Aznarul Islam · Prakriti Das ·
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Arun Kumar Singh *Editors*

Fluvial Systems in the Anthropocene

Process, Response and Modelling

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Editors
Aznarul Islam
Department of Geography
Aliah University
Kolkata, India

Prakriti Das
Department of Geography
Victoria Institution (College)
Kolkata, India

Sandipan Ghosh
Department of Geography
Chandrapur College
Bardhaman, West Bengal, India

Abarna Mukhopadhyay
Department of Geography
Ranaghat College
Nadia, West Bengal, India

Ayan Das Gupta
Post-Graduate Department of Geography
Chandernagore College
Chandannagar, West Bengal, India

Arun Kumar Singh
Foundation of Practising Geographers
Kolkata, India

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Preface

Man has settled along the banks of the river since the very inception of the civilizations for its hydrological and agro-ecological advantages. Thus, the ancient 'ecumenes' (settlements) were found to be located along the major rivers across the world. This legacy of the river-based civilization still continues in the modern days in different forms. However, in the era of 'Anthropocene' the fluvial systems are largely altered by the human interventions in the form of large-scale dams and barrages, changes in the land use and land cover, road-stream crossing, mining of sand and gravel, mushrooming of brickfield and expansion of modern agriculture, industrial growth and urbanization. Thus, the present-day development pattern poses a threat to the fluvial system, especially the riverine ecosystem. In brief, water pollution, eutrophication and related damages to aquatic organisms are the major concerns of the fluvial system. However, the recent changes due to the COVID-19 pandemic situation sometimes act as a potent factor for trend reversal due to lesser human interventions. Thus, it becomes imperative to review the deterioration of the major fluvial systems of the world due to Anthropocene effects and, on the other hand, it introspects the direction and pace of ecological revival due to reduced Anthropocene effects for the emergence of the COVID-19 pandemic. In brief, maintaining the 'environmental flow' of the major rivers of the world for the proper functioning of the riverine ecosystem and sustainable development is a global issue. Thus, the present book will address the various issues of the fluvial systems, processes governing them, and system response arising out of the human-nature interventions to better understand the system behaviour and restore the degraded ecosystem of the world.

We invited chapters from scholars with expertise in the field immediately after the Two-Day International Webinar on 'River and Changing Riverine Ecosystem' held on 25–26th September 2021 organized by the Foundation of Practising Geographers, Kolkata, was over. We received an overwhelming response from the webinar participants and other eminent experts from different disciplines. Thus, we could manage to collect 25 chapters on various facets of the 'Fluvial Systems in the Anthropocene—Process, Response and Modelling' from across the world including the countries like India, Bangladesh and Cameroon. We hope the reader's thirst for changing river systems in the Anthropocene will achieve contentment in this volume.

Academicians from a wide group of disciplines such as earth science, geology, geography, geomorphology, river science and river engineering, biologists, sociologist, environmentalists and regional planners will be benefitted to solve their own problems.

We express our heartfelt gratitude to the authors who offered their best for this volume. Special thanks to our family members, colleagues and friends especially the team of Foundation of Practising Geographers, Kolkata, for their sincere support. We sincerely thank all the members of the organizing committee of the international webinar, resource persons and our advisors for successfully planning this timely publication. Finally, we express our sincere gratitude to the Springer Nature Switzerland AG especially Dr. Alexis Vizcaino, Senior Editor, Petroleum Geology, Mineral Resources, Sedimentology, Geophysics and Nature Conservation, Springer Heidelberg; Dieter Merkle, Vice President, Springer Nature Switzerland AG; Guido Zosimo-Landolfo, Editorial Director/Asset Manager and their team for their interest in working with us.

Kolkata, West Bengal, India
April 2022

Aznarul Islam
Prakriti Das
Sandipan Ghosh
Abarna Mukhopadhyay
Ayan Das Gupta
Arun Kumar Singh

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Editors and Contributors

About the Editors

Dr. Aznarul Islam is currently an Assistant Professor in the Department of Geography, Aliah University, Kolkata. Previously, he was engaged in teaching and research at the Department of Geography, Barasat Government College, West Bengal. He did M.Sc. in 2010 in geography from Kalyani University, West Bengal, and M.Phil. (2013) and Ph.D. (2016) in geography from the University of Burdwan, West Bengal. He has already published more than 45 research papers in different journals of national and international repute including more than 20 publications in the SCI and equivalent journals. He is one of the editors of four books: (1) Neo-Thinking on Ganges-Brahmaputra Basin Geomorphology (ISBN 978-3-319-26442-4), (2) Quaternary Geomorphology in India: Case Studies from the Lower Ganga Basin (ISBN 978-3-319-90426-9), (3) Anthropogeomorphology of Bhagirathi-Hooghly River System in India (ISBN 978-0-367-55727-0) and (4) Drainage Basin Dynamics (ISBN 978-3-030-79634-1). He has also contributed seven book chapters in edited volumes and one conference proceedings. He has presented papers in more than 20 national and international seminar and conferences. He has completed one Major Research Project funded by the Indian Council of Social Science Research (ICSSR), Ministry of Human Resource Development, Government of India. He has delivered several invited lectures and special lectures in different national and regional programmes. He has been performing the role of editorial board member and reviewer in different national and international journals. He is a life member of Foundation of Practicing Geographers (FPG), Kolkata, and National Association of Geographers, India (NAGI), New Delhi. He was an Assistant Convenor of the Two-Day national seminar: Geography of Habitat (26–27 February 2016), organised by FPG. He has already successfully supervised one Ph.D. thesis and more than forty dissertations on various topics of geomorphology at the master's level. Currently he is supervising four Ph.D. students in geomorphology and related fields. His principal area of research includes hydro-geomorphological issues of the Bengal Delta, including channel shifting riverbank erosion, flood, ecological stress of the riverine tract and environmental flow.

Smt. Prakriti Das is presently an Assistant Professor and Head in the Department of Geography in Victoria Institution (College), Kolkata. She has done her M.A. in Geography with specialization in Population Studies from Jawaharlal Nehru University, New Delhi, and M.Phil. in Planning and Development from Indian Institute of Technology, Bombay. She has published 3 research papers in peer-reviewed national journals like *Indian Journal of Landscape System and Ecological Studies* and *Indian Journal of Regional*. She has presented research paper in 2 UGC sponsored National seminars and has contributed as editor in a book published by Foundation of Practising Geographers. She is a life member of Indian Geographical Foundation, Kolkata and The Indian Science Congress Association.

Dr. Sandipan Ghosh is an Applied Geographer with a postgraduation, M.Phil. and Ph.D. in geography from The University of Burdwan. He has published more than forty book chapters, international and national research articles in various renowned journals of geography and geo-sciences. He is the author of two books, *Flood Hydrology and Risk Assessment: Flood Study in a Dam-Controlled River of India* (ISBN 978-3-659-50098-5) and *Laterites of the Bengal Basin: Characterization, Geochronology and Evolution* (ISBN 978-3-030-22937-5). He is also one of the editors in four books: (1) *Neo-Thinking on*

Ganges-Brahmaputra Basin Geomorphology (ISBN 978-3-319-26442-4), (2) *Quaternary Geomorphology in India: Case Studies from the Lower Ganga Basin* (ISBN 978-3-319-90426-9), (3) Anthropogeomorphology of Bhagirathi-Hooghly River System in India (ISBN 978-0-367-55727-0) and (4) Drainage Basin Dynamics (ISBN 978-3-030-79634-1). He has performed as one of the editors in the *Asian Journal of Spatial Science* and *Journal of Geography and Cartography*. Alongside he has worked as a reviewer in many international geo-science journals of Taylor & Francis (*Geo-Carto International*), Springer (*Environment Development and Sustainability*, *Arabian Journal of Geosciences and Geosciences*, *Spatial Information Research*, *Journal of Earth System Sciences* and *Journal of Geological Society of India*), the International Water Association (*Water International*), *Journal of Nicolaus Copernicus University*, Torun (*Bulletin of Geography Physical Geography Series*) and Indian Academy of Sciences (*Current Science*). Dr. Ghosh is a lifetime member of The International Association of Hydrological Sciences (IAHS), Eastern Geographical Society (EGS) and Indian Geographical Foundation (IGF). His principal research fields are various dimensions of fluvial geomorphology, flood geomorphology, quaternary geology, soil erosion and laterite study. Currently he has worked on (a) the gully morphology and soil erosion on the lateritic terrain of West Bengal and (b) quaternary geomorphology and active tectonics in the Bengal Basin, West Bengal. At present he is an Assistant Professor at the Department of Geography, Chandrapur College, PurbaBarddhaman, West Bengal.

Dr. Abarna Mukhopadhyay is currently working as an Associate Professor in the Department of Geography in Ranaghat College under Kalyani University. She has obtained her Ph.D. Degree in Geography from Burdwan University specializing in Advanced Geomorphology. She has published 6 research papers in peer-reviewed journals like *Indian Journal of Landscape Systems and Ecological Studies* and *Practising Geographers*. She has contributed chapters in books like *Geo-Environmental Issues of the New Millennium: Sustainable Planning Perspectives* and *Gender roles and caste effects in Indian Social Setup*. She has also been one of the editors in editing 3 books: *The World of Geography*, *Dreaming Geography* and *Covid-19 Pandemic: A Geo-Ecological Perspective*. She has successfully completed one research project 'Impact of changing Land use on Environment and Society in the alluvial tract of south west Birbhum district, West Bengal' funded by UGC.

