. It recognized the Sundarbans as a 'single ecosystem' divided between the two countries. This recognition is important for joint management of the Sundarbans. Capacity building of the departments involved with Sundarbans is a prerequisite to understanding current and future climate vulnerabilities. Article VI (6) of the MoU expressed commitment regarding capacity building in many areas including climate change adaptation and sustainable socioeconomic development (GoB and GoI 2011). The action plans agreed in the MoU are progressing at a slow pace. Ortolano et al. (2016) argued that in the bilateral negotiations between India and Bangladesh, the Sundarbans received a low priority compared to the other issues, for examples, the treaty on sharing of the Teesta River waters, and an agreement regarding an exchange of near-border ‘enclaves’.

19.3.5 Monitoring and Evaluation of Adaptation Actions

Monitoring is a continuous process of data collection in the planning, implementation and the post-implementation stages to ensure better management (Sweeney 2009). At this stage, it is critical to engage all stakeholders as well as selection of indicators in order to ensure a broad consensus on any assessments (OECD 2009). In the evaluation process, assessment of the monitored data at various completed phases of a project or programme is conducted (Mathew et al. 2016). Monitoring and evaluation of adaptation programmes and practices are pre-requisites to assess their ability to increase or decrease vulnerability to climate risks of communities, infrastructure and natural resources (Ravindranath et al. 2014). Monitoring will require to focus on whether the identified adaptation measures are properly implemented, or any unwanted problems surfaced in the implementation or the post-implementation period. Monitoring should also address whether the adaptation measures had resulted in any adverse impacts on other sectors or regions as well as any exceedance of budgetary allocations. Evaluation should assess delivery of benefits of the implemented adaptation options and any unintended outcomes (OECD 2009).

With regard to monitoring and evaluation of climate change adaptations in the future, the Sundarbans will be a special case because of the changes that are presently undergoing. Two decades ago, in this context, FAO (1998 2.1.1 A monitoring system for the SRF) issued a cautionary note on the future of Bangladesh Sundarbans “The ecosystem is both complex and fragile and is currently undergoing changes which may be detrimental to its stability and even survival as a mangrove forest”. It mentioned the complexities regarding detection, quantification and analysis of the factors associated with the transformation of the Sundari (*Heritiera fomes*) – the most abundant and valuable species due to reduction of fresh water flows from the upstream and accelerated sedimentation and natural non-adaptation of the species.

Monitoring and evaluation of future adaptation measures are strongly linked with the past projects. The important issues are what kind of data base of indicators and capacity the past projects have created. For example, the FAO (1998) mentioned about availability of a holistic baseline data on the mangrove ecosystem of the Sundarbans. Bangladesh has recently implemented five projects in the Sundarbans on wildlife and biodiversity, livelihood and climate change. Enormous amount of baseline data have been collected under these recent projects. Baseline data were also collected from the projects implemented in the past. These projects have also contributed to capacity building of the stakeholders. One of the major objectives of the USAID supported “Climate-Resilient Ecosystems and Livelihoods (CREL)” project is to enhance knowledge and capacity of the key stakeholders for co-management implementation, natural resource management and climate resilience. Stakeholders such as Co-management Organization (CMO), Village Conservation Forum members and Local Government officials are being trained through customized training modules. The project also provides technical assistance, mentoring, and small grants to conduct research on biodiversity and monitoring and assessment of environmental impacts (USAID undated). The MoU signed between Bangladesh and India in 2011 on the Sundarbans agreed to consider and adopt appropriate joint management and joint monitoring of resources (GoB and GoI 2011).

19.4 Entry Points for Mainstreaming

The Sundarbans has priceless ecological, environmental and economic values. Future climate change, sea level rise associated inundation, salinity intrusion, and reduction of surface water flow into the ecosystem would put the Sundarbans ecosystem as well as livelihoods of the people dependent on it at risk. The risk can be reduced through mainstreaming climate change adaptation into the development planning of the Sundarbans. Two levels of entry points are suggested. *First*, at the national level development policies and climate change policies. Mainstreaming is missing in the climate change policies of India and Bangladesh; and *second*, mainstreaming at all tiers of organizations' level. For the latter, the most important task for mainstreaming is the identification of key public sector organizations, NGOs and Civil Society actors, development partners, Universities and national and international Research institutions who are currently associated with the Sundarbans at various capacities. The World Bank (2014) identified 19 organizations of the Government of West Bengal that had mandate(s) on the Sundarbans. Table 19.2 shows mainstreaming tasks and possible responses within their own mandates/ functions to tackle the impacts of climate change and reduce vulnerability in the Indian Sundarbans. Bangladesh Forest Department under the Ministry of Environment and Forests is mainly responsible for the management of the Sundarbans.

19.5 Challenges of Mainstreaming

Countries those share the Sundarbans have been at the risks of various types of natural hazards. Climate change is an additional stimulus that would modify the hazards and associated risks. Management of the climate induced additional risks thorough mainstreaming of adaptations will be challenging as these countries are already facing multi-faceted socio-economic and development difficulties. Begum

Table 19.2 Mainstreaming tasks and possible responses of the selected organizations involved with the Sundarbans in India

Organization	Functions	Mainstreaming tasks and possible future responses in the Sundarbans under climate change
Department of Sundarbans Affairs (DSA) with Sunbarban Development Board (SDB) and Sundarbans Infrastructure Development Corporation)	Implementation of special area development plan; coordination and integration of plans; and performance assessment and monitoring	Climate resilient socio-economic and livelihood development. The DSA needs properly trained manpower to run programs on climate change
Department of Forests	Enforces Indian Forest Act (1927), Forest Conservation Act (1980), and Wildlife Protection Act (1972), among other responsibilities, Developmental role for soil conservation, nonsocial forestry, and timber yield	Introduce policies to meet the challenges of climate change in national park, reserve forest and sanctuaries, and wildlife. Development of climate resilient forest co-management framework
Department of Irrigation and Waterways	Flood control through protection of embankments in Sundarbans; drainage	New design codes and standards for embankments taking into account climate change and sea level rise. Modified clearance for bridges and drainage structures
Department of Water Investigation and Development	Tubewells; licensing for groundwater extraction	Monitor any intrusion of saline water into the ground water aquifers and demarcate areas accordingly
Department of Environment	Enforcement of environmental regulations, mostly through the state pollution control board; lead agency for state's biodiversity strategy and action plan	Design and implement climate resilient biodiversity strategy and action plan for West Bengal with specific focus on the Sundarbans
Department of Fisheries and Aquaculture	Responsible for conservation of fish species, creation of infrastructure for fishing activities (including jetties), surveying, undertaking programs of skill upgrading, and livelihoods	Assess the impacts of climate change and sea level rise on various fish species; train fishers for sustainable fish farming and harvest and in specific cases design alternative livelihoods
Department of Agriculture	Provides information on agriculture, schematic implementation at grassroots level, soil analysis, pest management, seed firms in districts and blocks, etc.	Assess sensitivity of crops to climate change, introduce new climate resistant crop varieties, advanced water conservation techniques, and modify pest management
Department of Panchayat and Rural Development	Social forestry; administers the three-tier local government at district, block, and village	Development of awareness program on climate change in the areas of agriculture

(continued)

Table 19.2 (continued)

Organization	Functions	Mainstreaming tasks and possible future responses in the Sundarbans under climate change
	levels; supports local governments with appropriate budget, technical support, and policies	including social forestry, health, education, and socio-economic activities in the rural settings
Department of Animal Husbandry	Provides support, inputs, and guidance for improving livestock	Assessment of impacts climate change on livestock; introduce climate change in the extension services; train farmers on appropriate measures to safeguard livestock to changed climate
Department of Nonconventional Energy	Awareness programs for non-grid power; implementation of non-grid power projects	Introduce solar irrigation projects to support irrigation in the rain-fed agriculture and domestic water supplies
Department of Scheduled Castes and Scheduled Tribes	Development and improvement of sociocultural and livelihood aspects of scheduled caste and scheduled tribe populations; provides financial assistance and implements employment generation schemes for scheduled castes and scheduled tribes	Introduce climate change policies in the department; assess the risk of lives and livelihoods of the disadvantaged people to climate change and support alternative climate resilient livelihoods
Department of Tourism	Promotion and development of tourism; administers conducted tours; develops properties for tourism purposes	Promote and develop climate resilient tourism
Department of Disaster Management	The state disaster management authority is responsible for planning and implementation of disaster management schemes and coordinating relief and rehabilitation	Mainstream climate change into disaster risk reduction
Department of Health and Family Welfare	Protects health of people through preventive, promotive, and curative measures	Assess impacts on climate change on human health and re-design heath system to tackle climate change
Department of Education (primary, secondary and tertiary)	All three departments of education are active across the state	Introduce climate change in the education curricula; train-up instructors; construct climate resilient infrastructure and retro-fit whenever possible
Department of Public Health Engineering	Piped water supply; construction of tubewells; certifying	Take climate change into account during design, construction and management of

(continued)

Table 19.2 (continued)

Organization	Functions	Mainstreaming tasks and possible future responses in the Sundarbans under climate change
	quality of water investigation for water sources	water supply and sanitation systems
Public Works Department	Responsible for infrastructure and construction-related works through its own human resources	Develop new design codes and standards for climate resilient infrastructure

Source: World Bank (2014). Column 3 developed by the authors

(2012) listed some challenges of mainstreaming adaptation particularly for Bangladesh. Agrawala and van Aalst (2005) also discussed some mainstreaming constraints.

19.5.1 National and International Gap of Priority

Currently there are limited international priority on adaptation for the developing and the least developed countries. International efforts are mostly limited to negotiation documents on technological and financial support and it is a top-down approach (Begum 2012). So far, developing and the least developed countries received very insignificant international technological and financial support for adaptation and the process is also very complex and time-consuming (Uprety 2015). Adaptation is a local priority and the solutions require inputs from local level stakeholders. The local knowledge and experience should be integrated with the national level policies with a bottom up approach (Ayers et al. 2010).

19.5.2 Vulnerability, Impact, Adaptation (VIA) and Risk Assessment

Countries of the Sundarbans regions have acquired significant expertise in VIA and risk assessment. For example, the local experts have prepared National Communications to the UNFCCC. The Sundarbans region requires specific VIA and risk assessment with the participation of experts of both countries who will work on future climate scenarios from the same models and will assess VIA and the risk using common methodologies. This will enable them to share experience with each other's team and develop a common storyline for crafting appropriate adaptation measures.

19.5.3 Temporal Scales of Development and Adaptation Policies

In Bangladesh and India, development activities are planned on a 5-year term and budgetary allocations are approved on an annual basis. On the other hand, adaptation requires long-term planning, allocation of resources and action programmes. Many developing countries lack the capacity to integrate long-term climate risk into short-term development planning (Begum 2012). Bangladesh and India are not exceptions to this. Both countries need to develop strategies to integrate long-term adaptation into the short-term development programmes without any discontinuity.

19.5.4 Communication with the Stakeholders

Lack of communication could lead to unsuccessful mainstreaming. All stakeholders of the Sundarbans should be in the communication loop regarding climate scenarios and associated uncertainties, the impacts and risks due to climate change and sea level, adaptation measures, implementation mechanisms for adaptation, any potential adverse impacts from adaptation measures, methods and strategies for rectification, and financial needs. Information communications require investments and strengthening of institutions (UNDP-UNEP 2011).

19.5.5 Poverty

Poor people are usually exposed more to the extreme weather events and poverty increases their vulnerability to climate change, and vice versa (Mirza 2003; Eriksen and O'Brien 2007; IPCC 2007). Poverty is an important obstacle to mainstreaming because poor people cannot respond to the impacts of extreme hazards (Pittock 2009). In 2016, poverty rates (using upper poverty line) in the three Sundarbans districts Bagerhat, Khulna and Satkrira in Bangladesh was 31, 30.8, and 18%, respectively (BBS 2017). Residents of the Indian part of the Sundarbans live in extreme poverty. Only 20% or 190 residents out of a typical 1000 could afford one meal per day and one-third of which was substandard meal (World Bank 2014).

19.5.6 Coordination Among the Ministries and Sectors

Lack of adequate coordination acts as an impediment to mainstreaming. World Bank (2014) stressed of greater coordination between Forestry and Irrigation Departments on the mangroves restoration programmes in the Indian Sundarbans. Begum (2012) mentioned about lack of coordination among the government agencies in Bangladesh regarding climate change adaptation programmes.

19.5.7 Financial Resources for Adaptation

Huge financial resources will be required for adaptation in the future in India (Garg et al. 2015) and Bangladesh (ADB 2014; World Bank 2011). Recently, the Asian Development Bank (ADB) (2014) estimated that South Asian countries would require to invest 0.48% of the GDP annually (US$40 billion) by 2050 for implementing adaptation activities under the Business as Usual Scenario. Between 2015–2030, India would require around US$206 billion (at 2014–2015 prices) for implementing adaptation actions in agriculture, forestry, fisheries infrastructure, water resources and ecosystems sectors. Strengthening of resilience and disaster management would need additional resources (MoEFCC 2015). The estimated cost of adaptation for added inundation due to climate change in Bangladesh was US $5.7 billion (at 2009 prices) by 2050. Of this amount, US$3.3 billion would be required for protecting infrastructure from inland monsoon floods and US$2.4 billion for storm surge protection (World Bank 2011; Begum 2012).

19.6 Conclusions

- As salinity will increase people living in the areas, surrounding the Sundarbans, will face tremendous challenges as productivity of farm products such as rice paddy will decrease significantly. The area will suffer from shortage of safe drinking water as well.
- Adaptation options for the Sundarbans are limited especially for salinity control. For the Bangladesh part, one of the effective options would be construction of a Barrage on the Ganges River, just downstream of the distributaries, namely the Gorai-Modhumati, and the Chandana-Barashia to restore freshwater supply to the South-west region at the level before commissioning of the Farakka Barrage in 1975. In the Indian part of the Sundarbans, embankment realignment complemented by mangrove bioshields are suggested to mitigate impacts of saltwater intrusion together with reduction of other threats. Construction of dams in Nepal would benefit both India and Bangladesh to augment flow of the Ganges River for the benefit of the Sundarbans.
- The process of mainstreaming has started in the countries those share the Sundarbans. But there are many challenges to tackle at different levels. The most crucial challenges are setting up of a process for effective cooperation among the agencies involved with the Sundarbans and arranging necessary resources for planning, implementing and monitoring of the adaptation programmes.

- Overall, so far, not enough research programmes have been undertaken to assess the impacts of climate change on the Sundarbans ecosystems and the livelihoods of the people dependent on it. It is an utmost imperative to launch comprehensive collaborative research programmes involving all stakeholders of Bangladesh and India.

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Part VIII
Regional Integration of Climate Change Policies for Disaster Risk Reduction

A desolate girl after the storm impact (Courtesy WWF-India, photo Chiranjib Chakrborty)

Chapter 20
Integration of National Policies towards Addressing the Challenges of Impacts of Climate Change in the GBM Region

M. Monirul Qader Mirza, Uttam Kumar Mandal, Md. Golam Rabbani, and Ainun Nishat

Abstract The countries those share watersheds of the Ganges, the Brahmaputra and the Meghna River (in short, the GBM Region) are particularly vulnerable to the impacts of climate change. They should be concerned because their unique natural systems are such that the Himalayan snow and glaciers, glacier lakes, and inland and coastal wetlands could suffer irreparable loss from climate change. Therefore, water resources and the dependent ecosystems will be affected. Changes in precipitation will affect water resources availability. Climate change will also alter magnitude and extent of extreme weather events, for example, timing of floods. Although the pattern of vulnerability and impacts would be similar (with some exceptions) in Bangladesh, Bhutan, India and Nepal, their climate change policies are mostly different. Regional integration of climate change policies is proposed under a suitable institutional framework. It is proposed that the BBIN Sub-Regional Cooperation Initiative under the SAARC may be the designated institution to address the key concerns and vulnerabilities. The GBM region is brought into focus in this discussion in order to understand the need for regional cooperation with respect to

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Sundarbans in the final chapter based on details of the features that exist on a much larger and root-level platform.

Keywords GBM region · National policies · Iintegration · Climate change · Institutional framework · Sub-regional cooperation · Sundarbans

20.1 Introduction

There is no doubt that climate change has emerged as one of the most pressing environmental problems of our time (Fielding and Hornsey 2016). No economic sectors and regions of the world would be immune to the impacts of climate change. Scientists are in a consensus that the developing and the least developed countries would be particularly vulnerable to the impacts of climate change mainly due to climatic, socio-economic conditions and low adaptive capacity (Parry et al. 2007). Although over the decades, some developing and the least developed countries have achieved significant progress in natural hazards and disaster management, they may not be able to keep the pace with the rate of changing climate and associated increased impacts. In South Asia, the territory covered by the watersheds of the Ganges, the Brahmaputra and the Meghna Rivers, in short, the GBM Region fall within such a category.

From the mountain to the delta, the contiguous Ganges region possesses many similar features in extreme weather events. In the very upstream in Nepal, landslides in the mountainous regions and riverine flooding in the plain lands in the Terai region in the south are very common. Areas downstream of mountains are also vulnerable to glacier lake outburst floods (GLOFs). Western Nepal is prone to occasional droughts mainly due to low and irregular rainfall. While, the western part of the Ganges basin in India is highly prone to droughts and the eastern part is susceptible to floods. The Brahmaputra, in India, is highly prone to riverine flooding but occurrences of droughts are very rare. Hazard characteristics of the Meghna/Barak in India are similar to that of the Brahmaputra. Watershed of the Brahmaputra, in Bhutan, suffers through problems that are similar to those of northern Nepal. In the downstream, Bangladesh is particularly vulnerable to various extreme hazards because of its geographical location. Northeast of the country is vulnerable to flash flooding. Southeast region occasionally experiences landslides due mainly to extreme rainfall coupled with human interventions. Central part of Bangladesh is highly prone to flooding from occasional synchronization of high flows of the Ganges and Brahmaputra Rivers. Northwest and the Southwest regions are particularly susceptible to droughts due to low rainfall and inadequate availability of surface water flows. Coastal Bangladesh is vulnerable to tidal and storm surge flooding. With climate change in the future, vulnerability to extreme hazards could further increase in South Asia (Sivakumar and Stefanski 2011). Apart from the natural hazards, this region is particularly vulnerable to the impacts of climate change due to high population, low per capita income, socio-economic inequality, extremely high dependency on natural resources and low adaptive capacity.

Countries of the GBM Region have been pursuing policies to address problems of natural hazards. Although these countries share contiguous rivers, the designed policies are mostly country specific with some exceptions. Under the premise of the South Asian Association for Regional Cooperation (SAARC), cooperation on disaster management is on principle agreed, but very insignificant progress is made due mainly to political complexities. As more extremes (except cyclones) are projected to be triggered by climate change in the future, countries of the GBM Region need to initiate a new paradigm of cooperation by integrating policies at the regional scale to address problems of extreme hazards as well as the string of other socio-economic, environmental and security problems to be created by climate change. Currently, a Sub-regional initiative under the SAARC, is perusing collaborative activities in communication sector among Bangladesh, Bhutan, India and Nepal (BBIN). This platform offers a practical and feasible option to be the platform for joint action on various areas within this Sub-region. This chapter discusses reasons for concern, key vulnerabilities and the options and strategies for the GBM Region for integration of climate change policies in Bhutan, India, Nepal and Bangladesh. The GBM region has been brought into focus in this discussion in order to understand the need for regional cooperation with respect to Sundarbans in the final chapter based on the details of the features that exist on a much larger and root-level platform.