Dr. Ayan Das Gupta is presently working as an Assistant Professor in the Department of Geography in Chandernagore College in Hooghly. Previously he was engaged in teaching as an Assistant Professor in Krishnagar Government College in Nadia. He did his M.Sc. degree and Ph.D. from the University of Calcutta in the year 2006 and 2014, respectively. He has already published 14 research papers in different national and international journals including *International Journal of Ecosystem*, *National Journal of the Landscape*, *Ecology and Ekistics (ILEE)* and the *Observer and Practising Geographers*. He has contributed as one of the editors for 3 renowned books and also two conference proceedings. He has presented research papers in more than 50 national and international seminars and conferences. He has successfully completed one UGC Minor Research Project 'Gradual Decay of River Piyali and Its Impact on Socio-economic Activities in the Selected CD Blocks of South 24 Parganas, West Bengal' and is presently associated with a Major Research Project 'Forest Livelihood Indexing to Ensure Sustainable Development for Tribal Communities at Selected CD Blocks of Bankura District, West Bengal-A Geoinformatic Appraisal' funded by WBDHESTBT. He has also participated in workshops of national and international repute. His areas of research interest include Urban Geography, Cartography, Geomorphology, Remote Sensing & GIS, Regional Planning and Geographical Thoughts.

Dr. Arun Kumar Singh is the Editor of geographical journal *Practising Geographers*. He joined Anthropological Survey of India in 1977 as a Human Ecologist and retired from Anthropological Survey of India in 2007 as Senior Ecologist. Before that he was working as Senior Research Assistant in the National Atlas and Thematic Mapping Organization, Government of India, Calcutta, from 1st July 1976 to 6th August 1977. He also served as Project Assistant in the Indian Institute of Management, Calcutta, from 18th March 1976 to 30th June 1976 in the project New Towns of India. He did his M.A. in Geography from Ranchi University in 1971 with specialization in Urban Geography and was awarded Ph.D. in Geography from Burdwan University in the year 1978. He has 6 books to his credit and has published nearly 50 research papers in reputed Geographical journals. He has also presented several papers in seminars and conferences of national and international repute. He is a life member of The Geographical Society of India, National Association of Geographers, Indian National Cartographic Association, The Allahabad Geographical Society and The Indian Anthropological Society.

Contributors

Bouba Lucas Départemement of Earth Sciences, University of Maroua, Maroua, Cameroon

Chakraborty Sandipan Department of Geography, Chandernagore (Govt.) College, Kolkata, India

Chanda Abhra School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India

Chattopadhyay Uttiya Department of Geography, Bhawanipur Education Society College, Kolkata, West Bengal, India

Das Gupta Ayan Post-Graduate Department of Geography, Chandernagore Government College, Hooghly, West Bengal, India

Das Balai Chandra Department of Geography, Krishnagar Government College, Nadia, West Bengal, India

Das Isha School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India

Das Moitrayee Department of Geography, Chandernagore College, Hooghly, West Bengal, India

Das Prakriti Department of Geography, Victoria Institution College, Kolkata, India

Das Rajib Agarpara Mahajati Vidyapith, Kolkata, India

Das Rima Department of Geography, Bhangar Mahavidyalaya, Bhangar, West Bengal, India

Das Sourav School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India

Gayen Shasanka Kumar Department of Geography, Cooch Behar Panchanan Barma University, Cooch Behar, West Bengal, India

Ghosh Puja Department of Geography, Krishnagar Government College, Krishnanagar, Nadia, West Bengal, India

Ghosh Sandipan Department of Geography, Chandrapur College, Purba Bardhaman, West Bengal, India

Ghosh Tanushree Department of Geography, Sailajananda Falguni Smriti Mahavidyalaya, Birbhum, West Bengal, India

Giri Sandip School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India

Gountié Dedzo Merlin Department of Life and Earth Science, High Teacher Training College, University of Maroua, Maroua, Cameroon

Guchhait Sanat Kumar Department of Geography, The University of Burdwan, Golapbag, West Bengal, India

Hazra Sugata School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India

Hossain Mallik Akram Department of Geography and Environment, Faculty of Life and Earth Science, Jagannath University, Dhaka, Bangladesh

Huq Md. Enamul College of Environmental Science, Hohai University, Nanjing, China

Islam Aznarul Department of Geography, Aliah University, Kolkata, India

Kar Amrita Earth Science Department, JIS University, Kolkata, India

Kumar Singh Arun Foundation of Practising Geographers, Kolkata, India

Kundu Anirban Department of Geography, Asutosh College, Kolkata, India

Kundu Soumya Department of Geography, Chandrapur College, Purba Bardhaman, West Bengal, India

Mafo Dongmo Irène Département of Earth Sciences, University of Maroua, Maroua, Cameroon

Majumder Arijit Department of Geography, Jadavpur University, Kolkata, India

Mondal Biraj Kanti Department of Geography, Netaji Subhas Open University, Kolkata, West Bengal, India

Mondal Madhumita Department of Geography, Bhairab Ganguly College, Belghoria, West Bengal, India

Mondal Sayoni Department of Geography, Presidency University, Kolkata, India

Mukherjee Sucheta Department of Geography, Sripat Singh College, Jiaganj, Murshidabad, India

Mukhopadhyay Abarna Department of Geography, Ranaghat College Affiliated to Kalyani University, Nadia, West Bengal, India

Mukhopadhyay Sayani Department of Geography, Asutosh College, Kolkata, India

Neogi Shatarupa Dey Department of Geography, Sarojini Naidu College for Women, Kolkata, India

Oraw Dipankar Department of Geography, Triveni Devi Bhalotia College, Raniganj, West Bengal, India

Pal Argha Pratim Department of Geography, Jadavpur University, Kolkata, India

Panja Sumit Department of Geography, Asutosh College, Kolkata, India

Patel Priyank Pravin Department of Geography, Presidency University, Kolkata, India

Polley Pradip Kr. Department of Geography, University of Calcutta, Kolkata, India

Rahman Md Mujibor Environmental Science Discipline, Khulna University, Khulna, Bangladesh

Rana M. M. Shah Porun Department of Geography and Environment, Faculty of Life and Earth Science, Jagannath University, Dhaka, Bangladesh

Ranjith Meera Mahatma Junior College of Education, Chembur, Mumbai, India

Roy Koyel Department of Geography, Cooch Behar Panchanan Barma University, Cooch Behar, West Bengal, India

Safi Md Department of Geography, Asansol Girls' College, Asansol, West Bengal, India

Saha Ujwal Deep Department of Geography, Vivekananda College for Women, Kolkata, India

Samanta Sourav School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India

Sarkar Atanu Department of Geography, Deshbandu College for Girls, Kolkata, India

Sarkar Biplab Department of Geography, Aliah University, Kolkata, West Bengal, India

Sarkar Prasanya Department of Geography, Cooch Behar College, Cooch Behar, India

Sarker Souvik Environmental Science Discipline, Khulna University, Khulna, Bangladesh

Sarma Utpal Seal Department of Geography, Cooch Behar Panchanan Barma University, Cooch Behar, West Bengal, India

Sattar Sanjukta Department of Geography, University of Mumbai, Mumbai, Maharashtra, India

Sen Arghyadip Banaras Hindu University, Benaras, India

Shaher Sania School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India

Sherla Ashwathy Ravindra Mahatma Junior College of Education, Chembur, Mumbai, India

Singh Shreyasi Centre for the Study of Social Systems (CSSS), Jawaharlal Nehru University, New Delhi, India

Zangmo Tefogoum Ghislain Département of Earth Sciences, University of Maroua, Maroua, Cameroon

Zouyane Nouhou Dama Hyacinthe Département of Earth Sciences, University of Maroua, Maroua, Cameroon

Fluvial Systems in the Anthropocene: Important Concepts, Issues and Research Needs

Sandipan Ghosh, Aznarul Islam, Prakriti Das, Abarna Mukhopadhyay, Ayan Das Gupta, and Arun Kumar Singh

Abstract In the Anthropocene, humans exert a geomorphic force that now rivals that of the natural Earth. Human disturbance of different types at different scales in river systems is a consequence of the perceived needs of human populations; however, these needs have to be in consonance with the needs of the river itself. For instance, the river requires its own space to perform such functions as flooding and floodplain development. Channel flow and forms are deliberately modified with the effect of increasing or decreasing stream power by dam building, embankment, in-channel agriculture, urbanization, gravel mining and dredging, roads, trails, ditches, channelization, and constriction by dikes. All rivers of the world respond to altered conditions of Anthropocene (as well as climate change), and the observed variability through time is important to know the adjustment, complexity and sensitivity against the threshold condition to save water resources. The key research questions are concentrated on the natural and anthropogenic factors and processes related to human modification of the rivers, and the future modelling of human-induced geomorphic changes. It is obvious that these research questions would require a multi-disciplinary approach involving geomorphologists, engineers, ecologists and social scientists.

S. Ghosh
Department of Geography, Chandrapur College, Purba Bardhaman, West Bengal 713145, India

A. Islam (✉)
Department of Geography, Aliah University, 17 Gora Chand Road, Kolkata 700014, India
e-mail: aznarulislam@gmail.com

P. Das
Department of Geography, Victoria Institution College, Kolkata, India

A. Mukhopadhyay
Department of Geography, Ranaghat College Affiliated to Kalyani University, Nadia, West Bengal, India

A. Das Gupta
Post-Graduate Department of Geography, Chandernagore Government College, Strand Road, Burrabazar, Hooghly, West Bengal 712136, India

A. Kumar Singh
Foundation of Practising Geographers, Shree Ranjani Housing Society, 662 Picnic Garden Road, Kolkata 700039, India

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River science and fluvial geomorphology provide an ideal platform to tackle such issues and it is time now to promote this science in India in a major way. This work, thus, intends to review the many facets of the fluvial response to the various stimuli in the Anthropocene. Finally, a summary of the different chapters of this multi-contributed volume has been presented to reveal the recent progress in the field of river science and water resources in the Anthropocene.

Keywords Anthropocene · River · River metamorphosis · River science · Equilibrium · Human activity

1 Introduction

The Anthropocene epitomizes the time period of intensified human action since human impacts become one of the key external forcings on the natural processes, and the term, introduced by Crutzen (2002), reflects an epoch when human activities have become so profound and pervasive that they rival or exceed the great forces of nature in influencing the various functions of Earth system (Das et al., 2021; Gibling, 2018; Goudie & Viles, 2016). The main point of interest is that human civilisations have been reshaping the landforms and landscapes for thousands of years, developing anthropogenic geomorphic features ranging the earthworks and reservoirs to settlements, mining, roads, canals, ditches and plough furrows that have discrete appearances (degradation of floodplain environment and river modification) compared with landforms produced by the natural processes (Das et al., 2021; Tarolli et al., 2019). In the epoch of Anthropocene, the components of fluvial systems are largely altered by human interventions in the form of large-scale dams and barrages, changes in the land use and land cover, road-stream crossing, mining of sand and gravel, mushrooming of brickfield and expansion of modern agriculture, industrial growth and urbanization (Graf, 2006; Jain et al., 2016; James, 2013; Tarolli et al., 2019). Thus, the present-day development pattern poses a threat to the fluvial system, especially the riverine ecosystem. In brief, water pollution, eutrophication and related damages to aquatic organisms are the major concerns of the fluvial system which consists of a network of channels and associated environments that transport sediment from a drainage basin to a depositional basin. Therefore, rivers are central to the debate about the Anthropocene because many human activities from antiquity focused on channels and floodplains (Gibling, 2018).

The ancient Greek philosopher Heraclitus famously asserted that one can never step into the same river twice, thus providing a physical metaphor for life's constant change (Poff, 2014). The riverine environment and floodplains are constantly changed due to the unaccountable growth of the human population and technological advances in the Anthropocene. Ecological complexity in river basins has been conceptualized scientifically by viewing these systems as existing in a kind of dynamic equilibrium, or balance, defined by prevailing hydro-climatic and watershed controls and by evolutionary species pools (Poff, 2014). Humans act to disrupt components of this equilibrium, causing "impacts" in the system (Poff, 2014). The human role as a transforming agent in rivers is also rich (Gregory, 2006), and today there is a general recognition of the environmental damage derived from the use and control of rivers for navigation, water consumption and power generation (García et al., 2021). A large geomorphological tradition has studied human effects on river systems (e.g., Belletti et al., 2020; García et al., 2021; Piégay et al., 2020; Scorpio & Rosskopf, 2016; Stecca et al., 2019) and opened new horizons for their conservation, restoration and coexistence (Table 1). In the last twenty years, river concerns are highly focused on by many researchers and planners, and river restoration has emphasized rehabilitating water (first) and sediment (later) fluxes (Ibisate et al., 2016; Tena et al., 2020), longitudinal connectivity, ecological integrity (Downs et al., 2011; Vugteveen et al., 2014), ecosystem services (Palmer et al., 2014; Thorp et al., 2006) or ecological justice (participation and equity).

Geomorphologists began to make their way slowly in river management, and although there is a long way for geomorphology to fully participate in the understanding of river ecology, proposals such as 'Fluvial Hydrosystems' (García et al., 2021). The evolution of environmental concerns and integrated approaches have converged in river sciences, within which geomorphology (and hydrology) has a critical place because it provides a holistic perspective and is key to improving river status (García et al., 2021). In Anthropocene a big question therefore is: can we continue to create 'disturbances' at different scales in the large river systems without obtaining a detailed multi-disciplinary knowledge base of these systems? (Sinha et al., 2013). Human disturbance of different types at different scales in river systems is a consequence of the perceived needs of human populations; however, these needs have to be in consonance with the needs of the river itself. For instance, the river requires its 'own space' to perform such functions as flooding and floodplain development (Sinha et al., 2013). Now, we must learn and effect change at a rate that is faster than the rate at which humans are currently using and degrading earth's limited resources. One premise of the Rivers of the Anthropocene study is that a transdisciplinary approach by the scholars of earth sciences will be more effective than single-, multi-, or interdisciplinary approaches to helping societies manage rivers. In the following sections the main focus and explanation are primarily concentrated on the stages of anthropogenic interventions in rivers, the human role as a geologic and geomorphic agent, changing perspectives of anthropogenic fluvial system, key concepts, principles and approaches of fluvial geomorphology applied in Anthropocene, the role of scholar and society on the sustainability of rivers, and research needs in India.

2 Stages of Anthropogenic Modifications in Fluvial System

A detectable human imprint on the environment extends back for thousands of years (Gibling, 2018). The human river footprint has expanded with great rapidity: such a duration is commonly represented in the geological record by a few metres of

Table 1 Important articles and books accounting world rivers in Anthropocene

Sl. No.	Title of articles/books	Theme of work	Authors
1	Man Makes the Earth	Man is considered as the geologic and geomorphic agent to change the face of the earth. Whilst an approximate between the order of weathering and natural denudation exists, the influence of human beings leads to an increase of the order of one 100-fold in rates of denudation	Brown (1970)
2	Man, a Geomorphological Agent: An Introduction to Anthropic Geomorphology	The term ‘ Anthropic Geomorphology’ was first introduced. The chapters are organized according to human activity: forestry, grazing, agriculture, mining, transportation, river and shore management, settlement, and a conclusion leading to a summary of all activities	Nir (1983)
3	The Human Role in Changing Fluvial Systems: Retrospect, Inventory and Prospect	Article includes documentation, inventory, and explanation of change, as well as a desire to ameliorate the destructive influences of humans on nature	James and Marcus (2006)
4	Anthropogenic Geomorphology A Guide to Man-Made Landforms	A largely Hungarian review that is especially strong on constructed and excavated landforms	
5	Rivers of the Anthropocene?	Humans act to disrupt components of the equilibrium, causing impacts that are quantified as measurable deviations in riverine biophysical processes and patterns from some unperturbed baseline condition	Poff (2014)

(continued)

Table 1 (continued)

Sl. No.	Title of articles/books	Theme of work	Authors
6	Geomorphology in the Anthropocene	In this comprehensive examination of human impacts on diverse landscapes, the book provides numerous examples and details of how human activities have altered and continue to alter Earth's surface	Goudie and Viles (2016)
7	River Systems in India: The Anthropocene Context	The present review provides a synthesis of studies on the Indian rivers at modern time scale. These studies highlight the significant impact of anthropogenic forcing on modern day river processes and behaviour	Jain et al. (2016)
8	River Systems and the Anthropocene: A Late Pleistocene and Holocene Timeline for Human Influence	Rivers are central to debate about the Anthropocene because many human activities from antiquity focused on channels and floodplains. Author elaborated the onset of human modification of rivers which identified six stages that represent key innovations	Gibling (2018)
9	Anthropogeomorphology of Bhagirathi-Hooghly River System in India	In this edited volume main chapters concentrate that the river valleys of Bhagirathi-Hooghly Basin in India is one of the most densely populated regions in the world and is undergoing rapid transformation of its natural landscape induced by human interventions, such as mushrooming of dams and barrages, deforestation, and urbanization	Das et al. (2021)
10	Promoting Fluvial Geomorphology to "Live with Rivers" in the Anthropocene Era	Article tries to explore potential answers to this question in terms of role, barriers, motivation and prospects for river management in the Anthropocene Era	García et al., 2021

(continued)

Table 1 (continued)

Sl. No.	Title of articles/books	Theme of work	Authors
11	Anthropogeomorphology: A Geospatial Technology Based Approach	This edited volume explores state-of-art techniques based on open-source software and statistical programming and modelling in modern geospatial applications in geomorphological, hydrological, bio-physical and social activities	Bhunia et al. (2022)

sediment on an alluvial plain, a few avulsions of a trunk channel, or part of a rhythm of sea-level rise (Gibling, 2018). Important earlier human effects with significant environmental consequences include megafaunal extinctions between 14,000 and 10,500 cal yr BP (Braje & Erlandson, 2013); domestication of plants and animals close to the start of the Holocene at 11,700 cal yr BP; agricultural practices and deforestation at 10,000 to 5000 cal yr BP (Braje & Erlandson, 2013); and widespread generation of anthropogenic soils at about 2000 cal yr BP (Ruddiman, 2003). The following chronological stages (Stages 2–6 encompassed less than 10,000 years of river history) of human footprints were detected in the river basins of the world (Brown et al., 2013, 2017; Edgeworth et al., 2015; Gibling, 2018; Klein Goldewijk et al., 2017):

- Minimal river effects before about 15,000 cal yr BP (Late Pleistocene), with the use of fire and gathering of plants and aquatic resources;
- Minor river effects from increased cultivation after about 15,000 cal yr BP, with plant and animal domestication after about 10,700 cal yr BP (activity included fisheries, ochre mining, and construction of early settlements);
- Agricultural era after about 9800 cal yr BP, with legacy sediments, widespread fire use, the first dams and irrigation, and mud-brick manufacture;
- Irrigation era from about 6500 cal yr BP, with large-scale irrigation, major cities, the first large dam, urban water supplies, expanded groundwater use, river fleets, and alluvial mining;
- Engineering era with embankments, dams, and watermills after about 3000 cal yr BP to about 1750 CE, especially in the Chinese and Roman empires, and the stage marks the onset of large-scale river engineering with the management of extensive embankments, canals, dams, and urban water supplies.; and
- Technological era after about 1800 CE showed the modern Big Dam Era from 1882 onwards ushered in technological river modification and regulation such that most rivers on Earth now experience major anthropogenic influence (Fig. 1).