20.2 Future Climate Change: Why Should the GBM Region be Concerned?

The IPCC (2001, 2014) discussed five integrative reasons for concern (Fig. 20.1) that illustrate the implications of warming and of adaptation limits for people, economies, and ecosystems. They are: Unique and threatened systems; extreme weather events; distribution of impacts; global aggregate impacts; and large-scale singular events. This section addresses some of the reasons for concern for the

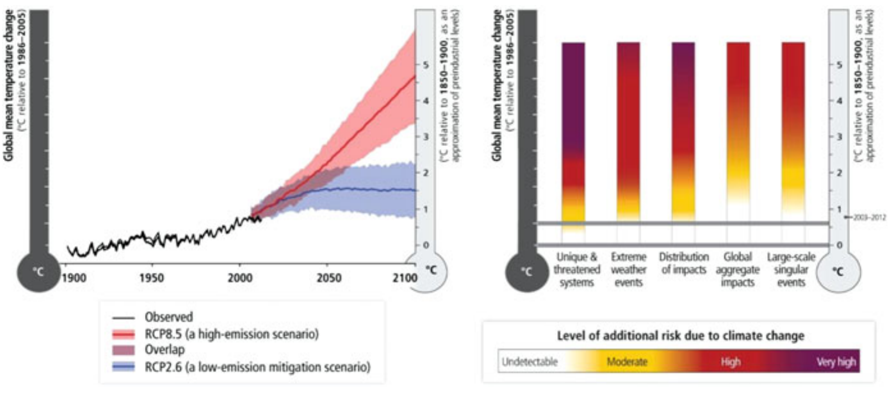

Fig. 20.1 A global perspective on climate-related risks. Risks associated with reasons for concern are shown at right for increasing levels of climate change. (IPCC WGII 2014)

unique ecosystems, extreme weather events and distribution of impacts in the GBM region countries together with changes in mean temperature and precipitation.

- *Global mean temperature increase and damage to or irreparable loss of unique and threatened natural systems*, such as the Himalayan snow and glaciers, glacier lakes and coastal and inland wetlands, may be irreparably harmed by changes in climate beyond certain thresholds. Water resources and the dependent ecosystems of the GBM countries will be affected.

The Himalayan glacial snowfields store about 12,000 km^3 of freshwater. About 9575 Himalayan glaciers form a unique reservoir, the largest concentrations of glaciers outside the Polar Regions supports perennial rivers such as the Indus, the Ganges, Brahmaputra, Yangtze and Yellow. These rivers, in turn, are a lifeline for over a billion people in Pakistan, Nepal, Bhutan, China, India and Bangladesh. The Himalayan Rivers supply an estimated 8500 km^3 of water annually. Roughly about 10–20% of this annual volume of water comes from the melt water contribution, which is vital for the dry season flows. For example, 71% of the dry season flow of the Ganges comes from tributaries originated in Nepal (Mirza 2004).

The Himalayan glaciers where the monsoon is the source of substantial part of the moisture have been retreating over the past century (World Bank 2013). Kulkarni and Karyakarte (2014) estimated that the mean loss in glacier mass in the Indian Himalayas has accelerated from -9 ± 4 to -20 ± 4 Gt/year from the decade 1975–1985 to 2000–2010. Synthesizing information from various studies, they found that most of the Himalayan glaciers were retreating but the rates were variable. As the glaciers are spread over a large area and altitude, the terrain and meteorological parameters influence the rates of retreat. From glacier to glacier, the rates were therefore found from a few meters to almost 61 m/year. Kulkarni and Karyakarte (2014) also mapped almost 11,000 out of 40,000 sq. km of glaciated area that was spread in all major climatic zones of the Himalayas. The mapping result suggested an almost 13% loss in glacier area in the 4–5 decades back from 2010. One particular example is a glacier in the Sagarmatha region in Nepal has receded 330 feet (100 m) vertically since 1920 and that resulted in forming of new glacier lakes (GoN 2011).

Retreat of the Himalayan glaciers will have at least two major implications. *First*, in the short-term, in the process of continued retreat, more water will be supplied in the glacier dependent perennial rivers in the Himalayas (Shrestha and Aryal 2011). Government of Nepal (2011) predicts an increase in river flows until 2030 due to melting but is projected to decrease significantly by the end of this century. With the increase in dry season flow, sediment supply in the rivers may increase. Water carrying capacity of the rivers may be reduced due to faster siltation of the channels. *Second*, in the long-term, dry season flow in the Himalayan rivers could be greatly reduced due to depletion of the glacier mass, posing serious eco-environmental problems. The snowmelt water in the dry season is particularly crucial for Bangladesh and West Bengal (India) in the downstream of the Ganges River because it supports vulnerable ecosystems, for example, the "Sundarbans"- the largest single tract of mangrove forest in the world (Fig. 20.2). The Sundarbans are also threatened from sea level rise. Note that with the increase in population and economic activities,

Fig. 20.2 Sundarbans in Bangladesh and India. (https://www.pinterest.co.uk/pin/308144799480768186/)

water demand will likely be higher in the long-run. Therefore, the gap between the demand and supply will be widened by the alteration of present equilibrium of flow pattern. As a result, irrigation could significantly be impacted. This would affect food security situation in the river basins as well as the livelihoods of millions of people (World Bank 2013).

- *Global mean temperature increase, changes in precipitation, and impacts on and vulnerability to water resources:* The regional difference in impacts and vulnerability may be conspicuous depending on climatic and hydrological dynamics as well as geographical, population and ecosystem distribution. At present, the great pressure on water resources is from rising human populations, particularly growing concentrations in urban areas. Possible increases in water requirements due to increased agricultural production to meet the growing needs of the burgeoning population and rapid economic growth to tackle widespread poverty would likely increase the total water requirements substantially. Freshwater availability in large river basins is projected to decrease due to climate change (IPCC 2014). Note that for the South Asia region including Bangladesh, the monsoon flow may increase but it does not mean that availability will also automatically increase particularly for Bangladesh located in the tail end of the GBM region. As the country does not have any potential storage sites, the monsoon water would be a waste. Rivers in Bangladesh have a high seasonality and due to this factor, per capita freshwater availability will decrease despite an overall annual increase. There will also be regional variations in water availability. Due to sea level rise and intrusion of saline water, coastal fresh and ground water sources would likely become polluted. Salinity has become a problem over a large part of the coastal area of Bangladesh, mainly due to reduced surface water flow in the coastal rivers. A 45-cm sea level rise could inundate 11% of Bangladesh (IPCC 2001). A recent estimate shows that with a 62-cm sea level rise by the end of the present century, 20% of Bangladesh or 62% of the coastal region could be inundated (Nishat et al. 2013). Salinity intrusion due to rising sea level could also significantly affect coastal agriculture, human settlements, agriculture and forestry and fresh water and ground water aquifers. Future scenario for India and Nepal might not be as critical as for Bangladesh. Both countries have plenty of storage potentials and they can explore investment opportunities in water storage infrastructure from increased river flows in spring and in monsoon to facilitate irrigation in the lean season (World Bank 2013). The downstream countries, Bangladesh and the lower Gangetic plain in India, could also benefit from the storage infrastructure as they will augment dry season flows in the rivers. Increased rainfall could increase recharge of the ground water tables. In many areas in India ground water tables are falling at faster rates due to excessive withdrawal to meet the growing demand. The trend could be exacerbated in the future to meet increasing demand for water from a growing population, more affluent life styles, as well as from the services sector and industry (World Bank 2013). Rapid falling of ground water tables is also a problem in Bangladesh and it could act as a threat to the country's food supply by 2030 (Amarasinghe et al. 2014).

- *Global mean temperature increase and the probability of extreme weather events*: Future climate change will significantly impact monsoon and winter temperature and precipitation dynamics, increasing the vulnerability of water resources by increasing the frequency and magnitude of droughts and floods in South Asia, particularly the GBM Region. Countries of this Region would expect unusual and unprecedented spells of hot weather more frequently in the future. Relative to the pre-industrial times, mean warming in India could be between 1.7-2 °C by 2030 and 3.3–4.8 °C by 2080s under the business-as-usual (between RCP6.0 and RCP8.5) scenario. Another significant aspect of climate change is the increase in the frequency of occurrence of extreme events such as droughts, floods, and cyclones. The IPCC (2013) has also projected that some extreme weather events would occur with different likelihood level (Table 20.1). India-wide precipitation change is projected to increase from 4% to 5% by 2030s and from 6% to 14% by 2080s compared to the 1961–1990 baseline period. For the decades, 2060s and beyond, results from the model simulations demonstrate a consistent positive trend in frequency of extreme precipitation days (e.g. > 40 mm/day) in India (Chaturvedi et al. 2012). Climate models are in agreement about increase in monsoon precipitation as well as associated extremes in the Indian monsoon region (Christensen et al. 2013). It is very likely that flooding events will increase in the monsoon regions especially in the mega-delta areas of GBM rivers (Parry et al. 2007). For India, magnitude of the present 100-year event would likely to be transformed into a 10-year event at 4 °C warming. Significant increase in peak flow is projected at 4 °C warming for the Brahmaputra River and 50% increase in runoff could occur for the Ganges River. The low flow of the Ganges and Brahmaputra is expected to decrease by 13% at 2 °C warming (World Bank 2013). Mirza et al. (2003) concluded that a 2 °C rise in global mean temperature could increase mean flooded areas in Bangladesh by 23–29%. Due to increases in the magnitude of peak discharges of major rivers in Bangladesh, the recurrence interval of extreme floods will also change. Mirza (2002) analyzed the probability of occurrence of a current 20-year flood (5% annual probability of equalled or exceeded) magnitude of the GBM rivers in the future in the context of a 2 °C, 4 °C and 6 °C global mean temperature change scenario. The results show that floods with a magnitude of the current 20-years would occur more frequently in future.

The coasts of Bangladesh and the eastern India are highly vulnerable to cyclones (Fig. 20.3). The coast of Bangladesh receives more cyclones than the eastern coast of India. About 5% of global tropical cyclones originate in the Bay of Bengal, but Bangladesh, India and Myanmar experience more than 75% of the global casualties. Bangladesh is hit by about 0.93% (~1%) of the world's total tropical storms, India by 3.34%, Myanmar by 0.51%, Sri Lanka by 0.22%, and 0.50% die in the Bay without hitting any country. If the world's tropical cyclones with death tolls in excess of 5000 are considered, it is found that 16 out of the 35 such disasters occurred in Bangladesh and 11 in India. About 53% of the world deaths from these cyclones

Table 20.1 Recent trends, assessment of human influence on the trend, and projections for extreme weather events for which there is an observed late twentieth century trend

Phenomenon and direction of change	Global assessment that changes occurred (as per IPCC AR5)	Historical assessment of the GBM region countries	Likelihood of further changes in Late twenty-first century globally
Warmer and/or fewer cold days and nights over most of the land areas	***Very likely***	India: Dash and Mamgain (2011) Bangladesh: Shahid et al. (2012) *Nepal*: GoN (2017)	***Virtually certain***
Warmer and/or more frequent hot days and nights over most of land areas	***Very likely***	India: Mazdiyasni et al. (2017) Bangladesh: Shahid et al. (2012) Nepal: GoN (2017)	***Virtually certain***
Warm spells/heat waves. Frequency and/or duration increases over most land areas	***Medium confidence*** on a global scale. Likely in large parts of Europe, Asia and Australia	India: Rohini et al. (2016) Nepal: GoN (2017)	***Very likely***
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation	***Likely*** more land areas increase than decrease	India: Goswami et al. (2006), Ghosh et al. (2012), Chaturvedi et al. (2012)	***Very likely*** over most of the mid-latitude land masses and over wet tropical regions
Increases in intensity and/or duration of drought	***Low confidence*** on a global scale ***Likely*** changes in some areas	India: Rama Rao et al. (2013)	*Likely (medium confidence)* on a regional to global scale
Increases in intense tropical cyclone activity	***Low confidence*** in long term (centennial) changes ***Virtually certain*** in North Atlantic since 1970	India: Singh (2007)	***More likely than not*** in the Western North Pacific and North Atlantic
Increased incidence and/or magnitude of extreme high sea level	***Likely*** (since 1970)	India: Unnikrishnan et al. (2015)	***Very Likely***

took place in Bangladesh and about 23% in India, for a combined total of 78% in these two countries. Bangladesh and India suffer most, although both of them together are hit by only 4.27% of the world storms (Rahman and Rahman 2015). In terms of impacts, Bangladesh is vulnerable to at least 40% of the impacts of total storm surges in the world (World Bank 2010). Ali (1979) listed several physical features those are directly influenced, and these include: shallow coastal water, convergence of the bay, high astronomical tides, thickly populated low-lying islands, favourable cyclone track, and innumerable number of inlets including the Ganges, Brahmaputra and Meghna rivers. The cyclones and associated surges kill people, mostly women and children, and has devastating effects on the Sundarbans

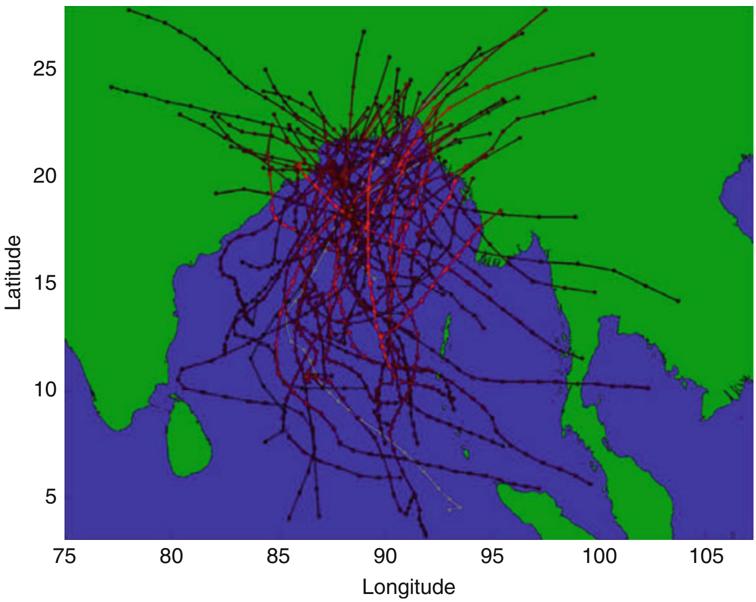

Fig. 20.3 Cyclone tracks in the northern Bay of Bengal between 1977–2013. (Chiu and Small 2015; permission received). Tracks shown in grey occurred in and after 2011 for which the authors did not have water level data. Filled circles correspond to 6-h intervals for which wind speed estimates are available

ecosystem. The April 29 cyclone of 1991 killed about 140,000 people in the coastal districts in Bangladesh. Cyclone induced saline water intrusion in surface water and soil resources becomes a serious challenge and significant limitation of adaptation practices for the local farmers. Climate change could likely increase intensity of tropical cyclones and associated precipitation and there is an uncertainty about the increase of their frequencies (Christensen et al. 2013).

20.3 Climate Change Policies

Apart from the use of technological advances to combat climate change, there has to be sound and supportive policy framework. The policy framework should address the issues of redesigning social sectors with focus on vulnerable areas under extreme weather events. Focus may be on integrating national development policies into a sustainable development framework that complements technological adaptation options. There is also a need to take steps towards a carbon and energy efficient economy leading to sustainable food security through integrating innovations, technologies, efficient resource use, sound public policies, establishment of new institutions, and development of infrastructure.

20.3.1 Bangladesh

Bangladesh has two major strategies dealing with climate change: the NAPA (National Adaptation Program of Action) 2005 (updated in 2009) and the BCCSAP (Bangladesh climate change strategy and action plan) 2009. Until 2005, Bangladesh did not have any climate change strategy or plan. As the country experiences natural hazards/disasters almost every year, government has been taking several measures in response to hazards/disasters. A wide variety of those measures implemented as part of key policies had the potential to reduce the vulnerability to climate change (Tanner et al. 2007). NAPA was formulated with strategic goal and objective of reducing adverse effects of climate change (MoEF 2005). But NAPA 2005 considered only urgent and immediate priorities for adaptation and engaged sector-based line ministries (Alam et al. 2011).

In the post NAPA 2005 years, a significant shift occurred in planning process in response to climate change. Influence of international climate change policies and politics became more predominant over national policy processes. At the same time, political and stakeholders' awareness grew (Khan 2012). Moreover, incentives were created by an expectation of significant climate change-related funding (Alam et al. 2011). All these were driving forces behind the formulation of a new strategy for climate change and update of NAPA 2005.

In 2008, The Ministry of Environment and Forests prepared Bangladesh Climate Change Strategy and Action Plan prior to the UK-Bangladesh Climate Change Conference in London. This BCCSAP was revised a year later and accepted in 2009. The BCCSAP demonstrates policies and strategies to become resilient to climate change. The strategy entails the following six pillars (World Bank 2009 and GoB 2009) and illustrated in Fig. 20.4.

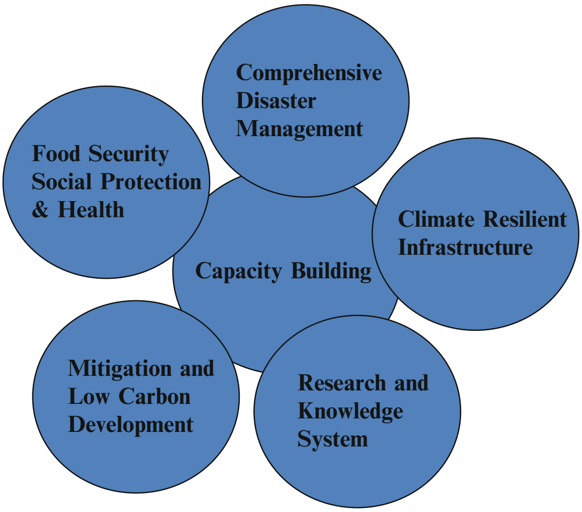

Fig. 20.4 The six pillars of Bangladesh climate change policy and strategy. (based on GoB 2009)

Pillar 1 Food security, social protection and health. The low income poorest section of the society is likely to be affected by climate change. Therefore, the activities outlined under this pillar will focus on the needs of the most vulnerable group for food security, safe housing, livelihood, employment and access to basic services, including health.

Pillar 2 Comprehensive disaster management. Activities organized under this pillar will contribute to strengthening of the existing comprehensive disaster management programmes and systems to tackle future extreme natural hazards as a result of climate change.

Pillar 3 Building resilient infrastructure. Climate proofing of existing infrastructure for storm surge (coastal embankment) and flood (river embankment) management and construction of emergency infrastructure (e.g., cyclone shelters and drainage outlets) are planned under this pillar to deal with the coastal zone and other climate risk areas.

Pillar 4 Increasing the knowledge base. Research to project and predict possible magnitude and timing of climate change impacts on the key economic sectors to better planning of future investment strategies. The other key objective to ascertain that Bangladesh is effectively linked to regional and national knowledge networks of climate change.

Pillar 5 Mitigation and low carbon development. Bangladesh's contribution to the global greenhouse gas emission is very insignificant. Despite this, Bangladesh is planning to follow a low carbon development path focusing on reducing carbon emissions across the economic sectors.

Pillar 6 Capacity building and institutional strengthening. The capacity of government ministries and agencies, civil society and the private sector will be strengthened under this pillar to tackle the challenges posed by climate change.

The BCCSAP provides a 10-year programme (2009–2018) of capacity and resilience building of the country to meet the challenge of climate change. After the acceptance of the BCCSAP, Bangladesh pledged US $75 million for 5 years to support to implement the plans outlined in the document. Initially a Multi Donor Trust Fund (MDTF) was established to get funding from donors especially from the United Kingdom. In 2010, this MDTF evolved into the Bangladesh Climate Change Resilience Fund (BCCRF). Government also created the Bangladesh Climate Change Trust Fund (BCCTF), through the Climate Change Trust Fund Act 2010, with the objective of implementing the actions and programme of the BCCSAP. Financing of the BCCTF comes from country's internal resources and the Government allocated about $253 million for the 3- year period 2009–2012 (UN-REDD Programme 2012). Both BCCRF and BCCTF are managed by government and the World Bank provided technical support in fund management of the BCCRF. The BCCRF was wound up in 2017 as the World Bank declined to manage it due to lower rate of service charge (Daily Star 2018).