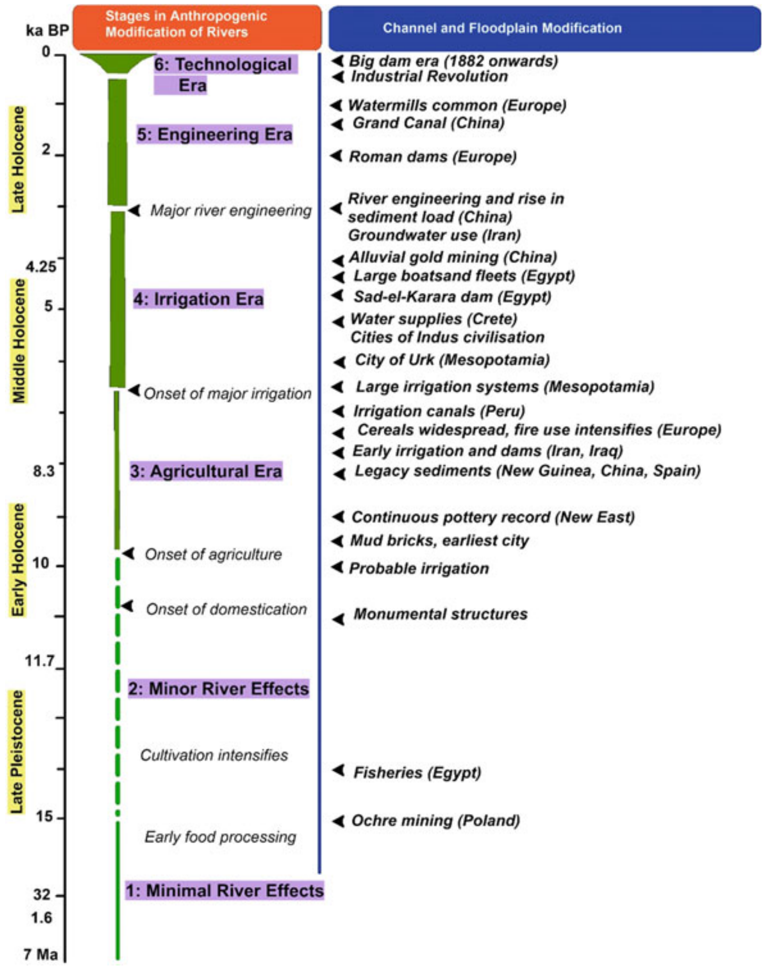

Fig. 1 A summary on timelines and stages of human modification of rivers during Anthropocene, reflecting six stages of anthropogenic modification (modified from Gibling, 2018)

3 Modern River Systems and Human Activity

From Late Pleistocene and Holocene epoch, the key anthropogenic influences on modern river landscapes (Table 2) are recognised fire use, agriculture and deforestation, animals used for food, ploughing, and transport, an embankment along channels, dams and irrigation systems, navigation and bank structures, city water supplies, warfare, extraction of channel and floodplain materials, extraction of aquatic materials and cultural events (Gibling, 2018). The influences may have direct or indirect effects on rivers, commonly altering the boundary conditions of processes such as sediment erosion and transport. They are substantiated in the table with references that demonstrate their impact in modern and sub modern settings. Fire is used for hunting and deforestation and, along with other anthropogenic vegetation changes, converts forests and other undisturbed ecosystems to cropland and grazing land, commonly with terrace construction. Cropland, grazing land and animal collectively influence the reduction of regolith strength and enhance erosion, increasing sediment supply to rivers (Islam et al., 2021a, b). More direct effects on rivers involve the modification of channels and changes to the connectivity of channels and floodplains, including the transfer of large volumes of water to floodplains for irrigation and other human uses (Sarkar & Islam, 2019; Islam et al., 2021b). Irrigation systems are commonly linked to dams and barrages, with the use of specialised irrigation technology (Islam et al., 2020). Bridges and river crossings are a common focus for human activity. The deliberate breaching of embankments during warfare has been responsible for catastrophic avulsions and widespread floodplain aggradation. The third set of influences involves resource extraction from floodplains and channels, commonly yielding technofossils. Major cultural events take place at rivers around the world. For example, tens of millions of people attend the festival of Khumba Mela, held every twelve years at the confluence of the Ganges and Yamuna rivers in India.

4 Human Activity and River Metamorphosis

River metamorphosis, introduced by Schumm (1969), reflects that natural and anthropogenic disturbances can lead to a wide range of responses in the fluvial system. It follows then that readjustments to a new set of environmental conditions (threshold and complex response) can affect the physical dispersal of sediment-borne trace metals in a variety of ways, each of which may vary in time and position along the valley floor (Miller & Miller, 2007). Rivers respond to altered conditions (e.g., intrinsic and extrinsic factors), therefore variability through time is important because a river or a reach may be out of character for a period as it adjusts. For example, Figs. 2 and 3 suggest how different types of channels respond to change (i.e., dam closure or river impoundment). A list of sixteen responses of channels to change, and the four major variables that influence them are summarized in Table 3. Time (history) is included with discharge (increase or decrease), sediment load (increase or decrease), and base level change (up or down), because channels change naturally through time, and time is an index of energy expended or work done. The changes are grouped according to the results of the change (erosion, deposition, pattern change, and metamorphosis). In Table 3, the changes that will be affected by the passage of time or by a change of discharge, sediment load or base level are indicated by an X.

Different types of human activity are known to cause channel erosion. These factors can be divided into four effects: reduction of sediment weight, increase in annual discharge and maximum discharge, increase in flow density and channel gradient. It was recognized that sixteen types of human activity can cause channel

Table 2 Summarizing the anthropogenic activities on rivers and floodplain systems through some cited literature

Sl. No.	Human activity	Effects on rivers	Important references
1	Fire use	Vegetation loss promotes rapid runoff, soil erosion, and enhanced sediment flux to rivers; change in soil structure and vegetation species	Vannière et al. (2016) and Gibling (2018)
2	Agriculture and deforestation	Reduced resistance of river banks and hillslopes where crops with shallow roots replace natural vegetation; widening of channels and sediment coarsening; slope failure and increased sediment flux	Brown et al. (2013) and Gibling (2018)
3	Animals used for food, ploughing and transport	Herds reduced vegetation cover and enhance soil erosion, gullying and sediment flux to rivers; trampling break down river banks and increased sediment load; ploughing intensified floodplain morphological changes	Trimble and Mendel (1995) and Dunne et al. (2011)
4	Embankments along channels	Embankment narrowed channels, reduced river migration, increased flow velocity and funnelled sediments to deltas; sediment trapping reduced floodplain inundation and loss of palaeochannels; it raised channel bed and promoted avulsion	Hudson et al. (2008) and Ghosh and Illahi (2020)
5	Dams and irrigation systems	Dams altered river flow regime and flood frequency, caused deposition in reservoirs and increased downstream erosion; irrigation reduced river discharge and use of river and groundwater promoted soil waterlogging and salination	Kondolf (1997) and Ghosh and Guchhait (2016)

(continued)

Table 2 (continued)

Sl. No.	Human activity	Effects on rivers	Important references
6	Navigation and bank structures	Dredging, riverbed scour and removal of wood snags and jams to aid navigation altered river morphology; reduced number of delta distributary channels aids year-round navigation	Smith et al. (2016)
7	City water supplies	Remove river and groundwater from the hydrological system, with water pollution from sewage and waste	Brown et al. (2009)
8	Warfare	River diversions during warfare causes catastrophic floods and floodplain aggradation	Lary (2001)
9	Extraction of channel and floodplain materials	Alluvial mining of channels and terraces for sand, gold and other minerals increases aggradation and erosion rate locally; pits on floodplains for bricks, tiles, pottery and ochre, and on terraces for laterite remove soils and aquifer media cause soil erosion	Santhosh et al. (2013) and Ghosh et al. (2016)
10	Extraction of aquatic materials	Reeds, papyrus and other in-channel plants influence flow dynamics and sedimentation; fisheries and aquatic harvesting enhanced human activity on river banks	Leonard et al. (2002)
11	Cultural events	Water festivals involve large populations with infrastructure on river banks and sand bars	Kar et al. (2017)

incision (Casado, 2013; Schumm, 1999, 2005): (1) dam construction; (2) sediment diversion, (3) flow diversion, (4) urbanization, (5) dam removal or failure, (6) lowering lake and reservoir levels, (7) meander cutoff, (8) underground mining, (9) groundwater withdrawal and hydrocompaction, (10) gravel and sand mining, (11) dredging, (12) roads, trails and ditches, (13) channelization, (14) construction of flow, (15) deforestation and (16) fire. Low sediment load may be due to the construction of dams, urbanization, expansion of silt in other channels like canals and gravel mining and dredging (Schumm, 2005). Average discharge and maximum discharge