20.3.2 India

To address the future challenges, in June 2007, the Government of India announced the constitution of a high-level advisory group on climate change and prepared a **'National Action Plan on Climate Change (NAPCC)'** and that was released by the Hon'ble Prime minister of India on June 30, 2008 *outlining existing and future policies and programmes addressing climate mitigation and adaptation* which is in line with the international commitments and relates to sustainable development, co – benefits to society at large, focus on adaptation, mitigation, and scientific research (GoI 2008). The plan to be implemented is through eight missions representing multi-pronged, long-term and integrated strategies for achieving the key goals (Table 20.2).

20.3.3 Nepal

In 2011, Nepal drafted its Climate Change Policy which is comprised of following seven (7) pillars: Climate adaptation and disaster risk reduction; Low carbon development and climate resilience; Access to financial resources and utilization; Capacity building, peoples' participation and empowerment; Study and research; Technology development, transfer and utilization; and Climate-friendly natural resources management. The major highlights of the policies are described below.

Climate Adaptation and Disaster Risk Reduction Activities under this pillar will focus on the implementation of National Adaptation Program of Action (NAPA) and monitoring of glaciers and glacier lakes and implementing adaptation activities in the prioritized vulnerable glaciers. It also emphasized on forecasting water related hazards, implementation of early warning systems, and development of preventive measures. The other important features of this pillar are identification of communities and areas to be impacted by climate change and implementation of adaptation and mitigation measures based on local knowledge, skills and technologies, and development of necessary mechanism for forecasting and preventing vector-borne, infectious and communicable diseases by climate change.

Low Carbon Development and Climate Resilience Pillar two focuses on low carbon emissions and climate-resilient development path for socio-economic growth. In order to do so, it emphasized on carbon sequestration through scientific management of forests, land use plans and controlling deforestation. Renewable energy development, expansion of clean energy technologies, energy auditing in industries, increase of energy efficiencies and development climate resilient infrastructures are the other major highlights of this pillar.

Access to Financial Resources and Utilization Under this pillar, the policy document is intended to create a Climate Change Fund (CCF) through mobilizing resources from public and private as well as external sources to address the

Table 20.2 Salient features of policies and action programmes embedded in the India's National Action Plan on Climate Change (NAPCC), 2008

Policy pillars	Climate change policy
Solar energy	The policy aiming at promoting the development and use of solar energy for power generation and other uses. The ultimate objective of this policy is to bring solar energy at the competitive level with fossil fuel based energy options. It also recognizes to expand the scope of other renewable and non-fossil options that include nuclear, wind and biomass energy sources. Of India's ambitious target of putting in place 175GW of clean energy capacity by 2022, 100GW is to come from solar projects. The present budget (2018–2019) eliminated the 5% customs duty on solar tempered glass used for manufacturing cells, panels and modules and this will make finished solar panels relatively cheaper.,
	In the institutional aspect, the policy considers establishment of a solar research Centre to facilitate international collaboration on technology research and development for strengthening of domestic manufacturing capacity to make available cheaper solar power systems to the grassroots level.
Energy efficiency	Improvement of energy efficiency through reduction of energy consumption in large energy consuming industries, with a system to trade energy-saving certificates.
	Focusing on the demand side management for all sectors and creation of mechanism to finance the programmes.
	Reduction of taxes and implementing other financial measures on energy-efficient appliances to make the products more affordable.
Sustainable habitat	Promoting energy efficiency building codes in the design of new and large commercial buildings to optimize their energy demand.
	Envisioning recycling and urban waste management as a major component of ecologically sustainable economic development.
	Shifting to strong public transport system to facilitate growth of medium and small cities.
	Addressing the need to adapt to future climate change through increasing infrastructure resilience, implementing community based disaster management and measures for improving the warning systems for extreme weather events.

(continued)

Table 20.2 (continued)

Policy pillars	Climate change policy
Water mission	Developing a framework to optimize water use efficiency by 20% through pricing and regulatory mechanisms.
	Meeting a large portion of urban water needs through recycling of waste water; adoption of new and appropriate technologies, for example, low temperature desalination technologies to meet water demand of the coastal cities.
Sustaining the Himalayan Ecosystem	Understanding Himalayan glacier system, and their extent of recessions by launching a joint effort of climatologists, glaciologists and other experts.
	Exchange of information with the South Asian countries and countries those share the Himalayan ecology.
	Maintenance of two-thirds of mountainous regions under forest cover to prevent soil erosion and land degradation.
Green cover Currently forest cover is 23.5% of India's territory. The recorded forest area in the country are 76.96 million ha and includes 41.90 million ha of Reserve Forests (RF), 21.66 million ha of Protected Forests (PF) and 13.44 million ha of Unclassed Forests (UF) (FSI 2008). https://www.iufro.org/download/file/7400/5122/India_pdf/	Implementing massive afforestation programme in the degraded forest lands through direct involvement of communities and increasing forest cover by 10% from the current level in order to create carbon sink, preservation of ecological balance and maintenance of bio-diversity.
Sustainable agriculture	Making Indian agriculture more resilient to climate change through development of new varieties of crops those are thermal resistant as well as capable of withstanding weather extremes, long dry periods, and flooding and variable levels of moisture.
	Introduction of new credit and insurance mechanisms to adapt to projected climate change.
Knowledge of climate change	Policy to create Climate Science Research Fund, improved climate modelling, and increased international collaboration to understand climate science better, impacts and challenges.
	Encourages private sector initiatives to develop innovative technologies through venture capital funds for adaptation and mitigation.

challenges of climate change. It would also generate resources by promoting carbon trade, clean development mechanism and from the polluters.

Capacity Building, Peoples' Participation and Empowerment This pillar focuses on capacity building of people from local to policy level on various aspects of climate change such as adaptation, mitigation of impacts, low carbon growth, technology development and transfer and carbon trade. It further focuses on the participation of poor and marginalized indigenous communities, women, children and youth in the implementation process of climate adaptation and climate change relevant programmes as well as participation of local institutions, NGOs and civil society particularly for information dissemination, awareness raising, training and empowerment.

Study and Research This pillar has emphasized on conducting study and research to facilitate implementation of adaptation measures to tackle adverse impacts of climate change and accrue benefit from positive impacts. The programme includes utilization of regional climate models (RCMs) and other models, research and monitoring of risks, bio-fuel and participatory research.

Technology, Development, Transfer and Utilization The primary focus of this pillar is identification and development of appropriate technologies for mitigating the impacts of climate change. It further emphasizes on climate-friendly traditional techniques, indigenous skills and knowledge and their utilization.

Climate-Friendly Natural Resources Management This pillar emphasizes on several important topics. They are: alternative livelihoods through proper utilization, promotion, conservation of forest resources; encouraging investments from national, regional and international sources to develop clean energy especially hydropower; soil and water conservation; carbon sequestration; and adoption of basin approach for water management.

20.4 Comparative Analysis of Policies, Key Risks, and Regional Integration

Nepal, India and Bangladesh – these three GBM region countries adopted their climate change policies almost at the same time. In general, it is evident from the previous Section that the policies of Bangladesh and Nepal have some similarities. The policies of India are significantly different from those of Nepal and Bangladesh. In this Section we will present a comparative analysis of the climate change policies of the three countries in terms of mitigation and adaptation, how the IPCC identified key vulnerabilities have appeared in the policies and strategies for regional integration of the policies.

20.4.1 Mitigation and Adaptation Policies

Mitigation Nepal, India and Bangladesh share most of the contiguous region of the GBM rivers. However, their mitigation policies and targets are quite different. Per capita emissions of these countries are very low compared to the developed countries and they do not have any binding mitigation obligations as per the UNFCCC.

The *Indian* climate change policies are heavily emphasized on reduction of greenhouse gases. This is perhaps due to substantial international pressure on the country to reduce GHG emissions. In the Intended Nationally Determined Contribution (INDC) submitted to the UNFCCC, India committed a voluntary goal of reduction of emission intensity of its GDP by 33–35% by 2030 from 2005 levels. Indian policies are highly focused on expansion of renewables and afforestation. By 2030, India's non-fossil based power generation capacity would increase to 40% and create an additional carbon sink of 2.5–3 GtCO_2e through expanded forest and tree cover.

In October 2016, *Nepal* submitted Nationally Determined Contribution (NDC) document to UNFCCC. This plan was found to be more ambitious than what INDC submitted in early of that year. The NDC contains 14 targets compared to 10 of the INDC. These targets include plans to increase renewable energy production with specific importance to hydropower development which demonstrates Nepal's commitment to shift to a low carbon development pathway. The NDC does not include any overall greenhouse gas (GHG) emission reduction targets.

Bangladesh's INDC has strongly intended to participate in the global efforts to limit temperature rise to two degrees or preferably 1.5 ° above pre-industrial levels. The Country is also committed to a low-carbon, climate-resilient economy and to becoming a middle-income country by 2021 whilst ensuring that it will not cross the average per capita emissions of the developing world. Bangladesh's specific targets focused on power, transport and industry sectors. The reduction goals are: (1) an unconditional contribution to reduce GHG emissions by 5% from Business-as-Usual (BAU) levels by 2030 using local resources; and (2) elevating the reduction to 15% subject to appropriate international support in the form of finance, investment, technology development and transfer, and capacity building.

Adaptation The term "adaptation" appears only a few times in the India's National Action Plan on Climate Change. Among the seven outlined principles of the plan, only one of them directly addresses adaptation through adoption of appropriate technologies. However, climate change policies of Bangladesh and Nepal are highly focused on adaptation. Three out of six pillars of Bangladesh's BCCSAP directly address adaptation issues and outlined 21 sub-programs on: *food security, social protection and health*; *comprehensive disaster management* and *infrastructure*. The '*Research and Knowledge Management*' and '*Capacity Building and Institutional Strengthening*' pillars constitute many programmes which are designed to facilitate adaptation indirectly. Nepal's climate change policies are highly focused on adaptation. Section 8.1 of the document is completely devoted to policies on climate change adaptation and risk reduction. The adaptation objectives target flow of at least 80% of the resources at the grassroots level in the communities to increase resilience and is committed to implement adaptation programmes as per national development agenda to maximize benefits by enhancing positive impacts and mitigating the adverse impacts.

20.4.2 Addressing the Key Risks

The IPCC (2014) identified a list of key risks associated with the "Reasons of Concern (RFC)" (Fig. 20.1). In this subsection, we will illustrate how these key risks appeared or addressed directly/indirectly in the climate change policies of India, Nepal and Bangladesh.

(i) **Risk of death, injury, ill-health or disrupted livelihoods**: Low-lying coastal zones and urban areas are particularly vulnerable to these risks from sea level rise, storm surges and inland flooding. The Eight Missions of India's 'National Action Plan on Climate Change' policy document does not address sea level rise, storm surges and urban flooding issues. However, Section 4.4 of the background document (GoI 2008) mentions coastal protection and outlines some soft activities which include high resolution modeling, development of salt tolerant crops, timely forecasting and warming of cyclones and floods, and enhanced plantation and regeneration of mangroves and coastal forests. These activities would perhaps reduce risks of death, injury, ill-health and disrupted livelihoods. There is no mention of defence infrastructure such as coastal embankment to protect population from storm surge and sea level rise or protection of urban population from inland flooding. Bangladesh's BCCSAP (GoB 2009) comprehensively addresses the risks in terms of strengthening cyclone and flood forecasting and early warning systems, coastal afforestation, coastal polders/embankment and inland flood embankments, drainage infrastructure and urban drainage systems, and repair and maintenance of coastal cyclone shelters.

(ii) **Risk of breakdown of infrastructure due to extreme weather events:** Floods, landslides, cyclones and storm surges cause significant damage to infrastructure in the GBM countries. Increased risks of infrastructure damage are cited in the policy documents. Section 4.3.1 of the Indian policy (GoI 2008) document addresses the risk reduction of infrastructure through better design taking climate change into account, enforcement of building codes, better urban planning and zoning of vulnerable areas. Pillar 3 of Bangladesh's BCCSAP entirely focuses on infrastructure. It emphasized on well-maintained infrastructure (coastal and river embankment) and urgently needed infrastructure (cyclone shelters and urban drainage) to tackle short- and medium-term impacts of climate change (GoB 2009). It further emphasized to undertake strategic planning of future infrastructure needs, taking into account future socio-economic development pattern and changing hydrology of Bangladesh due to climate change. Nepal's climate change policy clearly acknowledged the risk of infrastructure damage from the extreme hazards to be induced by climate change. At the outset, it underscored the need of climate resilient infrastructure, and formulation and implementation of design standards and technology for them (GoN 2011).

(iii) **Risk of mortality and morbidity of extreme heat:** Heat waves have already become a public health threat in South Asia but it is preventable. A severe heat wave in May 2015 claimed lives of more than 2500 people in the southeastern parts of India (Rohini et al. 2016). While the developed countries vulnerable to heat waves have designed and implemented adaptation mechanisms, for example, in response to 2003 European heat wave, developing countries are much behind. The Indian policy document does not address heat waves problem directly. Section 4.5 of the background document identifies GIS mapping of access routes to health facilities in areas prone to climatic extremes (GoI 2008). However, it does not provide any guidance on how the vulnerable people would be made aware of these routes. Bangladesh's BCCSAP and Nepal's Climate Change Policy Document also do not address heat waves as a health risk at present or in the future.

(iv) **Risk of food insecurity:** An estimated 15% population of India, Bangladesh and Nepal are food insecured despite tremendous progress has been achieved in agriculture productivity (FAO 2015). Climate variability and extremes presently often affect food production and its availability, access, prices, and employment in agriculture, and they are likely to be impacted more in the future. The Indian policy document does not discuss "food security and climate change" directly. However, it underscores the need of development of thermal tolerant crops and alternative cropping patterns, capable of withstanding extreme weather, long dry spells, flooding and variable moisture availability. It emphasized on risk management, access to information and biotechnology to facilitate adaptation of agriculture to climate change. The issue of food security is addressed with very high priority in the Bangladesh's BCCSAP (GoB 2009). In its Pillar one of the policy, emphasis is particularly given to ensure food security of the population most vulnerable to climate change especially women and children. Policy has been outlined to develop climate resilient cropping system which are tolerant to floods, droughts and salinity, as well as fisheries and livestock systems to ensure food security at local and national levels. Nepal's climate change policy acknowledged the effect of climate change on food security (GoN 2011). However, strategy and work plan to tackle food security issue from climate change are missing.

(v) **Risk of rural livelihoods and income:** Most of the poor people live in the rural areas and are dependent on subsistence agriculture. IPCC AR5 (2014) is in high agreement that climate variability and extremes directly affect poor people's lives through impacts on livelihoods, such as losses in crop yields, loss of employment, destroyed homes, food insecurity, and indirectly through increased food prices. None of the eight missions of the India's policy document addresses risk of rural livelihoods and income from climate change.

BCCSAP addresses increase of resilience of vulnerable population through livelihood diversification (GoB 2009). Nepal acknowledges loss of livelihoods by climate-induced disasters (GoN 2011).

(vi) **Risk of loss of marine and coastal ecosystems and biodiversity:** Coastal areas of India and Bangladesh are of high economic and environmental values. Ecologically sensitive the largest single patch of mangroves forest "Sundarbans" is shared by India and Bangladesh. In India, at least 250 million people live within 50 kilometers of the coast line (UNISDR/UNDP 2012). In Bangladesh, coastal zone was the abode of 25% of the population in 2011 (CCC 2016). The Indian climate change policy document does not discuss the policies and strategies to tackle loss of coastal and marine ecosystems due to sea level rise. BCCSAP of Bangladesh in general mentions about monitoring of climate change impact on ecosystem and biodiversity.

(vii) **Risk of loss of terrestrial and inland ecosystems**: IPCC AR5 (2014) projected that climate change would be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the twenty-first century, especially under high-warming scenario. In South Asia, the forest ecosystems of the Himalayan eco-region are the most vulnerable to climate change (ADB 2014). Indian climate change policy document states that the Himalayan ecosystem is vital to the ecological security of the Indian landmass through various services it provides, and outlines strategies to conserve the ecosystem (GoI 2008). BCCSAP does not discuss any strategy to mitigate impact of climate change on inland ecosystem (GoB 2009). Nepalese climate change policy emphasizes on proper utilization, promotion, conservation of forest resources as a means of alternative livelihoods; and prioritizing and implementing programmes on the sustainable management of forests, agro-forestry, pasture, rangeland, and soil conservation to address the impacts of climate change (GoN 2011).

20.4.3 Regional Integration of Policies

Countries of the GBM Region are vulnerable to climate variability and extremes. Every year extreme natural hazards cause enormous loss of lives and property. From the mountain to the coasts, these countries will certainly be more vulnerable to future climate change and associated hazards. Climate change will expose these countries to many risks in terms of personal injury and death, infrastructure, mortality and morbidity, food insecurity, loss of rural livelihoods and income, loss of marine and coastal ecosystems and biodiversity, and terrestrial and inland ecosystems. Although the rivers are contiguous, climate change policies of the GBM countries are individual in nature except Nepal which calls for promotion of regional cooperation to tackle adverse impacts of climate change in the upstream and downstream areas. Integration of climate change and disaster management policies is the first step towards greater regional cooperation.

Since early 1990s, six countries within the Mekong River basin have grouped together with the assistance of transnational communities (e.g. Asian Development Bank) to facilitate multiple development forums in trans-boundary river cooperation. It is timely to realize the urgency for a series of collaboration among all the countries (India, Nepal, Bhutan and Bangladesh including China) connected by the GBM System. The growing demand of water for domestic uses, industrial use in the region is also expected to increase. While the demand of water is mounting in the GBM Region, the supply of water flow is decreasing gradually. The research estimates that India and Bangladesh will have shortfall of water up to about 70 and 60%, respectively (Condon et al. 2009, 32–33). Water demand in India requires more diversion of water stream and dam construction on its rivers, including the Ganges. Such activities are likely to cause more stress on the already tense situation between India and its neighbouring states over water resources. A potential impact of loss of livelihood option is internal displacement or cross border forced migration.

Discontinuity in sustainable water supply is another major problem for the riparian countries. The lack of steady water supply in the dry seasons provokes these states to build large water storage dam to conserve monsoon water. Nonetheless, it generates negative consequences for other regional neighbours.

The GBM Region has a huge potential for hydropower project which is also a contentious issue for the region. All the riparian countries are primarily interested in hydropower for minimizing increased demands of electricity for domestic use, for irrigation, for flood regulation and for energy security to work together for sustainable cooperation on regional development.

Therefore, there is a high potential that a combined force of civil society and informed experts and multilateral bodies (e.g. donors—ADB, World Bank) can form an effective cognitive community that aims to contribute in collecting and disseminating information among the countries to let the people and government understand the nature of the problem and advocate for workable solutions to the crisis.

Countries in the GBM Region view water as an important resource that fulfils diversified demands of domestic water and energy needs. Crisis with water flows due to environmental and manmade degradations would have serious consequences on the people of the region and influence negative relations among neighbours. New kinds of regional agreements are desired among all the GBM riparian countries in order to attain the optimum benefits of water resources for the common good of the whole region.

Indo-Bangladesh cooperation on the Ganges has been limited to just water sharing and exchange of partial data during flood season. It needs to be expanded to a more collective regional water management approach, and to view the Ganges as a precious resource, one that must be jointly managed to maximize benefits. To develop arrangements for the mutual benefit of all the riparian countries, collective efforts and joint studies are needed. These include studies on the hydrological and morphological changes in the Ganges, feasibility studies of the construction of storage reservoirs upstream, and modelling of the hydrology of the basin. Joint optimum water utilization, legal water sharing arrangements and institutions for sustainable management of the Ganges water resources would result in socio-economic development and ecological benefits, and improve the livelihoods of the entire population of the Ganges depended area. A more equitable and sustainable solution to the contemporary challenges could be achieved by shifting the focus from just water sharing to the wider development objectives of utilizing the benefits from integrated water management and development of the river's watershed. To achieve these objectives, the riparian countries must approach the basin as a single ecological entity and the elements of sustainability and equity should be incorporated in water planning and policy goals.

Integration of policies needs a platform acceptable to all partners. We propose that BBIN Sub-Regional Forum of the South Asian Association for Regional Cooperation (SAARC), that has been set-up recently, to be the platform for such purpose. Currently, the Sub-Regional Forum focuses on Communication Sector. Mandate of the BBIN may easily be extended to cover natural disasters and climate change related concerns. Following are the major development concerning environment took place under the SAARC: study on "Protection and Preservation of the Environment and the Causes and Consequences of Natural Disasters (1987–1991); expressed concerns on the unprecedented climatic changes predicted by the Intergovernmental Panel on Climate Change (IPCC) (1990); urged the member countries to promote cooperation amongst themselves for enhancing their respective disaster management capabilities and for undertaking specific work programmes for protection and preservation of the environment (1991); recognized that international cooperation was vital for building up national capabilities, transfer of appropriate technology and promotion of multilateral projects and research efforts in natural disaster reduction (1995); noted the satisfaction about the growing public awareness of the need for protecting the environment within the framework of regional cooperation (2002); proposed to draft a Regional Environment Treaty as well as for the effective implementation of the SAARC Environment Plan of Action which is of utmost importance to the region being highly prone to natural calamities; emphasized the need for assessing and managing its risks and impacts and called for adaptation of initiatives and programmes as well as cooperation in early forecasting, warning and monitoring; sharing of knowledge on consequences of climate change for pursuing a climate resilient development in South Asia (2007); expressed "deep concern" over the global climate change and agreed to commission a team of regional experts to identify collective actions in this regard (2007); adopted SAARC Action Plan on Climate Change during the SAARC Ministerial Meeting on Climate Change (2008); reiterated the need to intensify cooperation within an expanded regional environmental protection framework to deal in particular with climate change issues (2008); climate change was the central issue of the summit with summit's theme "Towards a Green and Happy South Asia" (2010); and adopted a resolution to forge effective cooperation among the member states in a host of areas including economy, connectivity, climate change, food security, and to ensure timely implementation of the Thimpu Statement on Climate Change (2011).

Despite many resolutions and initiatives undertaken at the highest level of the SAARC since the organization's formal launching in 1985, the real progress is very insignificant in environment and in other relevant areas. Nepal, India and

Bangladesh share the Ganges basin and there are enormous opportunities of cooperation that exist among these three countries in terms of environment, trade and human development. Although in recent years, the magnitude of cooperation is increasing but much more is required. There are many hurdles for fostering cooperation and integration. Kher (2012) identified lack of confidence and huge trust deficit are the most critical elements in the integration process among the South Asian countries.

Climate variability and extremes have already caused dent to the development process of the GBM Region countries in South Asia. Future climate change together with other stressors will certainly cause larger development challenges. Following are the suggested actions and strategies for regional integration of climate change.

- Identification of reasons of mistrust among the countries that create hurdles for cooperation. Discussion should be with open-mind keeping well-being of the people as the central theme of any such initiative.
- Environmental imperatives in general and responses to climate change challenges in particular need to be integrated into the overall processes of planning, financing and implementation (Kakakhel 2012). Significant progresses have so far been made at individual country level and the countries could consult together to foster regional level integration and cooperation.
- Assessment of existing disaster management policies of the countries and integrating climate change is one of the key challenges. Countries can then initiate discussion on the common grounds for cooperation that would be mutually beneficial.
- Development of a regional framework for climate change through knowledge sharing, fostering structured and regular dialogue at all levels, and ensuring synergies and coordination of current and future actions are of paramount importance. Such initiative would enhance regional problem solving as well as increase the effectivity of national and subnational actions dealing with transboundary issues related to climate change (ADB 2014).
- Countries of the region have already identified low carbon economic development as the priority. Therefore, regional cooperation targeting low carbon economy could effectively be promoted through clean energy and technology transfer, and doing regional benchmarking of clean energy practices and performance (ADB 2014).
- Kakakhel (2012) had recommended setting up of appropriate institutional mechanism. BBIN Sub-regional initiative may be developed as the institutions to address the negative impacts of climate change and policy integration.

20.5 Conclusions

Climate change could cause irreparable damages to the unique ecosystems in the watersheds of the GBM System. Coastal ecosystem, for example, the Sundarbans mangrove, would be impacted from the reduced dry season flow in the Ganges River as well as from the sea level rise. Impacts on the water resources in terms of availability and extreme hazards would affect food security and livelihoods in the GBM Region.

Countries those share the GBM Region have already formulated national climate change policies only to address respective country level threats. India's climate change policies are broadly focused on mitigation; and adaptation has received lesser attention. The key risks that are associated with climate change are either addressed with unequal weightage or ignored in the national climate change policies.

Integration of policies in the GBM Region to address the key vulnerabilities requires a platform. Instead of creating any new platform, it would useful to utilize the existing one that is likely to function properly. We recommend that the BBIN Sub-regional platform of the SAARC would be an appropriate platform for integration of policies. Under the SAARC umbrella, integration on response measure on disasters and climate change related activities have already been mandated.

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Part IX
Road Map for the Future

Chapter 21
Climate-Risk Sundarbans Needs Multi-Pronged and Unified Approach for Ecological Sustenance a Necessity for Improved Livelihood: Summary and Concluding Remarks

H. S. Sen

Abstract The Sundarbans is an agglomeration of about 200 islands, separated by some 400 interconnected tidal rivers, creeks and canals spanning across two neighbouring countries of India and Bangladesh, is one of the largest productive deltas in the world and located in the Ganges-Brahmaputra-Meghna river basin. It has a rich heritage of biodiversity of flora and fauna possibly unparallel to coastal or any other ecosystem in the world. Only 29 nations and territories in the world have a population density higher than that in Sundarbans. The populace of Sundarbans suffers due to abject poverty with poor livelihood security because of various constraints including climate-related disasters. There is need for a holistic look at the entire problem being essentially of transboundary nature, since the problems and solutions of the two are not only mutually dependent but also complementary to each other, and therefore attempts were made in this book seeking for a future road map for higher and sustainable productivity and improved livelihood status of this contiguous area. The compendium embodies a unique fusion of various risk factor analyses with respect to geohydrological, climatic, disaster, natural, and anthropological aspects in search of the goal while the ecology of the entire area is to be protected a necessity to ensure improved livelihood. While analysing various areas on a holistic note it was urged to explore the prospects of ecotourism, a non-farm activity, with mangrove destinations, on transboundary mode to support livelihood security particularly during stress periods.

Keywords Sundarbans livelihood security · Climate change policy · Mainstreaming climate change and adaptation strategies · Tidal river management · E-flow and hydrogeological conditions in rivers · Biodiversity conservation and forest nmangement · Soil, water and crop management · Sweet and brackish water fisheries and aquaculture · Economics risk factor analysis · Ecotourism a non-farm sector

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21.1 Introduction

The Sundarbans is an agglomeration of about 200 islands, separated by some 400 interconnected tidal rivers, creeks and canals spanning across two neighbouring countries of India and Bangladesh, is one of the largest productive deltas in the world and located in the Ganges-Brahmaputra-Meghna river basin over parts of Bangladesh and India. The coastal mangrove wetland is playing a potential role in balancing the ecology, community socio-economy, and livelihoods of the community. It has been declared by UNESCO as World Natural Heritage Site in 1997. It is a hotspot of mangrove biodiversity with 373 faunal and 324 floral species. It is the habitat of world's largest contiguous mangrove forest and abode for the enigmatic Royal Bengal Tiger. The area, over time, has been continuously truncated in size and at present it is approximately three-fifths the size of what existed 200 years ago (about 16,700 sq km), the rest having been cleared and converted to agriculture and allied activities. Of the present expanse of 10,217 sq km, 4262 sq km (41.7%) is in India. About half of the area in India (2320 sq km) is land mass. The rest 5955 sq km (58.3%) is in Bangladesh. The Sundarbans eco-region holds about 0.1% of the global population, 137 countries/territories have population less than the Sundarbans, 67 countries/territories are smaller in size, and only 29 nations and territories have a higher population density. The region, therefore, is globally significant not only for the natural area and biodiversity, but also for the number of people who inhabit.

The eco-region, which is particularly sensitive, has huge significance in terms of the deluge of ecological services and functions for human welfare. But unbridled and naive anthropogenic avarice is taking a heavy toll of Sundarbans resources in both the countries ripping people of the region off their precious livelihoods. Obviously, the future steps for improvement should be of mutual benefit to both the countries, more specifically the tidal dominated eco-region. There is need for a holistic look at the entire problem being essentially of transboundary nature, so much so that the problems and solutions of the two are not only mutually dependent but also complementary to each other, and therefore attempts were made in this book seeking for a future road map for ecological sustenance towards higher and sustainable productivity and improved livelihood status of this contiguous area. The compendium embodies a unique fusion of various risk factor analyses with respect to geohydrological, climatic, disaster, natural, and anthropological aspects in search of the goal while the ecology of the entire area is protected.

21.2 Need for Policy Integration on Climate Change

The eco-region across Bangladesh and India falls prey to climate change variabilities and extremes, as a result of which, livelihood of farmers and other inhabitants suffer. Both countries have their individual policies on climate change, unfortunately there are wide gaps in approaches with few commonalities. This is striking, since in spite of the very presence of SAARC since 1985, having mandate to address such vital issues between the riparian countries, little progress has been made, as a result both continue to suffer. For example, GoI considers the Himalayan ecosystem is vital to ecological security, as the basic, of the Indian landmass through various action plans, while GoB does not consider the inland ecosystem being possibly not its priority. Policies with respect to Sundarbans eco-region have been compared and critically analysed to identify; most importantly, the National Action Plan and Climate Change Policy of India (2008) does not address sea level rise, storm surges, and urban flooding issues with emphasis, ignoring their impact on low-lying coastal zones. Construction of embankments to prevent flooding of the low-lying areas has been missing, so much so that the risk of rural livelihoods, income, and important issue like food security due to climate change were not addressed. Bangladesh gives appropriate emphasis on these issues. However, the coverage of GoI on coastal protection has been limited to soft activities which include high resolution modelling, development of salt tolerant crops, timely forecasting and warning of flood and cyclones occurrences, and enhanced plantation and regeneration of mangroves and coastal forests. Unlike Bangladesh, 'adaptation' to the miseries due to the weather extremes has been little emphasized in the policy of India. 'Mitigation' policies are also widely different in the two countries. Even policies and strategies to tackle loss of marine and coastal eco-region are widely different. India however gives considerable importance to mitigating greenhouse gas emission through expansion of renewable wastes and afforestation. Making note of such wide variation in the country-wise policies on key issues on climate change it is strongly advocated, to start with, undertake integration of the policies of the two countries, and possibly Nepal also, all sharing the GBM basin, under the aegis of SAARC, to address key concerns and vulnerabilities, and discuss all related issues with open mind having full regards to geo-political sovereignty of the countries.

21.3 Deteriorated E-Flow in the Ganges and Need to Upswing: Joint Action Plan to Monitor and Suggest Future Improvements

If climate change were an issue to ponder upon with utmost emphasis, it is possibly equally important to have a look at the role of Farakka Barrage, and deteriorated hydrology of surface and ground water, and their impacts on the eco-region down to the south. The construction of Farakka Barrage across the Ganges is located 17 km upstream of the diversion of the river into Hooghly-Bhagirathi flowing through India and Padma-Brahmaputra-Meghna and their tributaries into Bangladesh – all finally terminating into the Bay of Bengal. It has been observed by a few of the barrage to be too inadequate to bring about any positive impact either to flush out sediment load or to increase navigational prospect for the Kolkata Port or to share dry season flow between the two countries for their mutual benefits, the very purposes for which it was conceived. There is little compatibility between the computed flow in 1977 and the actually available flow into Farakka after that, owing possibly to large and continual diversion of the river water at the upstream by a long list of hydro-power and irrigation projects in the later decades leading to deteriorating E-flow of water in the upstream stretch of the river Ganges within the Indian territory. Ganges is now one of the world's top ten rivers at risk due to over-extraction and pollution of water quoting the data of WWF-International, Gland, Switzerland. India's role as sharing entirely the upstream flow of water passing through a number of states before reaching the Farakka Barrage in West Bengal is therefore crucial in studying the impact of alleged wrong-doings both at public and private sectors on the South Bengal (India) and a major part of Bangladesh. This appears to be a glaring factor for a series of problems created therefrom causing saline water intrusion inland, rise of salinity in soil and water, affecting adversely both agriculture and sweet water aquaculture in Sundarbans in both countries. Although there are reports available in the Indian part that the navigation in Kolkata Port suffers significantly due to increasing sedimentation in rivers over time, there is considerable concern of saline water intrusion in Bangladesh. The affected lower Ganges delta in Bangladesh is much larger in area and possibly requires critical attention. Discharge data of the Ganges river for the period of 1970–2011, according to one analysis, show that dry season (November–May) flow has decreased up to 82% after the construction of Farakka Barrage.

Deteriorating hydrology in the rivers are also responsible for higher rate of erosion than accretion in the river banks, as result the islands in the Sundarbans are continually being modified. Appropriate interventions are needed to resuscitate the Ganges to arrest the adverse trend of hydrology considered to be possibly the most important component in terms of deteriorating E-flow at the earliest and, in due course, reverse it for sustainable ecology. Norms on drawing of quantum of water by the hydro-power stations mostly in Uttarakhand with respect to the flow rate have been so far arbitrarily decided during planning and without provision for sound assessment of the impacts, although some attempts have been made lately for such assessment, noteworthy of which has been by WWF-India. Dwindling water flow and deteriorating water quality in the downstream thus affect drastically the livelihood in the delta in many ways.

Questions are often raised about the trend in the change of biodiversity due to reducing amount of flow over time in the lower delta, especially in Sundarbans spread over both countries. Now the ecosystem is changing rapidly and biodiversity is depleting fast with the extinction of some species of the mangrove forest species. It however still provides ideal habitats for a variety of unique plants, aquatic organisms, and animals. A number of factors have been identified for the loss of biodiversity over time in the whole delta. Though it is not possible to attribute quantitatively the loss to different factors, most of them are directly and indirectly linked with reduced water flow in conjunction with various anthropogenic factors and climate change.

Indo-Bangladesh cooperation on the Ganges has been limited to just water sharing and exchange of partial data during flood season. It needs to be expanded to a more collective regional water management approach, and to view the Ganges as a precious resource, one that must be jointly managed to maximize benefits. To develop arrangements for the mutual benefit of all the riparian countries, collective efforts and joint studies are needed. These include studies on the hydrological and morphological changes in the Ganges, feasibility studies of the construction of storage reservoirs upstream and modelling of the hydrology of the basin. Joint optimum water utilization, legal water sharing arrangements and institutions for sustainable management of the Ganges water resources would result in socioeconomic development and ecological benefits and improve the livelihoods of the entire population of the Ganges dependent area. A more equitable and sustainable solution to the contemporary challenges could be achieved by shifting the focus from just water sharing to the wider development objectives of utilizing the benefits from integrated water management and development of the river's watershed. To achieve these objectives, the riparian countries must approach the basin as a single ecological entity and the elements of sustainability and equity should be incorporated in water planning and policy goals.

It is, therefore, important to place on record, in light of the above background, that the lower Ganges delta of both India (south of Farakka) and Bangladesh (southwest), which shares the same ecology, faces threats due to dwindling water diversion via Farakka Barrage and deteriorating E-flow and water quality of the river in the upstream at different places in India. This, other than the need for integration of climate change policies of the two countries, necessitates a holistic plan to be taken up by the governments of both countries through mutually exclusive agreements, and for the latter the following suggestions are made to seek for a lasting solution.

- There appears to be a need for revisiting the design of the Farakka Barrage, as well as the discharge and distribution norms of water in the interest of the two countries, keeping in view of the predicted flow of upstream Ganges water in long-term perspectives, and if necessary, fresh norms to be decided.
- Predicted flow of water through Ganges-Brahmaputra, both originating in Tibet, river system on account of retreat of glaciers and other parametric uncertainties due to climate change needs to be studied and refined with appropriate climate models in deciding the future norms for distribution of water via Farakka Barrage with as much precision as possible in different time scales.
- Need for fresh installation of hydro-electric power and irrigation projects in India must be given extremely careful consideration with stringent norms for discharge of river water in the upstream, along with impact analysis as a mandatory requirement, so that ecology of the area is not disturbed.
- Past hydro-electric power and irrigation projects in the upstream already in commission need also to be reviewed in terms of the norms for discharge of water, and if necessary, to be revised, so that ecology of the area is not disturbed.
- Strict administrative vigilance to be maintained to stop acts on unscrupulous diversion of water forthwith by private agencies in India.

- Location-specific integrated water development and management schemes at strategic points over the entire flow length in different time scales to be prepared and their methods of implementation be worked out, with adequate participation and vigilance from the local inhabitants, to ensure maintaining prescribed water quality throughout the year in India.
- In India, in particular, impacts of the water flow at different strategic points into lower delta in respect of salinity in soil & water, flow rate, tidal amplitude and fluctuations, sedimentation/hydrological parameters, navigation through rivers and in Kolkata Port, ground water table depths and qualities, important components of biodiversity, and any other related parameters should be taken up and monitored with a holistic plan, over minimum 5 year phases, through a central task force comprising of scientists, NGOs, government officials, local inhabitants, and the same placed in public domain. Similar programmes should be simultaneously planned and taken up by Bangladesh. A core team consisting of key members drawn from both countries should interact and monitor the progress once in each year and suggest for improvement with respect to targets fixed.

Technological advancements reported at country-level are focused in the following sections worth mutual attention and holistic application.

21.4 Mainstreaming of Climate Change Adaptation Strategies

Because of geo-physical characteristics of the Sundarbans, the adaptation options to tackle the impacts of climate change and sea level rise are limited. Perhaps the most effective step will be to restore the fresh water supply that the southwest region used to receive in pre-1975 period. Construction of a Barrage on the Ganges, just downstream of the distributaries, namely the Gorai-Modhumati, and, the Chandana-Barashia in Bangladesh will be able to restore the flow partially. For this purpose, a collaborative action, jointly, by India and Bangladesh may be pursued to ensure proper management of the adverse impacts of climate change and fight the sea level rise-induced salinity that is likely to rise further. For the Bangladesh part of the Sundarbans, it is suggested that the major aim of adaptation for Sundarbans would be to modify the threats of permanent inundation from the sea level rise-induced submergence. It was opined that the submergence process could not be stopped as most of the sea level rise would occur from the tectonic subsidence. One of the options is to retard the inundation process by enhancing sedimentation on the forest floor by applying guided sedimentation techniques. However, such techniques need to be piloted before formal application in the forest. The second but the most important adaptation option would be targeting to reduce the threat due to salinity intrusion as well as bringing down its concentration. This could be done through: (a) increasing freshwater flows from upstream areas; (b) resuscitation of existing river networks towards improving flow regime along the forest; and (c) artificial enhancement of existing river networks to facilitate freshwater flow regime along the rivers supplying freshwater to the western parts of the forest. Building hydropower dams in Nepal could also be an effective cross-border adaptation option for the Sundarbans. Flow of the Ganges can be doubled in the dry months by storing a small portion of monsoon flows in the Nepalese dams. Low flow augmentation could check saline water intrusion and help sustaining the Sundarbans ecosystem. For the Indian Sundarbans, World Bank recommended to consider long- and short-term adaption options and suggested the following: (a) *estuary management* measures such as embankment realignment, mangrove restoration, and salinity management to reduce long-term threats; and (ii) *disaster risk management* interventions such as early warning systems, emergency preparedness, and cyclone shelters to tackle near-term threats. It is stressed that inclusion of Nepal during the negotiations in the spirit of the 1977 Ganges Water Agreement will be beneficial for both parties.

21.5 Engineering Intervention on Tidal River Management and Scope for Creating On-Farm Water Storage Structure for Integrated Water Management

The reduction in flow and sediment abetted by sea level rise has led to increased flooding of low-lying agricultural lands. The freshwater availability during non-monsoon is highly deficient. Estuary management by way of closure though engineering structure has been adopted in several countries to create freshwater storage, and this holds promise for Sundarbans as well. Tidal river management (TRM), a practice which has been adopted in Bangladesh, has the potential of reducing the flood hazard. However, introduction of this ecotechnology requires careful considerations including: sequential availability of *beels*, limits on trapping silt, and the duration for this can be practised at a given location. In India, the idea of creating a freshwater storage is recommended by damming Saptamukhi river or elsewhere, using suitable state-of-the-art technology through phased development, and it is likely to reduce the vulnerability of Sundarbans to natural hazards – the practice therefore needs a serious re-look.