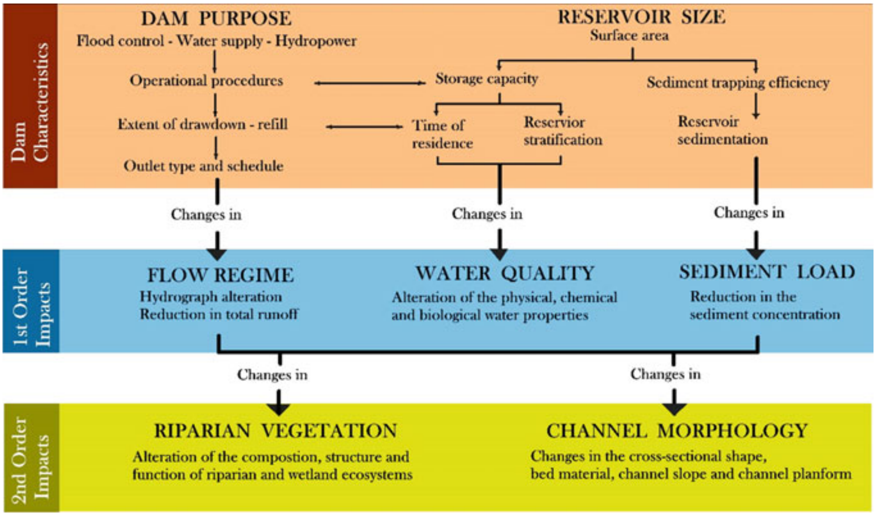

Fig. 2 Identified orders of changes in an impounded river system (dam purpose and reservoir size), affecting flow regime, water quality and sediment load (modified from Casado, 2013)

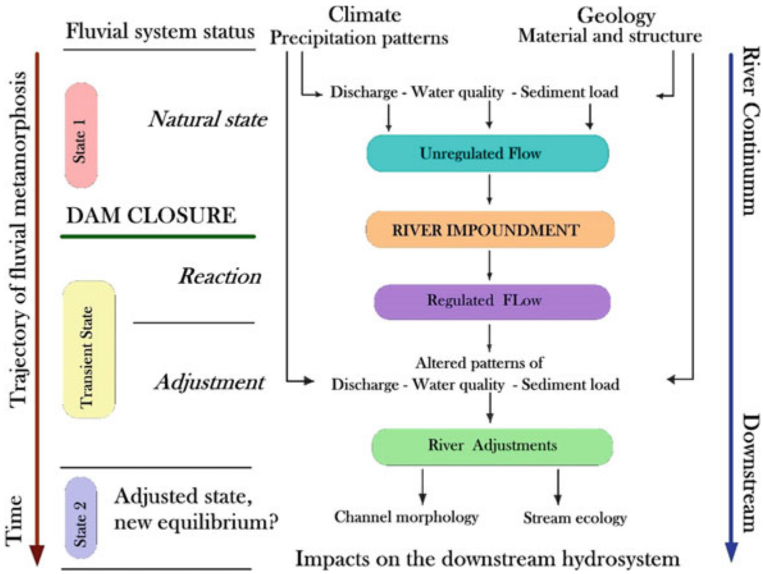

Fig. 3 A conceptual scheme to understand the fluvial response to dam closure and river metamorphosis (modified from Casado, 2013)

Table 3 Anthropogenic changes in variables affecting channels and metamorphosis (X indicates channel response; + indicates positive change; − indicates negative change)

Channel Response	Variables						
	Time	Discharge		Sediment Load		Base Level	
		+	−	+	−	+	−
Erosion							
Degradation (incision)		X			X		X
Knickpoint formation and migration		X			X		X
Bank erosion	X	X		X	X	X	X
Deposition							
Aggradation			X	X		X	
Back and downfilling			X	X		X	
Berming			X	X			
Pattern change							
Meander growth and shift	X	X					
Island and bar formation and shift	X	X		X			
Cutoffs	X	X		X		X	X
Avulsion	X	X		X		X	
Metamorphosis							
Straight to meandering		X		X			X
Straight to braided			X	X		X	X
Braided to meandering		X			X		X
Braided to straight			X		X		X
Meandering to straight		X		X		X	X
Meandering to braided			X	X		X	

Source Schumm (2005)

can be increased by flow diversion, urbanization, removal of dams and deforestation. The flow can be centralized by increasing the strength of the flow through gravel excavation and dredging, road, trail, shaft, channelization and compression by dyke. The gradient can be increased by removing dams, lowering water levels in lakes and reservoirs, mandar cutoff, mining, drainage and hydro-condensation, gravel mining, dredging and channelization (Schumm, 2005).

In the context of the Ganga-Brahmoutra-Meghna Delta, channel metamorphosis is a significant facet of the evolution of river courses in the Anthropocene due to different anthropogenic interventions. Of them, the construction of dams and barrages over the rivers plays a pivotal role in channel modifications. For example, the construction Farakka Barrage Project (FBP over the Ganga river created the problem of in-channel sedimentation above the FBP and riverbank erosion below the barrage along the River Bhagirathi and the Padma (Islam & Guchhait, 2017). The problem of bank erosion, meandering and braiding are the major responses due to the variable river regime in the lean months induced by the Indo-Bangladesh water-sharing treaty (Guchhait et al., 2016; Islam & Guchhait, 2020). The disconnection of the Jalangi River, Ichhamati and Mathabhanga-Churni are also to some extent triggered by the reduced flow through the Padma from the FBP in the lean months (Sarkar et al., 2020). Similarly, the hydro-geomorphological evolution of the other rivers of the Bengal Basin like the Damodar river (Bhattacharyya, 2011; Ghosh & Guchhait, 2014), and the Mayurakshi River (Islam & Ghosh, 2022; Pal & Mandal, 2017) are also well documented in the context of dams and barrages. Besides, channel modifications are revealed through the impact of road-stream crossing (Roy & Sahu, 2018), agricultural expansion (Sarkar et al., 2020), deforestation (Islam et al., 2020), sand and gravel mining (Islam et al., 2021a, b; Pal & Mandal, 2017), development of brick kiln industries (Das & Bhattacharya, 2020), in different rivers basins of the GBM delta.

5 Plastics in Fluvial Deposits

Plastics, a signature of the human footprint, are existing in all ecosystems, and these are found in a variety of environments around the world. The global abundance of plastics, the long-term effects, the apparent temporal depiction of plastics, and the lack of a geological background have also led plastics to be considered a potential indicator of a proposed new post-Holocene Cenozoic era, ‘Anthropocene’ (Weber & Lechthaler, 2021; Zalasiewicz et al., 2011). In principle, the first plastic deposits discovered in the marine environment are understood to be the last point of the plastic transport system that extends from land to oceans via rivers (Weber & Lechthaler, 2021). The importance of Anthropocene rivers is highlighted that since the lion’s share of global plastics production is produced and consumed on land, it has been shown that rivers and river systems are the main plastic corridors and transport routes in the environment (Weber & Lechthaler, 2021). Ubiquitous in the environment, plastics have the potential to become a ‘novel’ stratigraphic marker for recent sediments, and especially fluvial sediments. This potential is due to their occurrence in fluvial systems, their properties, and their preservation. The detection of plastic particles is usable in two different ways: (1) as a proxy of environmental contamination, and (2) as marker in a sedimentary context. In the future, it will be possible to record recent sediment dynamics in fluvial systems, to classify them stratigraphically, and monitor them (Weber & Lechthaler, 2021). As a new specific marker, the protective mask has entered the environment during the Covid-19 pandemic situation in the world. It may emerge in the future as a 2020 marker due to its visual properties and species composition. Despite the widespread use of face masks in certain regions or during previous virus outbreaks, the explosive global increase in mask production in 2020 is accompanied by a worldwide spread and high potential for littering of used masks (Weber & Lechthaler, 2021).

6 Application of Geomorphic Concepts in Anthropocene Rivers

In the future, a growing population and resource exploitation will cause the dependence of a greater number of human beings on our river systems. According to Sinha et al. (2013) a big question therefore is: can we continue to create 'disturbances' at different scales in the large river systems without obtaining a detailed multi-disciplinary knowledge base of these systems? Technological interventions should therefore be practised on the basis of a holistic approach encompassing all aspects of river systems and 'River Science' offers such an opportunity (Sinha et al., 2013). River science refers to the study of a variety of processes affecting river systems. This is a truly interdisciplinary science and requires the explicit joining of two or more areas of understanding into a single conceptual-empirical structure. To study the anthropogenic influence on river dynamics Jain et al. (2012) prescribed the following geomorphic concepts and principles of river science which can be applied in Indian rivers to know the effects of Anthropocene:

- Equilibrium Process and State—The fluvial system tries to maintain a constant linear relationship between input (cause) and output (effect) and the system oscillates around that linear relationship to achieve an equilibrium state or form. An equilibrium landform tends to maintain relatively stable characteristics even after minor perturbations, but human disturbance can create an imbalance in the system.
- Magnitude and Frequency—The magnitude of an event (e.g., dam) generally refers to the amount of work carried out or the degree of landform change experienced due to river modification. The frequency of an event of a specific magnitude is expressed as the average length of time between events of that magnitude.
- Threshold—Threshold steps are responsible for achieving a new equilibrium stage after any major or prolonged human perturbation, that results in a nonlinear relationship between forcing mechanism and landform change. River planform changes may occur through the crossing of internal or external thresholds.