It was suggested from water balance analysis conducted in India considerable scope of rainwater harvesting in on-farm reservoir (OFR) for irrigation and raise multiple crops in a year. It was recommended for this purpose to convert 20% of the farm area into OFR. Simulation of surface drainage improvement with and without OFR indicated surface drainage improvement, at the same time, up to 75% in low-lying rice areas at one site, thus providing scope for cultivation of HYV of rice in rainfed lowlands.

21.6 Erosion and Accretion of the River Banks: Dynamic Shifting of the Islands

The low-lying coastal areas of Sundarbans mostly covered by mangrove forests is threatened by erosion. Multi-temporal satellite imageries were used attempting to address the issues of erosion and sea level rise in the mangrove forested islands of entire Sundarbans covering India and Bangladesh. Near about 325 sq km of land area has been found to be eroded during this period over nearly three decades (1990–2017). Another spatio-temporal study using satellite remote sensing showed, while the mangroves' areal extent has not changed much in the recent past, accretion rate of coastline has declined as against erosion rate which has remained relatively high in the recent years. As a result, the delta front has undergone a net erosion of ~170 km^2 of coastal land during 1973–2010. It could be inferred, from the two satellite studies that the relative loss of landmass has increased with time, and this is alarming.

21.7 Disaster Monitoring and Forecast, and Preparedness for Relief Actions

ISRO (India) observed from remote sensing satellites studies that although the disaster of the ecosystem cannot be averted completely the impact and loss of life can be minimized by effective implementation of frontier technologies like information communication technology (ICT) through advance warning, last mile communication, preparedness, monitoring, and damage assessment. Satellite data products are used in pre-disaster planning, which includes vulnerability zonation. In the flood prevention phase services of meteorological satellites can be used to detect various aspects of hydrological cycle especially cloud type, precipitation rate, moisture transport, and surface soil wetness which are vital inputs for runoff modelling. Flood extent is determined from moderate to high resolution remote sensing satellite, viz. IRS, Landsat, Spot, etc. The model-derived potential flood extent can help emergency managers to develop contingency plans well in advance. In response phase of disaster mitigation, remote sensing data are used for damage assessment. The case studies applied to Sundarbans showed application of the remote sensing technologies to monitor ecological disturbances following cyclones and landmass change due to accretion and erosion, the latter causing change in the boundary of islands, a dynamic phenomenon, often not accessible physically due to remoteness, particularly during post-hazards period. It is prudent, therefore, that although both countries made individual efforts to make such studies using advanced technologies to cope up with hazards being essentially of transboundary in nature, a combined approach using similar sensors and with frequent exchange of data could be more effective in the preparation and implementation of policy framework for early warning systems, preparedness, monitoring, and mitigating loss due to hazards, including rehabilitation, which are otherwise rituals affecting adversely the lives and socioeconomic conditions of the inhabitants.

For instance, cyclone *Aila* in 2009 proved that a low-magnitude cyclone of category 1 could have devastating and long-lasting impacts to the impoverished coastal residents of the affected areas. Such impacts were unexpected by the governments of both Bangladesh and India. They were also not well prepared for this event. For example, a sample survey conducted in the Indian part of the Sundarbans reported that only 5% people had knowledge about Cyclone *Aila* before it made landfall. This implies that the cyclone forecasting and warning systems were deployed in an untimely manner or failed to reach the coastal residents. On the other hand, the Government of Bangladesh downplayed the impacts of *Aila* by not declaring an official emergency in its immediate aftermath and not requesting for external assistance. This supports the argument that public cyclone preparedness was not adequate to protect these embankments.

21.8 Climate Change and Biodiversity Conservation

The mangroves, the largest and most precious community in Sundarbans out of the whole world, are extremely valuable heritage on account of mainly, its role in blocking the storm surge and cyclones to mitigate damage to inlands, maintaining ecology comprising of major 45 species including its role as food chain of the flora and fauna, and as source of economy and livelihood of the local inhabitants. Tropical mangroves forests are now among the most threatened habitats in the world. Studies indicated that mangrove forest degradation due to anthropogenic activities has been checked to a great extent. Nevertheless, there is a growing concern of latent degradation of mangroves vegetation across the transboundary Sundarbans due to certain environmental causes, such as (i) increased salinity, (ii) erosion of forest-lands, and (iii) increased frequency of natural hazards. These issues are unlikely to develop any sudden impact on mangroves vegetation covering large scale areas, but their persistent effect may alter vegetation dynamics in long term. In this context, Indian part needs to recreate environment using and managing sediment-laden freshwater of the feeder canal. Recreation of the Bangladesh Sundarbans environment involves two steps- (i) dredging sand bars from the Ganges and distributaries leading to the Sundarbans and allowing uniform sediment-laden freshwater flow inside the Sundarbans for maintaining oligohaline environment, and (ii) uniform deposition of sedimentation around forest-lands. Unfortunately, no joint effort engaging experts from both the countries has been effective to protect mangroves and its ecosystem until now. Either part of the transboundary Sundarbans has been subject to individual effort to protect and promote the Sundarbans, but these means are insufficient, since they are mutually dependent on each other, and therefore a united effort is required. The difficulty to compile a biological resource inventory as a unified unit in each taxonomic hierarchy across the transboundary Sundarbans has been compounded. There are different enumerations of biological organisms in the respective Sundarbans and so there are chances of more errors surfacing. In such case ambiguity may occur when the Sundarbans – a united block of mangroves forest covering both countries is considered. Until recently, global warming and sea level rise has been predicted to cause adversity to the transboundary Sundarbans and in such case, further, joint effort is urgently needed to protect the Sundarbans by way of plantation of climate resilient mangroves and develop a uniform management practices. Sincerely, a joint collaboration involving both countries, is required, else the fate of the unique eco-region across the transboundary Sundarbans may be at stake.

In a study in Bangladesh, the conservative prediction of IPCC clearly stated that the sea level will rise by 7–23 inches by the end of the century. Glaciers are melting resulting in sea level rise. Coral reefs, which are highly sensitive to small changes in water temperature and acidity of water, suffered the most and many succumbed to death. An upsurge in the number and intensity of extreme weather events, such as forest fires, heat waves, cyclones, floods, etc. has become established. It has been cautioned by many that up to 30% of animal and plant species could be wiped out by a global temperature rise of 2.7–4.5°C. Under such change the nature might adjust (i.e. adaptation). It is already visible that some species that love low saline condition, such as Sundri (*Heritierra fomes*), Shingra (*Cynometra ramiflora*), etc. have started to die in Sundarbans, while Passur (*Xylocarpus* spp) has become almost rare now. More salt tolerant species, such as Goran (*Ceriops roxburgii*), Jhana (*Rhizophora mucronata*), etc. will come to occupy these sites. Similar impact is seen on aquatic fauna as well. With the climate change impact, the fresh water availability in the Sundarbans Impact Zone will further decline and ultimately will get devoid of any fresh water, both surface and ground water. The cyclonic storms and tidal surges will gradually get enhanced and ultimately get very severe, which will cause a mass migration of population of the SIZ area to further north. Under such anticipated devastating predictions, a close and intensive monitoring on a regular basis to activate early warning protocol is essential.

The lower species in plant kingdom, the algae, are normally undermined. As a group, they do not include single taxa but is an agglomeration of absolutely unrelated or distantly related groups of organisms. This confers them a variety of morphology, structure, process, and characteristics unknown in any other single group of organisms. Sundarbans, spread across India and Bangladesh, is reportedly quite rich in terms of its algal flora with the presence of 762 species of algae, documented possibly for the first time. It is possible to delineate their presence in different zones of Sundarbans with notes on the habitats they occupy, while their dynamics in the ecosystem are dependent on many different environmental variables. The water quality data did not reveal much in terms of change but application of a diatom-based palaeo-limnological analysis suggests a subtle, yet distinct species assemblage shift 1987 onwards, along with climate change. It is therefore important to pay increased attention to algae, particularly diatom flora in Sundarbans, while inferring climate change effects in the past, for the purpose of predicting future climate dynamics, and also for possible impacts of climate change on the system.

21.9 Spatio-Temporal Variability of Soil and Water Characteristics: Need for Detailed Study on Groundwater System

Scores of data are being generated on soil and water characteristics in both India and Bangladesh. It is clear from the trend, which is spatio-temporally variable in nature, that rivers and estuaries are tending to become principally tide-fed with time since there appears to be lesser flow of water from the mighty Ganges in the upstream, being common to both countries, due to siltation and poor solid waste management. While, this is a matter of serious concern in so far as surface water hydrology and the related soil characteristics, being constraints limiting the crop productivity, leaving aside the frequent occurrence of climatic hazard and its influence in the eco-region, very little progress has been made on the groundwater and its utilization having tremendous potential otherwise from the point of view of its capacity along the coastal tract. It is indicative, though not conclusive so far from the limited studies, contrary to the observations from other coastal ecosystems in the globe, that the groundwater in Sundarbans is possibly not influenced by the adjoining rivers and the sea. In order of planning for exploitation of the coastal groundwater, specific programme needs to be undertaken, preferably in transboundary mode, to arrive at a definite conclusion and plan for the mode and nature of its use for irrigation and domestic purposes without affecting the ecology of the region.

21.10 Improved Land, Nutrient, Water, Crop Management Practices, and Key Features for Sustainable Economics of Cultivation

On the scope for use of stress-tolerant crops and other improved management aspects, it is advocated to adopt cropping system intensification in the Sundarbans by growing low water-requiring field crops, vegetable and fruits in *rabi*/summer season, and introduction of high-value commercial crops under protected cultivation, which are commercially viable and having good market demand; adoption of high frequency-low volume irrigation practices, like drip or pitcher, implementation of integrated nutrient management involving sources having high nutrient-use efficiency; and use of improved agronomic management practices like drum-seeder for rice transplantaion. Land-shaping model has been advocated, in particular, for use of various crop intensification models including pisciculture and duckery. Diversification of agriculture through agroforestry may be an important proponent for resource utilization, enhancing farm income, and livelihood security of farmers in these traditionally mono-cropped coastal areas. Upon cropping system intensification and mechanization, energy requirement for agriculture should grow rapidly for round the year cultivation. To meet the demand for future energy requirement as well as to reduce the dependence on conventional (non-renewable) energy resources, there is a need to explore the alternative (un-conventional or renewable) energy sources like solar, biological or natural resources. Advanced research methodologies to increase water productivity through the use of appropriate crop models can help in optimizing the water use, reduce the pressure on the ground water, and address salinity development under the imminent changing climate scenarios.

On the economics front, risk factors involved in agricultural practices and recommendations for improvement, based on location-specific constraints, should be the most important considerations for decision-making in farm management, adoption of new technologies, and enhancing farm income. Suitable cropping system intensification, with emphasis on introduction of high-value crops, can be one of the ways to agricultural risk mitigation. Complementarity between agriculture and industry/non-farm entrepreneurship are suggested as yet other ways for risk management. It is suggested that professional help is needed, who could act as key service providers to supply inputs and facilitate availing credits, buying insurance products, and selling of produce through single-window system. Such professionals will act as the facilitators between farmers and government agencies and help risk mitigation in agriculture. It is inferred that enhancing farmers' income in Sundarbans, West Bengal is a challenging task but can be performed satisfactorily when technology interventions are combined with appropriate policy support. The most critical concern for the farmers in the Sundarbans region is not only to achieve higher farmers' income level, but also to sustain the enhanced level across the different farmers' groups.

21.11 Improved Sweet and Brackish Water Fisheries and Aquaculture

Estuarine aquatic systems and braided rivers in and adjacent to the Sundarbans and the vast area of the Ganges tidal floodplain next to the core forest area in Bangladesh holds rice aquatic faunal diversity and provides plenty of opportunities to grow fish, shrimps and crabs. Currently these systems provide direct employment opportunity for 1.2 million people and indirect or seasonal livelihood for more than 10 million people across the southwest coast. Hilsa is the largest fishery in this region and shrimp brings the highest cash and export earnings. This vast fertile area provides great opportunity to improve fish and shrimp production and improving the livelihoods of the people in this region. Proper implementation of fisheries regulation is critical to ensure conservation of the rich fish diversity of this region as well as to continue to support livelihood of millions of people living on fisheries. While aquaculture is the major contributor to national fish production, agricultural GDP and export earning, it requires planned advancement from the current state to continue to grow in harmony with environment. Integration with rice and other crops, and with mangrove wherever possible can bring long-term sustainability of these systems. Change in the river flow due to siltation and reduced upstream flow, climate change, sea level rise, outbreak of disease in fish and crustaceans are major challenges for future growth and sustainability of both aquaculture and fisheries in this region. Land zoning for different products, landscape-based integrated approach for saving fisheries, and technological advancement for sustainable and resilient aquaculture vis-a-vis their environmental and societal impacts can be the future directions for growth and improvement of fisheries and aquaculture. In addition, there should be mechanism to bring research outputs into use and make impact on sustainability. A plan is required considering overlapping interest of fisheries and aquaculture with strong scientific base. Strengthening and activation of multi-stakeholder coastal zone management is essential for conservation and management of fisheries; enhancement of aquatic and wetland biodiversity; and sustainable intensification of aquaculture, along with developing means to monitor and mitigate the environmental and societal impacts. Finding ways to grow aquaculture and fishery in harmony in a mangrove ecosystem is of vital importance.

Shrimp farming in Bangladesh coastal areas is growing very rapidly in commercial interest and is associated with several environmental and societal impacts which hinder sustainable development in this blooming sector. It is necessary for the government to strictly enforce the existing law in order to restrict this dangerous trend of the useful agricultural land turning waste, and also with the purpose to protect the environment at large.

In India, freshwater aquaculture contributes parallel economy and livelihood security of the peoples living in close vicinity in the eco-region. But fish productivity in the range of 1000–1200 kg ha^{-1} $year^{-1}$ in this region in India is much lower at present in comparison to national average of 2840 kg ha^{-1} $year^{-1}$ mainly due to the non-scientific culture, poor quality fish seed, and overall lack of knowledge. Rainwater harvesting to get freshwater for multipurpose use like fish farming and integrating with livestock and crop production, land shaping, reclamation and re-excavation of sweet water sources including step-cutting or terracing on inward-slopes of the ponds, linkage between the fisheries output and effective marketing/ processing, and moreover development of alternative climate adaptive livelihood options for the fish farmers, which will match to their skill and capacity, should be developed. Awareness among the farmers through continuous training, technology demonstration and development of alternative climate adaptive livelihood options for the fish farmers will help in meeting the food security and sustainable development of Sundarbans aquaculture. ICAR-CIFA is doing a commendable job in this direction in Sundarbans, India.

With the introduction of Pacific white shrimp (*Penaeus vannamei*) during 2009, Indian brackishwater aquaculture industry has grown rapidly. In addition, certain marine/brackishwater fish such as, seabass, mullets, milkfish and pearlspot have shown a lot of promise. Successful domestication of indigenous Indian white shrimp (*Penaeus indicus*) and experimental farming using hatchery-produced seed by ICAR-CIBA showed encouraging results. Besides domestic consumption, fishery products exported from the state of West Bengal were 91,263 tons of value Rs. 34,390 million during 2015–16. Indian Sundarbans located in the southeast end of West Bengal offers congenial environment for growth of variety of fishes and shrimps. Frozen shrimp and live crab are the main export items from brackishwater aquaculture in Sundarbans. As the economic benefit is greater, there is a tendency of Sundarbans dwellers to shift from fishing to aquaculture for better livelihood. About 25% of 2.1 lakh ha potential brackishwater areas in West Bengal are under use and the state has been the Indian leader in tiger shrimp production while farmers adopted white leg shrimp farming late compared to other Indian maritime states after successful demonstration by ICAR-CIBA at its research centre at Kakdwip. There is vast scope for sustainable development of brackishwater aquaculture in Sundarbans to meet the livelihood demand utilizing the unused and underused areas and adopting advanced farming practices. Challenges faced by Sundarbans aquafarmers need to be tackled by appropriate management tools like social mobilization of aqua producers, technology assessment and refinement, participatory planning, and capacity building of key stakeholders. Besides the above, it is recommended to introduce water and soil testing facilities, supply of quality seeds and quality feed at affordable price, providing appropriate storage and value addition technologies necessary for marketing of the produce transported from remote areas, and making the farmers aware of environmental impact including soil degradation due to brackish water use, etc.

21.12 Non-farm Activity: Ecotourism a Potential Source with Wetland Mangrove Ecosystem as Destination

Review of societal transformation in the Sundarbans eco-region with intervention from administration time-to-time in respect of use of various professional practices over ages and lessons learnt therefrom showed interesting insights into their prospects and sustainability in as far as livelihood security was concerned. Climate change has been and is likely to complicate the prospects in future threatening the livelihood security. For instance, transformation of forests to agriculture was common, but in view of the knowledge that brackish river water was a serious constraint, rice cultivation was persisted with since independence. Rising population and tidal waters, declining land and productivity, as well as more intense storms made the already non-conducive situation worse. It is strongly suggested, based on the lessons learnt to explore newer development options for livelihood security, this time in non-farm sector. Thus, although ecotourism with mangrove destinations, preferably on transboundary mode, seeks to increase opportunities to a significant note, there are no automatic benefits associated with ecotourism; and the success depends on joint exercise desired on good planning and management.

21.13 Conclusions

All the above episodes should address the livelihood security, directly or indirectly, of the inhabitants of Sundarbans eco-region, preferably if not mandatorily, planned and executed in a transboundary mode for mutual benefit to both countries. I sincerely wish and urge the planners, scientists and workers concerned to make a beginning on this note, with the view to not only save the ecology of this remarkably precious eco-region, as nature's gift and a proud heritage, presently at its alarming stage of the very existence due to climate change, continually deteriorating hydrology of the rivers, and other anthropological interventions, but also suggest pathways for sustainable improvements of livelihood. Isolated strategies in the name of improvement without bothering for ecology for such sensitive areas as Sundarbans may prove highly dangerous for all time to come. To quote a simple example from India, the complacency of the administration to arrange roadways through silted-up river beds in Sundarbans by letting the rivers dry up due to sedimentation and reduced water flow in it is antithesis to development blunderingly ignoring ecology of the area.

There are lot of gaps in the planning and knowledge pool of the workers concerned, mostly because of isolated actions by both countries with very little attempts made so far on sharing and deliberating in open mind. I once again urge to explore and exploit non-farm actions, be it ecotourism or beyond, seriously, alongside application of on-farm activities, to improve livelihood sustainably with full protection to ecology of the area.