- Sensitivity—The sensitivity of the fluvial system describes its propensity for change and its ability to absorb any disturbing forces. If a geomorphic system is close to the threshold value, it will be highly sensitive to change.
- Connectivity—The way in which different landscape compartments (i.e., a landscape may be divided into different compartments which may be a large landform or a summation of smaller landforms) fit together in the catchment in a given time-frame.
- Complexity—Nonlinear relationship between the driving and geomorphic response at different space and time reflects the complexity in the fluvial system. In a complex system, the outputs will be inconsistent with inputs.

7 Living with Rivers

The human role as a transforming agent in rivers is also rich, and nowadays there is a general recognition of the environmental damage derived from the use and control of rivers for navigation, water consumption and power generation. A large geomorphological tradition has studied human effects on river systems and opened new horizons for their conservation, restoration and coexistence (García et al., 2021). From a particular perspective, geomorphology spans greater openness and the search for a niche from which it can develop more influence in river management. Geomorphologists began to make their way slowly in river management, and although there is a long way for geomorphology to fully participate in the understanding of river ecology, proposals such as 'Fluvial Hydrosystems' (García et al., 2021). Under the paradigm 'Living with rivers', Raven et al. (2002) and Garcia et al. (2021) proposed to manage and restore rivers as a hybrid plan of biophysical and socio-political processes moving around the concepts of "work with nature, not against it" or "working with natural processes". Three principles are acknowledged to achieve the goal (García et al., 2021):

- Work Across Disciplinary Frontiers—The multiple approaches from which a river can be studied imply cross-disciplinary interaction between sciences, mutual respect, and learning about the different visions of the river and the diversity of spatial and temporal scale analysis.
- Integrated Plans—This principle advocates for the unification of single management or work plan of the projects for river restoration, flood-risk management, and land planning; it considers the three sub-lines inseparable and in permanent feedback. An integrated plan (inclusion of river restoration, flood-risk management and land planning) is, in addition to being a technical process, a socio-political and cultural process to change the relationship between rivers and society.
- Fluvial Education—The goal of informing people is to correct them is understandings of river behaviour perceived by society, extending these to the forces that control what a river is, what restoration/management is and how it should be applied. This process involves moving from a vision of the river as a resource to

a fluvial framework in which societies adapt to the times, forms and processes of rivers.

8 Research Needs

Rivers, because of the services they provide to humans and other forms of life, are effective ecosystems for demonstrating the conflicts that arise when humans do not learn how to curb their desires or share the benefits of nature (Lubinski & Thoms, 2017). Scholars, people with advanced knowledge of a subject, play an important role in showing society the consequences of its decisions and actions (Lubinski & Thoms, 2017). River management strategies all around the world have moved from the engineering dominated command and control approach to an integrated ecosystem-based approach that relies on the synthesis of hydrological, geomorphological and ecological data (Sinha et al., 2013). Attempts are now on to design engineering solutions using the scientific framework of the river system as the basic template for human intervention. Some of the specific research needs and questions in river science of Anthropocene in the Indian context may be framed as follows (Jain et al., 2012; Sinha et al., 2013):

1. How will climate change and anthropogenic intervention affect the hydrological budget of the river system, their geomorphology, sediment transport characteristics and connectivity?
2. How dams and other river engineering structures can modify the stream hydrology, fluvial processes and water resources?
3. How is the river morphology related to current discharge and sediment load and how it is responding to changes in hydrologic regime due to natural and anthropogenic processes? How to differentiate the impacts of natural and anthropogenic impacts on river systems?
4. What is the sensitivity of the different reaches to known external forcings and how can such differential sensitivity help to prioritize management planning in a large river?
5. How can we model the future geomorphological (physical) changes on the basis of modelled future changes in flux and energy, i.e., prediction of geomorphic change on the basis of the anthropogenic change prediction model?
6. How have urbanized centres (megacities) affected the physical–chemical characteristics of the reaches of a large river and the river as a whole?
7. What is the nature of river–groundwater connectivity and what are its implications on water resources management and riverine ecosystem management?
8. What are the limits to the human disturbance of a large river system? How do we define and estimate the values of environmental flow at different reaches?

9 Summary of the Chapters

The chapters of the present volume will focus on the research needs mentioned above. The present volume contains 25 chapters including introductory chapter which has reviewed the various concepts and issues of the fluvial systems in the Anthropocene. Moreover, this chapter has set the tune of the volume by introducing the major areas of research that need attention from the different disciplines concerned with the river. Chapter 2 is concerned with the holistic view of the river and aquatic system revealing the interconnected nature of the river as a physical entity and social entity. Chapter 3 deals with the distressed conditions of the river from an evolutionary perspective. Chapter 4 presents conceptual and theoretical developments in the ecogeomorphological behaviours of the river and their application to river restoration. Rivers are probably lying in every pore of the society which is reflected in the literature. Thus, Chapter 5 very pertinently portrays the impact of the river on man and society in the light of some Bengali novels. Chapter 6 deals with the poor water quality due to unscrupulous human intervention in the Bhagirathi River in West Bengal, India. Similarly, Chapter 7 shows the pity condition of the Mithi River in Maharashtra, India. River water quality is below the standard for potable use even during the COVID 19 pandemic situation that calls for intervention from various stakeholders to restore this fluvial system. Chapter 8 reveals the flood susceptibility of the Mayurakshi river basin using Geospatial techniques and multi-criteria analysis. Chapter 9 critically examines the geometric irony of the Ajay river where narrowing of channel width downstream has been clearly observed. The natural forcing and role of human intervention are pivotal to such river morphology. Chapter 10 addresses the prioritization of the Pagla Jhora micro basin in the Darjeeling hilly area based on the fluvial morphometry parameters of a basin. The next chapter (11) similarly shows the sub-watershed prioritization using basin morphometry in the semiarid area like the Puruliya upland. Chapter 12 is an attempt to portray the integrated watershed development using correlation and association analysis between drainage basin morphometry and LULC characteristics. Chapter 13 also attempts to assess the nature of flood risk of sub-watersheds of Teesta River Basin using morphometric parameters through the application of Hazard Degree (HD) and Principal Component Analysis with Weighted Sum Approach (PCAWSA). Chapter 14 is concerned with the flood hazard in the North Bengal region and it portrays that flood-affected area has diminished in the recent decade, however, it is still occurring on a regular basis even after the structural interventions in the river basin. Chapter 15 intends to show the channel dynamics of the Hari River and its tributaries in the polder area of Bangladesh. The study indicates that the shifting of the channel is slow, however, the narrowing of the channel due to different natural and anthropogenic drivers poses a threat to its existence in future. Chapter 16 has succinctly portrayed the intense human interventions in the form of agricultural development and urbanization on the decay and fragmentation of the palaeochannels of the Damodar Fan Delta, India using a widely accepted approach in the Anthroplogeomorphology i.e. EPA (excavation, planation and accumulation). Similarly, Chapter 17 applying the

Multi-temporal Satellite Images and GIS has focused on the historical evolution and decay of the Jamuna River in West Bengal, India in recent times due to escalating human interventions. However, the outbreak of COVID 19 pandemaic has restricted human movement and curtailed the level of pollution of the river. Certainly, Chapter 18 is vital in the context of the critical assessment of river health in the wake of COVID 19 in India. Chapter 19 is concerned with the poor water quality and decay of the ox-box lakes of the Bhagirathi and Jalangi rivers due to accelerated human intervention. In the context of the Anthropocene, the growth of aquaculture ponds and methane emission is very crucial. Chapter 20 demonstrates the contrasting diffusive methane emission from two closely situated aquaculture ponds of varying salinity located in a wetland in eastern India. The sewage–fed freshwater and oligohaline aquaculture ponds show a marked difference in the methane emission. Besides the problems of the river and wetlands, the issues of the soil, and groundwater of the river basi are also important in the recent age (Human age). Thus, Chapter 21 portrays the accelerated soil loss from a tropical river basin (Jayanti River Basin, India) using the RUSLE model. Chapter 22 attempts to assess irrigation-induced groundwater depletion and groundwater prospects in an alluvial river basin of West Bengal, India. This chapter has examined how the groundwater exploitation for irrigation in Boro (summer rice) cultivation has led to the fall in groundwater levels. Similarly, Chapter 23 depicts the groundwater availability zone in Bangladesh using geo-spatial techniques. Finally, this volume also takes the consideration the role of the river in the social and cultural perspectives. Therefore, Chapter 24 examines the Mayo Tsanaga, Kaliao and Mizao (Maroua, Far North Cameroon) as a heritage for socio-economic activities. Chapter 25 similarly uphold the role of the river in Indian tourism and also the significance of river-based tourism towards the achievement of sustainable development goals.