Annex

Annex Table 1 Algal species reported from different zones of Sundarbans in India and Bangladesh

#	Algal species	Habitat	Zone 1	Zone 2	Zone 3	Zone 4
1	*Stigeoclonium variable*	Brackish water		✓		
2	*Uronema confervicola*	Epiphytic in brackish-water fisheries		✓		
3	*Chlorococcum infusionum*	Endozoic (molluscs) in brackish water		✓		
4	*Phyllobium dimorphum*	Planktonic in brackishwater fisheries		✓		
5	*Eudorina* sp.	Estuarine phytoplankton		✓		
6	*Pandorina morum*	Planktonic in low saline brackishwater		✓		
7	*Volvox* sp.	Planktonic in low saline brackishwater		✓		
8	*Oedocladium prescotti*	Fresh water		✓		
9	*Oedogonium mexicanum*	Aquatic		✓		
10	*Oedogonium anomalum*	Aquatic	✓			
11	*Oedogonium crispum*	Aquatic	✓			
12	*Oedogonium hindustanense*	Aquatic		✓		
13	*Oedogonium inversum*	Aquatic		✓		✓
14	*Oedogonium pringsheimii*	Aquatic	✓	✓		
15	*Oedogonium undulatum*	On submerged substratum/ free floating in brackishwater		✓		
16	*Pediastrum boryanum*	Planktonic in low-mid saline brackishwater fisheries		✓		

(continued)

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Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
17	*Pediastrum duplex*	Planktonic in low-mid saline brackishwater fisheries		✓		
18	*Pediastrum simplex*	Estuarine phytoplankton	✓		✓	
19	*Pediastrum tetras*	Planktonic in low saline brackishwater		✓		
20	*Microspora willeana*	Terrestrial, epiphytic	✓			
21	*Microspora floccosa*	Terrestrial, epiphytic	✓			
22	*Microspora abbreviata*	Terrestrial, epiphytic		✓		✓
23	*Radiococcus* sp.	Planktonic in low saline brackishwater		✓		
24	*Scenedesmus bijuga*	Planktonic in low saline brackishwater		✓		
25	*Scenedesmus dimorphus*	Brackish water		✓		
26	*Scenedesmus quadricauda*	Planktonic in low saline brackishwater		✓		
27	*Ankistrodesmus falcatus*	Brackish water	✓		✓	
28	*Sphaeroplea soleirolli* var. *crassisepta*	Free floating with green and blue green algae in brackishwater		✓		
29	*Chlorella marina*	Planktonic in low to high saline water	✓	✓		
30	*Chlorella vulgaris*	Planktonic in low saline brackishwater		✓		
31	*Dictyosphaerium pulchellum*	Free floating with filamentous green algae		✓		
32	*Franceia dorescheri*	Planktonic in low to mid saline fisheries		✓		
33	*Geminella minor*	Aquatic	✓			
34	*Oocystis pusilla*	Brackish water			✓	
35	*Crucigenia tetrapedia*	Brackish water	✓	✓		
36	*Closterium acutum*	Planktonic in mid-high saline brackishwater		✓		
37	*Closterium tumidium*	Brackish water		✓		
38	*Cosmarium depressum*	Planktonic in mid saline brackishwater		✓		
39	*Cosmarium paucigranulatum*	Planktonic in mid saline brackish water		✓	✓	
40	*Cosmarium regenlii*	Planktonic in mid saline brackish water		✓	✓	
41	*Cosmarium striolatum*	Planktonic in mid saline brackishwater		✓		
42	*Staurastrum orbiculare*	Brackish water			✓	
43	*Triplastrum abbreviatum*	Planktonic in mid saline brackishwater		✓		✓
44	*Triplastrum simplex*	Planktonic in mid saline brackishwater		✓		
45	*Triplocerus gracile*	Planktonic in mid saline brackish water		✓		
46	*Spirogyra brunnea*	Aquatic	✓			
47	*Spirogyra daedalea*	Aquatic	✓			

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
48	*Spirogyra dubia*	Free floating in low saline water bodies	✓			
49	*Spirogyra hyalina*	Aquatic	✓			
50	*Spirogyra hymerae*	Fresh water		✓		
51	*Spirogyra irregularis*	Free floating in brackishwater fisheries		✓		
52	*Spirogyra jaoense*	Fresh water	✓			
53	*Spirogyra juergensii*	Free floating with BGA in brackishwater		✓		
54	*Spirogyra maravillosa*	Aquatic	✓			
55	*Spirogyra plena*	Aquatic	✓			
56	*Spirogyra pseudoreticulata*	On jetty in brackish water areas	✓			
57	*Spirogyra punctulata*	Brackish water		✓		
58	*Spirogyra setiformis*	Floating in low – mid saline water bodies	✓	✓	✓	
59	*Spirogyra ternata*	Floating in low – mid saline water bodies		✓	✓	
60	*Spirogyra wabashensis*	Aquatic	✓			
61	*Temnogyra liana*	Aquatic		✓		
62	*Zygnema collinsianum*	Aquatic		✓		
63	*Zygnema oudhense*	Aquatic		✓		
64	*Bryopsis indica*	On rocky substratum, marine				✓
65	*Caulerpa cactoides*	On rocky substratum, marine				✓
66	*Caulerpa microphysa*	On rocky substratum, marine				✓
67	*Caulerpa okamurae*	On rocky substratum, marine				✓
68	*Caulerpa peltata*	On rocky substratum, marine				✓
69	*Caulerpa racemosa* var. *clavifera*	On rocky substratum, marine				✓
70	*Caulerpa racemosa* var. *occidentalis*	On rocky substratum, marine				✓
71	*Caulerpa racemosa* var. *turbinata*	On rocky substratum, marine				✓
72	*Caulerpa racemosa* var. *uvifera*	On rocky substratum, marine				✓
73	*Caulerpa scalpelliformis*	On rocky substratum, marine				✓
74	*Caulerpa serrulata*	On rocky substratum, marine				✓
75	*Caulerpa sertularioides*	On rocky substratum, marine				✓
76	*Caulerpa taxifolia*	On rocky substratum, marine				✓
77	*Codium extricatum*	On rocky substratum, marine				✓
78	*Codium fragile*	On rocky substratum, marine				✓
79	*Codium geppei*	On rocky substratum, marine			✓	✓

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
80	*Codium taitense*	Forest floor mid littoral		✓		✓
81	*Halimeda discoidea*	On rocky substratum, marine				✓
82	*Halimeda opuntia*	On rocky substratum, marine				✓
83	*Boodleopsis sundarbanensis*	On muddy substratum at upper littoral zone in high saline zone		✓	✓	✓
84	*Boodlea composita*	On rocky substratum, marine				✓
85	*Phyllodictyon anastomosans*	Epiphytic, high saline areas				✓
86	*Chaetomorpha aerea*	Free floating mass in high saline brackish water fisheries	✓	✓		✓
87	*Chaetomorpha brachygona*	Free floating/ attached to in high saline brackishwater fisheries		✓		✓
88	*Chaetomorpha gracilis*	On bricks, beaches; marine	✓	✓	✓	✓
89	*Chaetomorpha ligustica*	Aquatic	✓			
90	*Chaetomorpha linum*	Epiphytic in high saline areas				✓
91	*Chaetomorpha moniligera*	Epiphytic in high saline areas				✓
92	*Cladophora nitellopsis*	Marine water	✓			
93	*Cladophora aegagropila*	Aquatic	✓			
94	*Cladophora crispula*	Marine, on rocky substratum				✓
95	*Cladophora crystallina*	Freshwater	✓			
96	*Cladophora echinus*	Periphytic in brackishwater fisheries		✓		✓
97	*Cladophora fracta*	Terrestrial on mangrove roots	✓			
98	*Cladophora glomerata* var. *crassior*	Terrestrial on mangrove roots	✓			
99	*Cladophora nitellopsis*	Marine	✓			
100	*Cladophora patentiramea*	Marine, on rocky substratum				✓
101	*Cladophora prolifera*	Marine, on rocky substratum	✓			
102	*Cladophora sakaii*	Marine, on rocky substratum				✓
103	*Cladophora vagabunda*	Marine, on rocky substratum				✓
104	*Cladophora rivularis*	Terrestrial on mangrove roots		✓		
105	*Cladophorella sundarbanensis*	Benthic on forest floor, in brackish water fisheries in high saline area		✓		
106	*Cladophorella calcicola*	On rocky substratum, marine		✓	✓	

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
107	*Lola capillaris*	Free floating in brackishwater fisheries at mid-high saline areas	✓	✓	✓	
108	*Lola implexa*	Free floating in brackishwater fisheries at mid-high saline areas		✓		✓
109	*Lola tortuosa*	Free floating in brackishwater fisheries at high saline areas.	✓	✓		✓
110	*Rhizoclonium crassipellitum*	Free floating, brackish water		✓		
111	*Rhizoclonium fontanum*	Terrestrial, epiphytic on mangrove roots	✓			
112	*Rhizoclonium fontinales*	Aquatic in mangrove regions		✓		
113	*Rhizoclonium grande*	Periphytic on pneumatophores at high saline areas		✓		
114	*Rhizoclonium heiroglyphicum*	Brackish water	✓			
115	*Rhizoclonium hookeri*	Periphytic on pneumatophores in high saline areas		✓		✓
116	*Rhizoclonium kerneri*	Marine, on hard substratum			✓	✓
117	*Rhizoclonium pachydermum*	Marine	✓			
118	*Rhizoclonium riparium*	Periphytic on pneumatophores in high saline areas	✓	✓	✓	✓
119	*Rhizoclonium tortuosum*	Epiphytic on mangrove plant, brackish water	✓			✓
120	*Rhizoclonium africanum*	Marine	✓			
121	*Pithophora cleveana*	Marine	✓			
122	*Pithophora polymorpha*	Freshwater	✓			
123	*Pithophora roettleri*	Aquatic	✓			
124	*Dictyosphaeria cavernosa*	On rocky substratum, marine				✓
125	*Acetabularia calyculus*	On rocky substratum, marine				✓
126	*Trentepohlia abietina*	On tree bark in brackish water region	✓			
127	*Trentepohlia sundarbanensis*	Epiphytic on mangrove plant *Avicennia alba*		✓		
128	*Trentepohlia thevalliensis*	On tree bark of brackish water region	✓			
129	*Trentepohlia torulosa*	On tree bark of brackish water region	✓			
130	*Ulothrix tenuissima*	Aquatic	✓			

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
131	*Ulothrix zonata*	Aquatic	✓			
132	*Chara braunii*	Aquatic		✓		
133	*Chara zeylanica*	In brackishwater fisheries at high saline areas		✓		
134	*Nitella mirabilis*	Aquatic		✓		
135	*Bangia discoidea*	On *Polysiphonia* sp. in brackishwater area			✓	
136	*Porphyra* sp.	On rocky substratum, marine				✓
137	*Goniotrichum alsidii*	Epiphytic in high saline areas				✓
138	*Acrochaetium bengalicum*	Epiphytic in high saline areas				✓
139	*Acrochaetium crassipes*	Epiphytic in high saline areas				✓
140	*Acrochaetium nurulislamii*	On rocky substratum, marine				✓
141	*Acrochaetium polysporum*	On rocky substratum, marine				✓
142	*Acrochaetium sagraeanum*	On rocky substratum, marine				✓
143	*Acrochaetium zosterae*	On rocky substratum, marine				✓
144	*Asparagopsis taxiformis*	On rocky substratum, marine				✓
145	*Falkenbergia hillebrandii*	On rocky substratum, marine				✓
146	*Antithamnion sp.*	Epiphytic in high saline areas				✓
147	*Callithamnion sp.*	Epiphytic in high saline areas				✓
148	*Centroceras clavulatum*	On rocky substratum, marine				✓
149	*Ceramium manorensis*	Lithophyte, marine				✓
150	*Ceramium fastigiatum*	Epiphytic in high saline areas				✓
151	*Ceramium gracillimum*	Epiphytic in high saline areas				✓
152	*Ceramium tenerrimum*	Epiphytic in high saline areas				✓
153	*Ceramium brevizonatum*	Epiphytic in high saline areas				✓
154	*Crouania attenuate*	On rocky substratum, marine				✓
155	*Heterosiphonia* sp.	On the bark of *Aegialitis rotundifolia* and other mangroves in high saline areas		✓		
156	*Vanvoorstia coccinea*	On rocky substratum				✓
157	*Caloglossa adnata*	On pneumatophores and trunks of mangroves and other hard substrata in high saline areas		✓	✓	✓

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
158	*Caloglossa leprieurii*	On pneumatophores and other hard substrata in high saline areas		✓	✓	✓
159	*Acanthophora specifera*	On rocky/ muddy substratum in high saline zone				✓
160	*Bostrychia radicans*	Epiphytic on pneumatophores in littoral/above littoral zones in high saline areas and on rock		✓	✓	✓
161	*Bostrychia simpliciuscula*	Epiphytic on mangroves	✓	✓		
162	*Bostrychia tenella*	On pneumatophores/ rocks in high saline areas		✓	✓	✓
163	*Herposiphonia dendroidea*	On forest floor in littoral/ above littoral zones in high saline areas		✓		✓
164	*Herposiphonia dendroidea* var. *minor*	On rocky substratum, marine				✓
165	*Herposiphonia tenella* fa. *secumda*	On rocky substratum, marine				✓
166	*Laurencia obtusa*	On rocky substratum, marine				✓
167	*Laurencia* sp.	On rocky substratum, marine				✓
168	*Lophocladia trichoclados*	On rocky substratum, marine				✓
169	*Polysiphonia denudata*	Creeping on pneumatophores/ rocks in high saline areas	✓	✓		✓
170	*Polysiphonia harveyi*	On pneumatophores/ rocks in high saline areas				✓
171	*Polysiphonia mollis*	On pneumatophores/ rocks in high saline areas	✓	✓		✓
172	*Pterosiphonia pinnata*	On pneumatophores in high saline zones		✓	✓	✓
173	*Cottoniella filamentosa*	Epiphytic in high saline areas				✓
174	*Amphiroa fragilissima*	On rocky substratum, marine				✓
175	*Amphiroa anceps*	On rocky substratum, marine				✓
176	*Jania adhaerens*	On rocky substratum, marine				✓
177	*Jania ungulata*	On rocky substratum, marine				✓
178	*Lithothamnion* sp.	On rocky substratum, marine				✓
179	*Erythrotrichia carnea*	Epiphytic in high saline areas				✓
180	*Erythrocladia subintegra*	Epiphytic in high saline areas				✓
181	*Gelidiella acerosa*	As littoral forest floor flora and on mangrove bark in high saline areas			✓	
182	*Gelidiella tenera*	Lithophyte, marine				✓
183	*Gelidiella tenuissima*	Lithophyte/ entangled with other marine algae				✓
184	*Gellidium amansii*	Lithophyte, marine				✓
185	*Gelidium pusillum*	On hard substratum, marine	✓	✓		✓

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
186	*Catenella impudica*	Creeping on mangroves in high saline areas		✓		✓
187	*Catenella nipae*	On the barks of *E. agallocha* in the upper littoral zones	✓	✓	✓	✓
188	*Catenella repens*	Creeping on pneumatophores in high saline areas	✓		✓	✓
189	*Dudresnaya hawaiiensis*	On rocky substratum				✓
190	*Gigartina intermedia*	On rocky substratum				✓
191	*Callophyllis* sp.	On rocky substratum, marine				✓
192	*Callophyllis rangiferina*	On rocky substratum, marine				✓
193	*Kallymenia cribrosa*	On rocky substratum, marine				✓
194	*Kallymenia tasmanica*	On rocky substratum, marine				✓
195	*Kallymenia rosea*	On rocky substratum, marine				✓
196	*Kallymenia rubra*	On rocky substratum, marine				✓
197	*Eucheuma* sp.	On rocky substratum, marine				✓
198	*Sarconema jurcellatum*	Epiphytic in high saline areas				✓
199	*Hypnea boergesenii*	Epiphytic in high saline areas				✓
200	*Hypnea cornuta*	Epiphytic in high saline areas				✓
201	*Hypnea musciformis*	Epiphytic in high saline areas				✓
202	*Hypnea pannosa*	Epiphytic in high saline areas				✓
203	*Hypnea valentiae*	Epiphytic in high saline areas				✓
204	*Calliblepharis* sp.	On rocky substratum, marine				✓
205	*Gracilaria textorii*	On rocky substratum, marine				✓
206	*Gracilaria verrucosa*	On rocky substratum, marine				✓
207	*Halymenia discoidea*	Littoral, marine				✓
208	*Halymenia duchassaignii*	Littoral, marine				✓
209	*Halymenia floresia*	Littoral, marine				✓
210	*Melobesia confervicola*	Epiphytic in high saline areas				✓
211	*Messophyllum* sp.	Epiphytic in high saline areas				✓
212	*Actinotrichia fragilis*	On rocky substratum, marine				✓
213	*Liagora ceranoides*	On rocky substratum, marine				✓
214	*Liagora harveyiana*	On rocky substratum, marine				✓
215	*Liagora ferinosa*	On rocky substratum, marine				✓
216	*Scinaia complanata*	On rocky substratum, marine				✓
217	*Scinaia japonica*	On rocky substratum, marine				✓
218	*Champia parvula*	On rocky substratum, marine				✓
219	*Chrysymenia okamura*	On rocky substratum, marine				✓

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
220	*Chrysymenia enteromorpha.*	On rocky substratum, marine				✓
221	*Chrysymenia agardhii*	On rocky substratum, marine				✓
222	*Cthonoplastis* sp.	On rocky substratum, marine				✓
223	*Peyssonellia* sp.	On rocky substratum				✓
224	*Astasia cylindrica*	Estuarine phytoplankton			✓	
225	*Astasia longa*	Marine littoral zone			✓	
226	*Astasia longa* var. *truncata*	Marine littoral zone			✓	
227	*Euglena acus* var. *angularis*	Brackish water phytoplankton		✓		
228	*Euglena acus*	Brackish water phytoplankton		✓		
229	*Euglena gracilis*	Brackish water phytoplankton		✓		
230	*Euglena geniculata*	Brackish water phytoplankton		✓		
231	*Euglena granulata*	Brackish water phytoplankton		✓		
232	*Euglena oxyuris*	Fresh water and brackish water		✓		
233	*Euglena pisciformis*	Brackish water phytoplankton		✓		
234	*Euglena rostrifera*	Brackish water phytoplankton		✓		
235	*Euglena spathirhyncha*	Brackish water phytoplankton		✓	✓	
236	*Euglena splendens*	Brackish water phytoplankton		✓		
237	*Euglena thinophila*	Brackish water phytoplankton		✓		
238	*Euglenaformis proxima*	Brackish water phytoplankton		✓		
239	*Monomorphina pyrum*	Brackish water phytoplankton		✓		
240	*Monomorphina nordstedtii*	Brackish water phytoplankton		✓		
241	*Trachelomonas kelloggii*	Brackish water phytoplankton		✓		
242	*Trachelomonas rugulosa*	Brackish water phytoplankton		✓		
243	*Trachelomonas rugulosa* var. *meandrina*	Brackish water phytoplankton		✓		
244	*Lepocinclis acus*	Brackish water phytoplankton		✓		
245	*Lepocinclis americana*	Brackish water phytoplankton	✓			
246	*Lepocinclis claviformis*	Brackish water phytoplankton		✓		
247	*Lepocinclis fusiformis*	Brackish water phytoplankton		✓		

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
248	*Lepocinclis fusiformis* var. *amphirhynchus*	Brackish water phytoplankton		✓		
249	*Lepocinclis marssonii*	Brackish water phytoplankton		✓		
250	*Lepocinclis ovum*	Brackish water phytoplankton		✓		
251	*Lepocinclis oxyuris*	Brackish water phytoplankton	✓			
252	*Lepocinclis texta*	Brackish water phytoplankton		✓		
253	*Phacus acuminatus*	Brackish water phytoplankton		✓		
254	*Phacus alatus*	Brackish water phytoplankton		✓		
255	*Phacus angulatus*	Brackish water phytoplankton		✓		
256	*Phacus asymmetrica*	Brackish water phytoplankton		✓		
257	*Phacus circulates*	Brackish water phytoplankton	✓			
258	*Phacus helikoides*	Brackish water phytoplankton	✓			
259	*Phacus orbicularis*	Brackish water phytoplankton	✓			
260	*Phacus longicauda*	Brackish water phytoplankton		✓		
261	*Phacus parvulus*	Brackish water phytoplankton		✓		
262	*Phacus pleuronectes*	Brackish water phytoplankton		✓		
263	*Phacus pusillus*	Brackish water phytoplankton		✓		
264	*Phacus segretii* var. *ovum*	Brackish water phytoplankton	✓			
265	*Phacus sesquitortus*	Brackish water phytoplankton		✓		
266	*Phacus swirenkoi*	Brackish water phytoplankton	✓			
267	*Phacus triqueter*	Estuarine phytoplankton		✓		
268	*Phacus trypanon*	Brackish water phytoplankton	✓			
269	*Phacus viguieri*	Brackish water phytoplankton		✓		
270	*Phacus tortus*	Brackish water phytoplankton		✓		
271	*Phacus triqueter*	Brackish water phytoplankton		✓		
272	*Dinophysis caudata*	Estuarine phytoplankton	✓			
273	*Ceratium cylindrus*	Planktonic in high saline river	✓			
274	*Ceratium extensum*	Marine phytoplankton	✓	✓		
275	*Ceratium extensum* f. *strictum*	Marine phytoplankton				✓
276	*Ceratium furca*	Marine phytoplankton	✓	✓	✓	✓
277	*Ceratium fusus*	Estuarine phytoplankton	✓		✓	
278	*Ceratium horridum*	Marine phytoplankton				✓
279	*Ceratium inflatum*	Marine phytoplankton	✓			
280	*Ceratium longipes*	Planktonic in high saline rivers	✓			✓
281	*Ceratium teres*	Marine phytoplankton	✓	✓		
282	*Ceratium trichoceros*	Marine phytoplankton	✓	✓		
283	*Ceratium trichoceros* var. *contrarium*	Marine phytoplankton	✓			

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
284	*Ceratium tripos*	Marine phytoplankton	✓	✓	✓	✓
285	*Cladopyxis hemibrachiata*	Estuarine phytoplankton			✓	
286	*Noctiluca scintillans*	Estuarine phytoplankton	✓			✓
287	*Protoperidinium biconicum*	Planktonic in high saline rivers			✓	
288	*Protoperidinium borchi*	Marine phytoplankton				✓
289	*Protoperidinium brevipes*	Marine phytoplankton	✓			
290	*Protoperidinium claudicans*	Marine phytoplankton	✓			
291	*Protoperidinium crassipes*	Marine phytoplankton				✓
292	*Protoperidinium depressum*	Marine phytoplankton	✓			
293	*Protoperidinium divergens*	Marine phytoplankton	✓			
294	*Protoperidinium claudicans*	Marine phytoplankton				✓
295	*Protoperidinium ovatum*	Planktonic in high saline areas	✓			
296	*Protoperidinium leonis*	Planktonic in high saline areas			✓	✓
297	*Protoperidinium pallidum*	Marine phytoplankton	✓	✓		
298	*Protoperidinium punctulatum*	Planktonic in high saline areas			✓	
299	*Protoperidinium subinerme*	Planktonic in high saline areas			✓	
300	*Diplopsalis lenticula*	Marine and euryhaline plankton				✓
301	*Peridinium brevipes*	Marine phytoplankton	✓			
302	*Peridinium cinctum*	Marine and euryhaline plankton				✓
303	*Peridinium granii*	Marine and euryhaline plankton				✓
304	*Peridinium thorianum*	Estuarine / marine phytoplankton				✓
305	*Prorocentrum micans*	Marine phytoplankton	✓			
306	*Vaucheria prescotti*	On decomposed matter on forest floor		✓	✓	✓
307	*Vaucheria erythrospora*	Terrestrial				✓
308	*Vaucheria* sp.	With bottom biota in brackish water fishery		✓		
309	*Vaucheria mayyanadensis*	Terrestrial			✓	✓

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
310	*Vaucheria pronosperma*	Marine epilithic			✓	
311	*Centritractus belanophorus*	Estuarine phytoplankton			✓	
312	*Dictyopteris australis*	On rocky substratum, marine				✓
313	*Dictyopteris divarcatum*	On rocky substratum, marine		✓		✓
314	*Dictyota bratayresii*	On rocky substratum, marine				✓
315	*Dictyota ceylanica*	On pneumatophores in high saline areas				✓
316	*Dictyota ciliolata*	On rocky substratum, marine				✓
317	*Dictyota dichotoma*	On rocky substratum, marine				✓
318	*Dictyota divaricata*	On rocky substratum, marine				✓
319	*Dictyota friabilis*	On rocky substratum, marine				✓
320	*Dictyota patens*	On rocky substratum, marine				✓
321	*Lobophora variegata*	On rocky substratum, marine				✓
322	*Padina arborescens*	On rocky substratum, marine				✓
323	*Padina australis*	On rocky substratum, marine				✓
324	*Padina fraseri*	On rocky substratum, marine				✓
325	*Padina gymnospora*	On rocky substratum, marine				✓
326	*Padina pavonica*	On rocky substratum, marine				✓
327	*Padina sanctae-crucis*	On rocky substratum, marine				✓
328	*Padina tenuis*	On rocky substratum, marine				✓
329	*Padina tetrastromatica*	On rocky substratum, marine				✓
330	*Padina vickersiae*	On rocky substratum, marine				✓
331	*Feldmannia columellaris*	Epiphytic				✓
332	*Feldmannia elachistaeformis*	Epiphytic				✓
333	*Feldmannia indica*	Epiphytic				✓
334	*Feldmannia vaughani*	Epiphytic				✓
335	*Giffordia conifera*	Epiphytic				✓
336	*Giffordia irregularis*	Epiphytic				✓
337	*Giffordia mitchellae*	Epiphytic				✓
338	*Giffordia rallsae*	Epiphytic				✓
339	*Giffordia thyrsoideus*	Epiphytic				✓
340	*Myriactula arabica*	On rocky substratum, marine				✓
341	*Ectocarpus breviarticulatus*	Epiphytic				✓
342	*Ectocarpus rhodochortonoides*	Epiphytic				✓

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
343	*Chnoospora implexa*	On rocky substratum, marine				✓
344	*Colpomenia sinuosa*	On highly consolidated soil in the littoral zone		✓	✓	✓
345	*Colpomenia perigrina*	On rocky substratum, marine				✓
346	*Hydroclathrus* sp.	On rocky substratum, marine				✓
347	*Hydroclathrus clathratus*	On rocky substratum, marine				✓
348	*Petalonia fascia*	On rocky substratum, marine				✓
349	*Rosenvingea intricata*	On rocky substratum, marine				✓
350	*Rosenvingea orientalis*	On rocky substratum, marine				✓
351	*Rosenvingea sanctae-crucis*	On rocky substratum, marine				✓
352	*Sphacelaria tribuloides*	Epiphytic				✓
353	*Sphacelaria novae-hollandiae*	On rocky substratum, marine				✓
354	*Eisenia bicyclis*	On rocky substratum, marine				✓
355	*Ishigae okamurae*	On rocky substratum, marine				✓
356	*Sargassum caryophyllum*	On rocky substratum, marine				✓
357	*Sargassum coriifolium*	On rocky substratum, marine				✓
358	*Sargassum crassifolium*	On rocky substratum, marine				✓
359	*Sargassum cristaerfolium*	On rocky substratum, marine				✓
360	*Sargassum flavicans*	On rocky substratum, marine				✓
361	*Sargassum ilicifolium*	On rocky substratum, marine				✓
362	*Sargassum oligocystum*	On rocky substratum, marine				✓
363	*Sargassum vulgare*	On rocky substratum, marine				✓
364	*Sargassum wightii*	On rocky substratum, marine				✓
365	*Aulacoseira granulata*	Soil sediment		✓		
366	*Coscinodiscus angsti*	Estuarine phytoplankton				✓
367	*Coscinodiscus argus*	Estuarine phytoplankton		✓		
368	*Coscinodiscus centralis*	Estuarine phytoplankton	✓	✓	✓	✓
369	*Coscinodiscus concinnus*	Marine phytoplankton	✓		✓	

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
370	*Coscinodiscus curvatulus*	Estuarine phytoplankton			✓	✓
371	*Coscinodiscus eccentricus*	Planktonic from high saline river water	✓	✓	✓	✓
372	*Coscinodiscus gigas*	Planktonic from high saline river water	✓	✓	✓	✓
373	*Coscinodiscus granii*	Planktonic from high saline river water		✓	✓	
374	*Coscinodiscus hyalinus*	Estuarine phytoplankton	✓			
375	*Coscinodiscus jonesianus*	Marine phytoplankton	✓	✓	✓	✓
376	*Coscinodiscus lineatus*	Estuarine phytoplankton	✓		✓	✓
377	*Coscinodiscus marginatus*	Estuarine phytoplankton			✓	✓
378	*Coscinodiscus nitidus*	Estuarine phytoplankton			✓	
379	*Coscinodiscus oculus-iridis*	Marine phytoplankton	✓	✓	✓	✓
380	*Coscinodiscus perforatus* var. *pavillardi*	Marine phytoplankton	✓		✓	✓
381	*Coscinodiscus radiatus*	Marine phytoplankton	✓	✓	✓	✓
382	*Coscinodiscus spiniferus*	Estuarine phytoplankton			✓	
383	*Coscinodiscus symbolophorous*	Marine phytoplankton				✓
384	*Coscinodiscus tumidus*	Estuarine phytoplankton	✓		✓	
385	*Coscinodiscus wailesii*	Estuarine phytoplankton	✓		✓	
386	*Actinocyclus anulatus*	Estuarine phytoplankton			✓	
387	*Actinocyclus octonarius*	Estuarine phytoplankton	✓			
388	*Actinocyclus Pruniosus*	Estuarine phytoplankton			✓	
389	*Actinocyclus roperi*	Marine phytoplankton	✓			
390	*Hemidiscus cuneiformis*	Planktonic from high saline river	✓	✓		✓
391	*Hemidiscus hardmannianus*	Estuarine phytoplankton	✓	✓		
392	*Hemidiscus kanayanus*	Estuarine phytoplankton	✓			
393	*Roperia tesselata*	Estuarine phytoplankton			✓	

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
394	*Corethron criophilum*	Estuarine phytoplankton	✓			
395	*Corethron hystrix*	Estuarine phytoplankton		✓		✓
396	*Corethron inerme*	Estuarine phytoplankton	✓			
397	*Melosira granulata*	Planktonic in low-high saline river	✓			
398	*Melosira moniliformis*	Planktonic in low-high saline river		✓	✓	✓
399	*Melosira numuloides*	Estuarine phytoplankton			✓	✓
400	*Melosira sol*	Planktonic in high saline river		✓		✓
401	*Melosira sulcata*	Estuarine phytoplankton			✓	✓
402	*Melosira undulata*	Estuarine phytoplankton				✓
403	*Melosira varians*	Estuarine phytoplankton			✓	✓
404	*Paralia sulcata*	Estuarine phytoplankton	✓	✓		
405	*Proboscia alata* var. *gracillima*	Estuarine phytoplankton	✓			
406	*Proboscia alata* var. *indica*	Estuarine phytoplankton	✓			
407	*Guinerdia turgida*	Estuarine phytoplankton				✓
408	*Guinardia* sp.	Estuarine phytoplankton	✓			
409	*Guinardia flaccida*	Estuarine phytoplankton	✓			
410	*Rhizosolenia alata*	Marine phytoplankton	✓			✓
411	*Rhizozolenia calcaravis*	Estuarine phytoplankton				✓
412	*Rhizosolenia crassipina*	Planktonic in high saline river	✓	✓		
413	*Rhizozolenia delicatula*	Estuarine phytoplankton				✓
414	Rhizosolenia *hebetata*	Estuarine phytoplankton	✓			✓
415	*Rhizosolenia turgida*	Planktonic in high saline river		✓		✓
416	*Rhizosolenia robusta*	Marine phytoplankton				✓
417	*Rhizosolenia setigera*	Planktonic in high saline river	✓	✓	✓	✓
418	*Rhizozolenia styliformis*	Estuarine phytoplankton	✓			✓
419	*Rhizosolenia stolterfothii*	Marine phytoplankton				✓
420	*Stephanopyxis palmeriana*	Planktonic in high saline river	✓	✓		✓
421	*Stephanopyxis turris*	Estuarine phytoplankton	✓			
422	*Triceratium favus*	Marine phytoplankton	✓	✓	✓	✓
423	*Triceratium distinctum*	Estuarine phytoplankton	✓	✓		

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone 1	2	3	4
424	*Triceratium reticulatum*	Marine phytoplankton	✓	✓		
245	*Bellerochea mallus*	Estuarine phytoplankton				✓
426	*Biddulphia aurita*	Brackish water			✓	
427	*Biddulphia dubia*	Brackish water			✓	
428	*Biddulphia granulata*	Estuarine phytoplankton			✓	✓
429	*Biddulphia heteroceros*	Planktonic in high saline river	✓	✓		
430	*Biddulphia mobiliensis*	Planktonic in high saline river	✓	✓	✓	✓
431	*Biddulphia longicuris*	Planktonic in high saline river	✓			
432	*Biddulphia sinensis*	Planktonic in high saline river	✓	✓	✓	✓
433	*Biddulphia pulchella*	Planktonic in high saline river			✓	
434	*Eucampia zodiacus*	Marine phytoplankton	✓		✓	✓
435	*Eucampia cornuta*	Estuarine phytoplankton				✓
436	*Eucampia balaustium*	Estuarine phytoplankton				✓
437	*Bacteriastrum cosmosum*	Planktonic in high saline river	✓	✓	✓	✓
438	*Bacteriastrum delicatulum*	Marine phytoplankton	✓	✓	✓	✓
439	*Bacteriastrum hyalinum*	Marine phytoplankton	✓			
440	*Bacteriastrum hyalinum* var. *princeps*	Estuarine phytoplankton	✓	✓		
441	*Bacteriastrum varians*	Planktonic in high saline river	✓	✓		
442	*Chaetoceros affinis*	Estuarine phytoplankton			✓	
443	*Chaetoceros atlanticus*	Estuarine phytoplankton			✓	✓
444	*Chaetoceros compressus*	Planktonic in high saline river	✓	✓		
445	*Chaetoceros constrictus*	Estuarine phytoplankton	✓			
446	*Chaetoceros costatus*	Estuarine phytoplankton			✓	✓
447	*Chaetoceros curvisetus*	Planktonic in high saline river		✓	✓	✓
448	*Chaetoceros danicus*	Planktonic in high saline river	✓			
449	*Chaetoceros debile*	Estuarine phytoplankton	✓		✓	
450	*Chaetoceros decipiens*	Estuarine phytoplankton	✓			

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
451	*Chaetoceros diadema*	Estuarine phytoplankton	✓			
452	*Chaetoceros didymus*	Planktonic in high saline river	✓	✓		
453	*Chaetoceros eibenii*	Planktonic in high saline river	✓			
454	*Chaetoceros flexuosus*	Marine phytoplankton		✓		
455	*Chaetoceros impressus*	Estuarine phytoplankton	✓			
456	*Chaetoceros indicus*	Marine phytoplankton	✓			
457	*Chaetoceros laciniosus*	Marine phytoplankton	✓	✓		
458	*Chaetoceros lorenzianus*	Planktonic in high saline river	✓	✓		
459	*Chaetoceros minimus*	Estuarine phytoplankton	✓			
460	*Chaetoceros pendulus*	Planktonic in high saline river			✓	
461	*Chaetoceros peruvianus*	Planktonic in high saline river	✓	✓		
462	*Chaetoceros pseudocurvisetus*	Planktonic in high saline river		✓		
463	*Chaetoceros socialis*	Planktonic in high saline river			✓	✓
464	*Chaetoceros subsecundus*	Planktonic in high saline river		✓		
465	*Chaetoceros tenuissimus*	Brackish water fisheries		✓		
466	*Leptocylindrus danicus*	Estuarine phytoplankton	✓			✓
467	*Leptocylindrus minimus*	Estuarine phytoplankton	✓		✓	
468	*Odontella mobiliensis*	Estuarine phytoplankton	✓		✓	
469	*Odontella sinensis*	Estuarine phytoplankton			✓	
470	*Climacodium frauenfeldianum*	Planktonic in high saline river		✓		✓
471	*Hemiaulus hauckii*	Estuarine phytoplankton			✓	✓
472	*Hemiaulus membranaceus*	Estuarine phytoplankton				✓
473	*Hemiaulus sinensis*	Estuarine phytoplankton	✓			✓
474	*Isthmia enervis*	Planktonic in high saline river	✓			
475	*Ditylum brightwelli*	Estuarine phytoplankton	✓		✓	✓
476	*Ditylum buchananii*	Estuarine phytoplankton	✓			
477	*Ditylum sol*	Marine phytoplankton	✓	✓		✓

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
478	*Lithodesmium undulatum*	Estuarine phytoplankton				✓
479	*Tropidoneis elegans*	Estuarine phytoplankton	✓			
480	*Tropidoneis lepidoptera*	Estuarine phytoplankton	✓			
481	*Tropidoneis pusilla*	Estuarine phytoplankton	✓			
482	*Cyclotella caspia*	Estuarine phytoplankton	✓			
483	*Cyclotella comta*	Estuarine phytoplankton			✓	✓
484	*Cyclotella glomerata*	Estuarine phytoplankton		✓		
485	*Cyclotella littoralis*	Soil sediment		✓		
486	*Cyclotella meneghiniana*	Low salinity to high salinity water				✓
487	*Cyclotella striata*	Soil sediment and estuarine phytoplankton	✓	✓	✓	
488	*Cyclotella stylorum*	Estuarine phytoplankton	✓		✓	✓
489	*Coscinosira polychorda*	Estuarine phytoplankton				✓
490	*Thalassiosira angulata*	Estuarine phytoplankton			✓	
491	*Thalassiosira anguste-lineata*	Estuarine phytoplankton			✓	
492	*Thalassiosira condensata*	Estuarine phytoplankton	✓			
493	*Thalassiosira decipiens*	Estuarine phytoplankton				
494	*Thalassiosira ecentrica*	Estuarine phytoplankton			✓	
495	*Thalassiosira gravida*	Estuarine phytoplankton				✓
496	*Thalassiosira hyalina*	Estuarine phytoplankton	✓			
497	*Thalassiosira lundiana*	Estuarine phytoplankton			✓	
498	*Thalassiosira oestrupii*	Estuarine phytoplankton			✓	
499	*Thalassiosira rotula*	Estuarine phytoplankton			✓	✓
500	*Thalassiosira pseudonana*	Estuarine phytoplankton	✓			
501	*Thalassiosira punctigera*	Estuarine phytoplankton			✓	
502	*Thalassiosira subtilis*	Estuarine phytoplankton	✓	✓		✓
503	*Thalassiosira tenera*	Soil sediment		✓		
504	*Thalassiosira tumida*	Marine phytoplankton				✓
505	*Thalassiosira weisflogii*	Estuarine phytoplankton			✓	

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
506	*Thalassiosira wongii*	Estuarine phytoplankton			✓	
507	*Planktoniella blanda*	Estuarine phytoplankton		✓		
508	*Planktoniella sol*	Estuarine phytoplankton	✓	✓	✓	✓
509	*Lauderia annulata*	Marine phytoplankton	✓			
510	*Lauderia borealis*	Estuarine phytoplankton				✓
511	*Skeletonema costatum*	Marine phytoplankton	✓	✓	✓	✓
512	*Schroderella delicatula*	Estuarine phytoplankton				✓
513	*Climacosphenia elongate*	Estuarine phytoplankton	✓			
514	*Climacosphenia turgida*	Estuarine phytoplankton	✓	✓		
515	*Climacosphenia moniligera*	Estuarine phytoplankton			✓	✓
516	*Bacillaria paradoxa*	Estuarine phytoplankton	✓			
517	*Bacillaria paxillifera*	Estuarine phytoplankton	✓		✓	
518	*Cylindrotheca closterium*	Estuarine phytoplankton	✓			
519	*Cylindrotheca fusiformis*	Estuarine phytoplankton	✓		✓	
520	*Giffenia cocconeiformis*	Soil sediment		✓		
521	*Nitzschia acicularis*	Planktonic in low-high saline river/ brackishwater	✓	✓		
522	*Nitzschia behrei*	Estuarine phytoplankton			✓	
523	*Nitzschia bilobata*	Estuarine phytoplankton	✓			
524	*Nitzschia closterium*	Estuarine phytoplankton	✓	✓	✓	✓
525	*Nitzschia incurve*	Estuarine phytoplankton	✓			
526	*Nitzschia inconspicua*	Estuarine phytoplankton			✓	
527	*Nitzschia linearis*	Estuarine phytoplankton	✓			
528	*Nitzschia longissima*	Estuarine phytoplankton	✓		✓	
529	*Nitzschia lorenziana*	Estuarine phytoplankton			✓	
530	*Nitzschia paradoxa*	Estuarine phytoplankton			✓	✓
531	*Nitzschia pungens*	Estuarine phytoplankton			✓	✓
532	*Nitzschia romana*	Estuarine phytoplankton			✓	
533	*Nitzschia scalaris*	Planktonic in low-high saline river/ brackishwater		✓		
534	*Nitzschia seriata*	Estuarine phytoplankton			✓	✓
535	*Nitzschia sigma*	Estuarine phytoplankton	✓	✓	✓	✓
536	*Nitzschia sigmoidea*	Estuarine phytoplankton	✓	✓		
537	*Nitzschia sublinearis*	Estuarine phytoplankton	✓			