10 Conclusions

The fluvial systems, wetlands, and water resources are threatened in the Anthropocene due to the accelerated human interventions in different forms ranging from large-scale dams and barrage to the practices like agricultural expansion, groundwater exploitation and irrigation, and urbanization. This chapter has critically examined the basic principles, and concepts of the river metamorphosis in the context of anthropogenic activities, especially construction dams. Moreover, pollution of the river and water bodies is also sketched out briefly. Finally, this chapter has clearly identified the major research areas where the prime focus is needed to restore the fluvial system area indicated and the chapter briefs are also included to cover those research areas. This work will certainly aware the scientific community sparks their cognition about the current health of the fluvial systems and river basins so that the future restoration of the river basin may be one of the prime goals of the various stakeholders across the world.

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Discoursing River from Physical and Social Backdrops

Sanat Kumar Guchhait

Abstract The sinuous natural flow of a river as a fluvial process incorporating hydraulics with its concomitant erosion, transportation, deposition, development of landforms, flood etc. is the most lucrative study in geomorphology under the backdrop of channel development, valley configuration, basin dynamics, riparian regime and so on. Apart from this channelized flow, a large number of rivers and their drainage basins are viewed as the riverine landscape and also riverine ecology where the river, river basin and its adjacent terrestrial surface are conceptualized into an integrated complex of soil, water, biota, productive cropland and even the settlement. But due to the use, abuse, and overuse of rivers and non-judicious human activities, most of the riverine landscape of the world is degraded, some are extremely degraded. The social backdrop of the riverine landscape puts both a positive and negative outlook. In the social backdrop, a river with its materialistic and non-materialistic appeal influences the beliefs, thoughts, urge, and emotion of the people therein for ages after ages, shaping the economy and culture into a distinct pattern of life popularly coded as river valley civilization. Therefore, discoursing river associates and integrates not only as a channelized flow, but also as a process, a system, and also as a historical-socio-cultural construction.

Keywords River · Channel development · Historical-socio-cultural construction

1 Introduction

Civilization without river is almost unthinkable. Prosperous human civilization has developed by the side of the rivers due to hydrological reason (Dorostkar et al., 2016). Geomorphologists, hydrologists and potamologists define a river as the naturally created channelized perennial or non-perennial flow of water over the terrestrial surface but the study of a river as the physical entity, dynamic processes and hydrodynamic functionability are associated with the economy, culture of the society of

S. K. Guchhait (✉)
Department of Geography, The University of Burdwan, Golapbag, West Bengal, India
e-mail: sguchhait@geo.buruniv.ac.in

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that area such that it unfolds a diversified outlook rather than a simply channelized flow. In the field of academics introspection to rivers and river basins exerts a wider discourse in different disciplines from physical backdrop, economic perspective and socio-cultural context-the convergent point of this analysis. Keeping aside this integrated conceptualization at the beginning, it can be stated that the image of a river i.e., the basic perception, conception of a river are accentuated in a sinus flow of water through the channel, making it a reality, imagination, metaphoric expression and so on.

The most important of all the geomorphic (geologic) process is the running water. In the context of running water river plays the most important role, not only in shaping the earth's surface, but also in shaping of man's life on earth (Morisawa, 2017). River as the sinuous natural flow of water as a fluvial process including hydraulics with its concomitant erosion, transportation, deposition and development of landforms is the most lucrative study in geomorphology under the backdrop of channel development, valley configuration, basin dynamics, riparian regime and so on. Apart from this channelized flow, large rivers and their basins are viewed as the riverine landscape and also riverine ecology where the river, the river basin and its adjacent terrestrial surface is conceptualized into an integrated complex of soil, water, biota, productive cropland and even the settlement, but due to abuse and over use of rivers within the last two hundred years or so, rivers and streams are among the most endangered ecosystems throughout the world (Tare, 2013; Thomas et al., 2005). River corridors are fragmented, drastically altered (Fausch, 2002; Ward et al., 2002a), for which not only the riverine hazards have been intensified the future generations will face the tragedy. Keeping in mind the riverine landscape diversity and its rich ecological contribution, we have to we have to integrate the pattern and process for the benefit of ecology first and human need is the next consideration (Ward et al., 2002b).

Barring this physical backdrop, the role of a river in a region is frequently conceptualized from an economic perspective and social backdrop. As an economic entity, a river is the means of transportation, consumptive and non-consumptive use of water. Its water resource is used for human consumption and agricultural practices. Thereby, we have made the river silenced through the construction of dams and barrages (McCully, 1996). The flowing water is used for the disposal of industrial wastewater and sludge. Thus some of the rivers are transformed into dry valleys in the lower reaches, while others are transformed into urban sewage. This transformation has occurred only within the last 200 years only; based on which Raj Kapoor directed the film '*Ram Teri Ganga Maili*,' an episodic environmental metaphor of the degradation of rivers.

In the social backdrop, a river with its materialistic and non-materialistic appeal influences the beliefs, thoughts, urge and emotion of the people therein for ages after ages, shaping the economy and culture into a distinct pattern of life popularly coded as river valley civilization. Therefore, discoursing river associates and integrates not only as a channelized flow, but also a process, a system, and also as a historico-socio-cultural construction.

2 Physical Perspectives

The geographical and hydrological view of rivers and river basins is the initiation of channel, merging of small channels into large channels, flow of water and its related dynamics and ultimately basin dynamics related to point, line area and volume related functions tending towards the estimation of flow, load, discharge for the benefit of society. Under such an anthropocentric approach channels are modified to abduct more water from the channels, basin area are altered for development settlement and maximum production of biotic resources.

From the conceptual viewpoints, surface sheet flow and subsurface flow accumulation along with sediments are channelized into the linear flow along the deepest slope of the surface leading to the formation of a channel. It is axiomatically true that the components of environment are the gift of nature that requires thousands and millions of years to as a part of the environmental system. Rivers and river basins are not exception to this.

3 Dissection of Rivers and River Basins

From the twentieth century onward, there was a steady but continuous attempt to understand the dynamics of rivers and river basins through scientific principles, logical arguments and process related study. The essence of this is only to understand the rivers and river basins but to trace out how the rivers and river basins are tamed and administered for resource development for resource development. Such an attempt I would like to call the dissection of rivers and river basins and analyzed into four sections:

1. Graphical Dissection of Rivers and River Basins
2. Dissection of Rivers and River Basins through Field Operation
3. Dissection of Watershed
4. Intensive Dissection of through Virtual and Field operation

3.1 Graphical Dissection

The graphical dissection of rivers initially and river basins thereafter got the impetuous more or less from 1930s with the seminal idea of Horton from 1920s. Horton for the first time not only normalized the initiation of channel, he also mathematically outlined the point, linear and areal dimension of rivers and channels. Simultaneously, inquisitive channel hydraulics was unfolded by Horton, Izzard, Tailor and others during 1940 and 1950s. The decade of 1950s and 1960s were eliminated by Miller (1953), Schumm (1956) under the light of basin dynamics. Strahler's morphometric analysis and system analysis of Chorley et al. (1985) added another momentum about the intensive study of drainage basin. All these studies were basically the graphical representation through mathematical and statistical representation.

3.2 Dissection Through Field Operation

Field based operation of the rivers and their basins were initiated from 1930s with the idea of multipurpose river valley project. The construction of large dams and draining out of water from channel entered into the scenario with the seminal application by the TVA. Human beings started to tame and to train not only the rivers but also the river basins with the inauguration ceremony of Hoover dam on 30th September 1935. The triumph over nature was established was established with the utterance of Roosevelt, the then president of USA, "I came, I saw and I was conquered" (McCully, 1996). Human assault on rivers and river basins has become the common parlance with the massive construction of dams and multipurpose valley project with a stupendous growth of such activities mainly organized by six countries—USA, USSR, China, Turkey, Switzerland and India. China alone has constructed more than 20,000 big and medium size dams within 1980 to 2000. Graphical dissection thus got real success through field operations.

3.3 Dissection of Watershed

The idea of watershed development was taken in 1970s keeping the ecological tenet of river basins. Considering the negative impacts of big dams and multiple river valley project, ecologist and agriculturist propounded the resource development of drainage basin dividing it into slope, water, based zone sand proper ecological planning. Later on from 1980s integrated watershed management was adopted keeping the ecology and economy as if the marginal people are benefited. The purpose was good but in most cases profit maximization outlook betrayed the ecological stability and ultimate sub-water shed and small watershed at the higher slope and relief of the drainage basins which were out of the clutch of the multipurpose come under extensive exploitation. Thus ecologically rich small watershed which was small but beautiful lost the beauty and ecological harmony. Such a planning essentially requires bottom up approach where ecological people of highland watershed could be suggested the best planning strategy making a balance between ecology and economy, but they were least cared.

3.4 Intensive Dissection Through Virtual and Field Operation

The stupendous growth of remote sensing technology and overwhelming acceptance of computer simulation model transformed the knowledge and understanding for the extensive use and abuse of drainage basins, water sheds and river channels with highest precession level through theoretical knowledge, virtual modelling and practical application mainly from the middle of the 1990s in developed countries and from the new millennium in developing countries. Therefore, guarantee economic benefit and ecological retreat was attenuated through such combined virtual -actual planning leading to extreme degradation of rivers and drainage basins. Now we have realized that the health (ecological health) rivers (Liou et al., 2004; Tanja, 2012) and their basins are lost and now the planners are shouting for river and basin health estimation for the last one decade. Now the ecology is lost and also the economy is lost to a great extent.