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
538	*Nitzschia turgida*	Planktonic in low-high saline river/ brackishwater		✓		
539	*Pseudonitzschia delicatissima*	Estuarine phytoplankton	✓			
540	*Pseudonitzschia pseudodelicatissima*	Estuarine phytoplankton	✓			
541	*Pseudonitzschia seriata*	Estuarine phytoplankton	✓			
542	*Pseudonitzschia seriata f. seriata*	Estuarine phytoplankton	✓			
543	*Cocconeis placentula*	Epiphytic on red algae in high saline areas		✓		
544	*Cocconeis scutellum*	Estuarine phytoplankton	✓			
545	*Anomoeoneis exilis*	Planktonic in high saline river	✓			
546	*Cymbella ehrenbergii*	Planktonic in high saline river		✓		
547	*Cymbella stuxbergii*	Estuarine phytoplankton				✓
548	*Cymbella marina*	Estuarine phytoplankton	✓	✓		
549	*Okedenia inflexa*	Estuarine phytoplankton	✓			
550	*Gomphonema sphaerophorum*	Planktonic in high saline river		✓		
551	*Amphicampa eruca*	Estuarine phytoplankton		✓		
552	*Eunotia* sp.	Estuarine phytoplankton	✓			
553	*Eunotia pectinalis*	Estuarine phytoplankton		✓		
554	*Fragilaria oceanica*	Marine phytoplankton	✓	✓		
555	*Fragilaria vaucheriae*	Planktonic in high saline river		✓		
556	*Synedra oxyrhyncus*	Estuarine phytoplankton	✓			
557	*Synedra ulna*	Estuary and brakish water	✓	✓	✓	✓
558	*Licmophora abbreviate*	Estuarine phytoplankton				✓
559	*Licmophora flabellata*	Estuarine phytoplankton	✓			
560	*Achnanthes microcephala*	Epiphytic on red algae		✓		
561	*Achnanthes minutissima*	Epiphytic on red algae		✓		
562	*Achnanthes breviceps*	Estuarine phytoplankton	✓			
563	*Amphiprora alata*	Estuarine phytoplankton			✓	
564	*Amphiprora* sp.	Estuarine phytoplankton	✓			
565	*Frustulia* sp.	Estuarine phytoplankton	✓			
566	*Diploneis bombus*	Soil sediment		✓		
567	*Diploneis ovalis*	Soil sediment		✓		

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
568	*Diploneis robustus*	Marine phytoplankton	✓			
569	*Diploneis smithii*	Planktonic and sediment	✓	✓		
570	*Navicula arenaria*	Estuarine phytoplankton	✓			
571	*Navicula brekkaensis*	Estuarine phytoplankton			✓	
572	*Navicula clementis*	Estuarine phytoplankton	✓			
573	*Navicula cruciculoides*	Estuarine phytoplankton	✓			
574	*Navicula crucigera*	Estuarine phytoplankton	✓			
575	*Navicula cryptocephala*	Planktonic from high saline river		✓		
576	*Navicula directa*	Estuarine phytoplankton	✓			
577	*Navicula distans*	Estuarine phytoplankton	✓			✓
578	*Navicula ergadensis*	Estuarine phytoplankton	✓			
579	*Navicula fumarchica*	Estuarine phytoplankton	✓			
580	*Navicula maculosa*	Estuarine phytoplankton	✓			
581	*Navicula marina*	Estuarine phytoplankton	✓			
582	*Navicula meninscus*	Estuarine phytoplankton			✓	
583	*Navicula palpebralis*	Estuarine phytoplankton	✓			
584	*Navicula peregrine*	Estuarine phytoplankton	✓			
585	*Navicula pupalis*	Estuarine phytoplankton	✓			
586	*Navicula radiosa*	Planktonic/ periphytic from low–high saline river/ brackish water fisheries		✓		✓
587	*Navicula rostellata*	Estuarine phytoplankton	✓			
588	*Navicula salinarum*	Estuarine phytoplankton				✓
589	*Navicula socialis*	Estuarine phytoplankton	✓			
590	*Navicula transitans* var. *derasa*	Estuarine phytoplankton	✓			
591	*Navicula transitans* var. *transitans*	Estuarine phytoplankton	✓			
592	*Navicula viridis*	Estuarine phytoplankton	✓			
593	*Haslea wawrikae*	Estuarine phytoplankton	✓			
594	*Pinnularia ambigua*	Estuarine phytoplankton	✓			
595	*Pinnularia rectangulata*	Estuarine phytoplankton	✓			
596	*Pinularia viridis*	Estuarine phytoplankton	✓	✓		
597	*Gyrosigma acuminatum*	Planktonic from low –high saline river water/ brackish water		✓		✓
598	*Gyrosigma attenuatum*	Estuarine phytoplankton				✓
599	*Gyrosigma balticum*	Estuarine phytoplankton	✓	✓		✓
600	*Gyrosigma distortum* var. *parkeri*	Brackish water				✓
601	*Gyrosigma littorale*	Estuarine phytoplankton	✓			

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
602	*Gyrosigma scalproides*	Estuarine phytoplankton	✓			
603	*Gyrosigma spencerii*	Estuarine phytoplankton				✓
604	*Pleurosigma aestuarii*	Estuarine phytoplankton	✓			
605	*Pleurosigma affine*	Estuarine phytoplankton				✓
606	*Pleurosigma angulatum*	Planktonic from high saline river	✓	✓	✓	
607	*Pleurosigma directum*	Estuarine phytoplankton	✓		✓	
608	*Pleurosigma elongatum*	Marine phytoplankton	✓	✓	✓	✓
609	*Pleurosigma estuarii*	Estuarine phytoplankton			✓	
610	*Pleurosigma formosum*	Estuarine phytoplankton	✓			
611	*Pleurosigma intermedium*	Estuarine, marine phytoplankton				✓
612	*Pleurosigma normanii*	Marine phytoplankton	✓	✓	✓	✓
613	*Pleurosigma rigidum*	Estuarine phytoplankton				✓
614	*Stauroneis phoenicenteron*	Planktonic from high saline river	✓			
615	*Rhaphoneis rhombus*	Soil sediment		✓		
616	*Rhaphoneis amphiceros*	Estuarine phytoplankton	✓			
617	*Epithemia turgida*	Estuarine phytoplankton		✓		
618	*Entomoneis paludosa*	Estuarine phytoplankton			✓	
619	*Entomoneis sulcata*	Estuarine phytoplankton			✓	
620	*Campylodiscus clypeus*	Estuarine phytoplankton	✓			
621	*Campylodiscus impressus*	Estuarine phytoplankton	✓			
622	*Surirella fastuosa* var. *recedens*	Estuarine phytoplankton			✓	
623	*Surirella gemma*	Estuarine phytoplankton			✓	
624	*Surirella ovata*	Estuarine phytoplankton	✓			
625	*Surirella robusta*	Estuarine phytoplankton	✓			
626	*Asterionella japonica*	Planktonic from high saline river	✓	✓	✓	✓
627	*Diatoma anceps*	Estuarine phytoplankton	✓			
628	*Diatoma vulgare*	Planktonic from high saline river		✓	✓	✓
629	*Thallasionema nitzschioides*	Marine phytoplankton	✓	✓	✓	✓
630	*Thalassiothrix frauenfeldii*	Marine phytoplankton	✓	✓	✓	✓

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
631	*Thalassiothrix longissima*	Marine phytoplankton	✓	✓	✓	✓
632	*Lioloma delicatula*	Estuarine phytoplankton			✓	
633	*Lioloma elongatum*	Estuarine phytoplankton	✓			
634	*Amphora angustata*	Estuarine phytoplankton	✓			
635	*Amphora decussata*	Estuarine phytoplankton	✓			
636	*Amphora holastica*	Estuarine phytoplankton		✓		
637	*Amphora hyaline*	Estuarine phytoplankton	✓			
638	*Amphora ovalis*	Estuarine phytoplankton			✓	✓
639	*Amphora turgid*	Estuarine phytoplankton				✓
640	*Amphora veneta*	Estuarine phytoplankton		✓	✓	
641	*Aphanothece castagnei*	Free floating in a fresh water pond			✓	
642	*Aphanothece stagnina*	Free floating in a fresh water pond		✓		
643	*Johannesbaptistia pellucida*	Planktonic in low saline brackishwater fishery		✓		
644	*Gloeocapsa aeruginosa*	As crusts on bricks/walls in a high saline canal		✓		
645	*Gloeocapsa calcarea*	In paddy field	✓			
646	*Gloeocapsa decortican*	On wet soil in high saline area		✓		
647	*Gloeocapsa kuetzingiana*	On moist soil in mid saline area		✓		
648	*Gloeocapsa montana*	In paddy field		✓		
649	*Gloeocapsa punctata*	On brick/ cemented stairs of a fresh water pond		✓		
650	*Gloeocapsa rupestris*	On wet soil as benthic flora		✓		
651	*Microcystis bengalensis*	Planktonic in low saline brackishwater		✓		
652	*Microcystis flos-aquae*	Planktonic in brackishwater fisheries	✓			
653	*Microcystis littoralis*	In saline water ditches in high saline areas		✓		
654	*Microcystis marginata*	Planktonic in low saline fishery	✓			
655	*Microcystis pulverea* var. *incerta*	In saline water ditches in high saline areas	✓			
656	*Microcystis viridis*	Planktonic along with green algae	✓			
657	*Stichosiphon sansibaricus*	Epiphytes on *Lola* sp. and *Enteromorpha* spp.		✓		
658	*Anabaena anomala*	In high saline water bodies		✓		
659	*Anabaena baltica*	Estuarine, on soft mud	✓			
660	*Anabaena cf. flos-aquae*	Estuarine phytoplankton		✓	✓	

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
661	*Anabaena doliolum*	Planktonic in brackishwater fisheries		✓		
662	*Anabaena gelatinicola*	On *Porteresia coarctata* in high saline area		✓		
693	*Anabaena oscillarioides*	Estuarine with other algal association	✓			
694	*Anabaena sphaerica*	Low saline area		✓		
695	*Anabaena variabilis*	On wet river bed in mid to high saline area		✓	✓	
696	*Anabaenopsis arnoldii*	Planktonic in low saline fisheries		✓		
697	*Nostoc* commune	Low saline area, on soft mud		✓		
698	*Nostoc cerneum*	Low saline area with other algal association		✓		
669	*Nostoc linckia*	On wet river bed in mid saline area.		✓		
670	*Nostoc punctiforme*	Free floating in brackishwater fisheries		✓		
671	*Raphidiopsis curvata*	Planktonic in low saline fisheries		✓		
672	*Raphidiopsis indica*	Planktonic from high saline areas		✓		
673	*Scytonema bohneri*	Planktonic in low saline fisheries		✓		
674	*Scytonema hofmanni*	On stones/bricks in stagnant pools		✓		
675	*Scytonema siculum*	Epiphytic on plant twigs		✓		
676	*Calothrix bharadwajae*	Epiphytic on plant twigs		✓		
677	*Calothrix clavata*	Planktonic in low saline fisheries		✓		
678	*Calothrix contarenii*	Epiphytic on green algae at high saline areas		✓		
679	*Calothrix scytonemicola*	Epiphytic on green algae		✓		
680	*Gloeotrichia raciborskii* var. *kashiense*	In muddy saline soil of high saline areas		✓		
681	*Mastigocoleus testarum*	Growing on shells		✓		
682	*Dermocarpa leibleiniae*	Epiphytic on *Lyngbya* sp. in high saline areas		✓		
683	*Dermocarpa hemisphaerica*	On *Cladophora* in mangrove forest floor		✓		
684	*Dermocarpa sphaerica*	Epiphytic on *Lyngbya* sp. in brackishwater		✓		
685	*Xenococcus chaetomorphae*	Epiphytic on *Chaetomorpha* filament		✓		
686	*Xenococcus kerneri*	Epiphytic on Lyngbya spp.		✓		
687	*Xenococcus cladophorae*	Epiphytic on *Cladophora* and *Enteromorpha*		✓		
688	*Schizothrix fuscescens*	Bottom of stagnant water of a brackish water		✓		
689	*Schizothrix lamyii*	In stagnant water and on decomposed matter		✓	✓	

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
690	*Schizothrix telephoroides*	On wet soil and planktonic in brackish water		✓		
691	*Katagnymene pelagica*	Free floating in brackishwater fisheries		✓		
692	*Lyngbya aestuarii*	Planktonic in brackish water wetland		✓		
693	*Lyngbya birgei*	With other algae from paddy fields		✓		
694	*Lyngbya connectans*	Free-floating with other BGA in wetlands		✓		
695	*Lyngbya confervoides*	Bottom biota of high saline brackishwater	✓	✓	✓	✓
696	*Lyngbya gracilis*	Free floating in brackishwater fishery		✓		
697	*Lyngbya hieronymusii*	Planktonic /free floating in brackishwater		✓	✓	✓
698	*Lyngbya lutea*	On wet soil near high saline brackishwater		✓	✓	✓
699	*Lyngbya major*	Free-floating in brackish water		✓		
700	*Lyngbya majuscula*	Bottom biota of high saline brackishwater		✓		
701	*Lyngbya martensiana*	Free floating in stagnant brackishwater		✓		
702	*Lyngbya rubida*	On root network of halophytes		✓		
703	*Lyngbya semiplena*	Brackishwater fisheries		✓		
704	*Lyngbya sordida*	Free floating in brackishwater fishery		✓		
705	*Lyngbya truncicola*	On wet soil in brackish water		✓		
706	*Oscillatoria acuta*	On muddy substratum		✓		
707	*Oscillatoria amoena*	Estuarine, on soft mud			✓	
708	*Oscillatoria chalybea*	Free floating with other BGA		✓		
709	*Oscillatoria chlorina*	On high saline river bed soil		✓		
710	*Oscillatoria corallinae*	In low saline fisheries		✓		
711	*Oscillatoria curviceps*	Planktonic in low saline fisheries		✓		
712	*Oscillatoria decolorata*	Brackish water		✓		
713	*Oscillatoria irrigua*	Planktonic in brackishwater		✓		
714	*Oscillatoria jasorvensis*	In high saline river bank soil	✓			
715	*Oscillatoria limosa*	Periphytic on submerged substratum		✓		
716	*Oscillatoria laete-virens* var. *minimus*	Planktonic in brackish water		✓		
717	*Oscillatoria margaritifera*	On muddy soil substratum in high saline areas	✓			
718	*Oscillatoria nigroviridis*	Planktonic/ bottom biota		✓		
719	*Oscillatoria obscura*	Planktonic		✓		

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone			
			1	2	3	4
720	*Oscillatoria princeps*	Planktonic in brackishwater	✓	✓		
721	*Oscillatoria proboscidea*	On muddy substratum		✓		
722	*Oscillatoria subbrevis*	From dried up high saline river bed on *Porteresia coarctata*	✓	✓	✓	
723	*Oscillatoria tenuis*	On high saline river bed soil		✓	✓	
724	*Phormidium ambiguum*	Edge of brackishwater wetland		✓		
725	*Phormidium anomala*	Edge of brackishwater wetland		✓		
726	*Phormidium corium* var. *capitatum*	Attached to bamboo sticks in brackishwater		✓		
727	*Phormidium fragile*	Periphytic in high saline areas		✓		
728	*Phormidium microtomum*	On brackish water mud substratum		✓		
729	*Phormidium retzii*	In small water channels	✓			
730	*Phormidium rubroterricola*	Muddy substratum		✓		
731	*Phormidium stagnina*	Planktonic in high saline brackishwater fisheries		✓		
732	*Arthrospira platensis*	In stagnant water		✓		
733	*Hydrocoleum lyngbyaceum*	On high saline muddy substratum		✓		
734	*Hydrocoleum meneghinianum*	On river bank muddy substratum	✓			
735	*Microcoleus chthonoplastes*	On high saline muddy substratum		✓		✓
736	*Microcoleus lacustris*	Muddy substratum		✓		
737	*Microcoleus paludosus*	Muddy substratum		✓		
738	*Trichodesmium erythraeum*	Marine phytoplankton	✓	✓		
739	*Trichodesmium thiebautii*	Marine phytoplankton	✓			
740	*Spirulina gigantea*	Free-floating in brackish water		✓		
741	*Spirulina labyrinthiformis*	Free-floating in brackish water		✓		
742	*Spirulina laxissima*	Planktonic in brackish water		✓		
743	*Spirulina major*	Planktonic in stagnant water		✓		
744	*Spirulina meneghiniana*	Planktonic in medium-low saline brackish water fisheries		✓		
745	*Spirulina princeps*	Planktonic in medium-low saline brackish water fisheries		✓		
746	*Spirulina subsalsa*	Planktonic		✓		

(continued)

Annex Table 1 (continued)

#	Algal species	Habitat	Zone 1	2	3	4
747	*Spirulina subtilissima*	Associated with other algae in brackishwater wetlands		✓		
748	*Chamaesiphon curvatus*	Epiphytic on *Bostrychia, Polysiphonia* & *Caloglossa*		✓		
749	*Aphanocapsa biformis*	Planktonic in brackish water		✓		
750	*Aphanocapsa grevillei*	Planktonic in brackishwater		✓		
751	*Aphanocapsa littoralis*	Planktonic in high saline fisheries		✓		
752	*Aphanocapsa pulchra*	On wet soil		✓		
753	*Aphanocapsa virescens*	Planktonic in brackishwater	✓			
754	*Merismopedia glauca*	Low saline pond	✓			
755	*Merismopedia punctata*	Planktonic		✓		
756	*Merismopedia minima*	Low saline pond		✓		
757	*Merismopedia tenuissima*	Planktonic in estuarine system		✓		
758	*Leptolyngbya foveolarum*	Low saline pond		✓		
759	*Leptolyngbya frigida*	Brackish water plankton		✓		
760	*Leptolyngbya valderiana*	Planktonic in brackishwater		✓		
761	*Leptolyngbya tenuis*	Low saline pond		✓		
762	*Planktolyngbya minor*	Low saline pond		✓		

Source: In-house study

Annex Table 2 Classification of tropical cyclones with colour convention

Saffir-Simpson hurricane scale			Tropical cyclone intensity scale (Australian region)			Tropical cyclone intensity scale (IMD)	
Category	Wind speed (kmph)	Storm surge (m)	Category	Sustained wind (kmph)	Gusts (kmph)	Category	Sustained wind 3 min avg. (kmph)
Five	≥250	>5.5	Five	>200	>279	Super cyclonic storm	≥221
Four	210–249	4–5.5	Four	160–200	225–279	Extreme severe cyclonic storm	166–220
Three	178–209	2.7–3.7	Three	118–159	165–224	Very severe cyclonic storm	118–165
Two	154–177	1.8–2.4	Two	89–117	125–164	Severe cyclonic storm	89–117
One	119–153	1.2–1.5	One	63–88	91–125	Cyclonic storm	63–88
Additional classifications			Tropical low	<63		Deep depression	51–62
Tropical storm	63–117	0–0.9				Depression	31–50
Tropical depression	0–62	0					

Source: https://en.wikipedia.org/wiki/Tropical_cyclone_scales

Annex Table 3 Erosion/Accretion between two consecutive years

Year	Accretion (km^2)	Erosion (km^2)	Difference (km^2)	Rate (km^2)
1989~1999	155.97	57.92	98.05	9.80
1999~2010	51.41	148.03	−96.62	−8.78
2010~2017	46.91	101.14	−54.23	−7.74
1989~2017	139.07	199.19	−60.12	−2.22

Source: In-house study
+ ve value indicates accretion and –ve indicates erosion