4 Discoursing Rivers from Economic Backdrop

Keeping aside the physical ecology and economy of rivers and river basins there exist a social backdrop of rivers in general which can be intertwined from traditional social ecology and also the modern perspective. The tradition way of river-human interaction is to perceive the river as the blessings of nature**.** It directs our life, livelihood, culture, thoughts, beliefs customs where human beings follow the doctrine of the river, not to overcome it. Looking at the history of river centric civilizations of the world it can inarguably said that river is the lifeline of society in general. From the prehistoric times humans have used the rivers for material resources like water for consumptive and non-consumptive use, collecting flora, fauna for livelihood, means of communication, riverbed sans and sediments as building materials, flood plain sediments for agricultural use etc.

On the other hand modern perspective of rivers I would like to concentrate on deliberate modification of rivers, impact of urbanization on river and deforestation and its impact on river flow. To trend and to tame the rivers are the central motive in modern perspective. The Anglo-European tradition to tame and to trend the river and river basins has been augmented through the construction of dams, development of multipurpose river valley project, dechanneling of water (Marren, 2014), and use of rivers as the waste sink from urban-industrial sources (CCME,2001). The interest of economic development betraying ecology of rivers and river basins is so high that the livelihoods of the ecological people are ruthlessly threatened by the politicians and the planners revealed through Love Canal tragedy (Dabkowski, 2018), tragedy of the Aral Sea and so many others. Such a threat was voiced by Morarji Desai (1961), the then finance minister of India a public meeting in the context of submergence of the people nearby Pong dam: "We will request you to move from your houses after the dam comes up. If you move, it will be good; otherwise we shall release the waters and drown you all" (McCully, 1996).

5 Ecological Doctrine of Rivers and River Basins

Ecology as the simple idea is the study of interrelated interaction between the biotic and abiotic components. Thus in an ecological system everything is related to everything else (Commoner, 1971). The first law of geography expresses the same view that everything is related to everything else but nearer things are more related than distant things (Tobler, 1970). Therefore riverine ecology can be can be conceptualized in the same tune. It is inarguably true that the components of environment that has rendered the spirit of the earth ecosystem are the gifts of nature developed through evolutionary processes. River basins are not exception to this and those are also developed through evolutionary process through thousands of years. Though the physical perspective of rivers and river basins are conceptualized as the climato-geohydrological processes of formation of interconnected channels and development of river basins but the ecological doctrine of rivers and their basins are the integrated unit of channel water, flora and fauna in an intricate interdependent relation.

Even more clearly than soil water is the life blood of the biosphere (Harper, 2001) and river basin is the pivotal contributor in this regard. In a river basin, the network of rivers with their flow accumulation, hydraulics of erosion, transportation and deposition led to valley development, flood plain formation which is manifested as the not only as a surface configuration, rather it appears as an organismic function and also the life supporting ecological entity through different abiotic (land, soil and water) and biotic (flora, fauna, forest, crops) components. Therefore, ecosystem of rivers and river basins are the interdependent, interrelated and integrated organic whole rather than mere channelized flow, channel dynamics and basin morphology promoting the most luxurious and dynamic natural ecosystem of the land surface other than forest that provide the most effective resource provider in human civilization. Interdependent interaction of riverine ecology is a naturally guided systematic relation established through cybernetics. Land, slope, water, hydraulics of flow (Boston, 1959), discharge and load are in complex relation to develop the biotic components of the basins. Slope is the facet of land that control hydraulics (Chow, 1959). Hydraulics is the root of erosion transportation leading to the development of load in the channel and soil (Harr, 1977) in the flood plain (Chaw, 1959). Land and soil are responsible for the development of biota with distinct expression in the form of forest and wildlife (Milhous & Grenny, 1980). Forest once again controls the precipitation, soil erosion and sheet flow (Hewlett, 1982). Such intricate interrelation and existence is the ecological value of rivers and river basins.

6 Philosophy of Reductionism and Ecological Holism

In such attempt human-river interaction under the light of river and riverine ecology is sought forwarded in the line of Kantian philosophy of factual statement (is statement) and evaluative statement (aught statement). The factual statement of the riverine dynamics can be evaluated as the Human-Nature conflict. The theory of conflict can be outlined as dialectics physical ecology vs. human ecology. The tenet of physical ecology is the ecological integrity and stability through interconnected and interdependent relation among soil water, flora, fauna including human orchestrated through physical riverine process over thousands.

Do the Geomorphologists, hydrologists, hydrological engineers or river basin planners think of such an integrative approach? Perhaps it is not in most cases. Human beings through their greedy attempts have betrayed this ecological value through different interventions especially through the last two hundred years by rapid industrialization, massive urbanization and extensive advanced agricultural practices. Over the thousands of years this ecological value of rivers and river basins is the asset to the human civilization, However, human by their massive use and abuse have threatened and derelict the ecological value—the evaluative statement of rivers and river basins. The massive waves of big dam construction and multipurpose river valley projects on and from 1930s have signaled to trend the rivers and to tame the river basins (Lucien et al., 1989). The potamologists, river technocrats have continuously propagated the idea of dissection of rivers and river basins in such a way that river basins are almost under the control human beings where there is little scope for other biotic elements. They prefer in most cases the anti-ecological approach while literatures, social scientists and environmentalists and a section of common people are raising the voices against the exploitation of rivers and river basins and urge for river—society mutual interaction with a notion to protect rivers and river basins which can only be possible through caring, love and emotion towards those natural entities. Therefore physical perspective have in most cases concentrated on intensive use and abuse of rivers and river basins and social perspectives targets towards mental, spiritual and emotional attachment.

7 Discoursing Rivers and Riverine Ecology from Socio-Cultural Backdrop

The physical and economic perspective of rivers so far has been portrayed so far outlay the use and misuse of rivers where there is little room for ethics, emotion and urge. Socio-cultural perspective, on the other hand, espouses beliefs, ethics, aesthetics, love, care and emotions through intensive river-society bond.

7.1 Literary Perspective

Literary perception of rivers throughout the ages has outstandingly narrated in different literatures. Interactions between rivers and riverine society are the core idea of such literature where the society and the human mind are expressed by the metaphors of riverine dynamics erosion, deposition, river flow, riverscape etc. A handful of Bengali literatures can be cited in this regard. Of those the most notable Bengali literatures are '*Padma Nadir Majhi*' (1936) by Manik Bandopadhyay, '*Hansuli Banker Upakotha*' (1947) by Tarasankar Bandopadhyay, Ganga (1955) by Samaresh Basu, '*Titas Ekti Nadir Nam*' (1956) by Adiyatyo Mallabarman, '*Nadi o Nari*' (1960) by Humayum Kobir, '*Nadir Nam Tista*' (1966) by Samsul Haque, '*Matsa Gandha*' (1987) by Balaram Roy, '*Tista Parer Brityantyo*' (1988) by Debesh Roy etc.

In his novel, '*Padma Nadir Majhi*,' Manik Bandopadhyay has eloquently narrated the bond between river, society and man through ethical, aesthetical and emotional appeal. The novel starts with the appealing beauty of the river Padma during moonlight night where the fishermen start their work at mid night when rest of the society around the river is in deep sleep. Here, Padma river is not only a physical entity; it's live appearance through water, waves and social, cultural and economic interaction around the catching of hilsa fish has integrated the society and livelihood where poverty, hazardous life, emotion and love are interwoven making it a complex of physical and social whole. The panoramic beauty of the river is described by the vastness of the river, sparkled water of the river by the light of the moon with glittering waves, dancing of the fishing boats by the waves and blowing winds along with the regretted aspects due to bank erosion and stormy condition. This scenario is not only true for Padma, it is also found for of other large rivers at middle and lower courses. Contrarily, the struggle of the boatman to catch the hilsa fish during post-monsoon, poverty stricken life of the Kuber-the fisherman of the boat and the illicit life and aspiration of the people of the char land of Moyna Danga under the leadership of Hossain Miah denote the diverse social interaction marked with uncertainty of life, social exploitation, woes of poverty etc. Kuber is confused what to do by the appeal of love of Kopila—his divorced sister in law keeping in mind his poverty condition and his love towards his wife and offspring but envious of Jugal while Kopila gossip with him. The confusion is diluted when husband of Kopila takes her to his home after the death of his second wife. Even Kopila is dissatisfied with her second time family life. She ultimately comes once again returns back to Kuber and Kuber leaving his family now sets his journey with Kopila by boat through Padma to an un known destination where Padma and Kopila become the part and parcel of his life with full of uncertainty.

Nature is beautiful and complex with multiple dimensions. We the human being have a tendency to mastery over nature from the very beginning of civilization partially knowing the harmony of nature and the spirit of live earth. It is also true for river and riverine ecology. While drawing a sketch of discoursing river from physical and social backdrop, it is likely that physical perspective and social outlook would likely to be different from one another. In ethical consideration, integration of physical and social dynamics need to be integrated for environmental and social sustainability where river, river basin and riverine ecology should not be interpreted as the biased materialistic notion, rather such outlook must be incorporated with an integrated whole with the combination of materialistic, spiritual, ecological and emotional dimensions, in an approach of material-non-materialistic perspective. This integrated perspective is the essence of the book '*Padma Nadir Majhi*'. Kuber in the novel of *Padma Nadir Majhi* is an experienced fisherman spending a greater part of his life over Padma and he is also a dedicated family man but the unknown destination of Kuber with kopila through boat over the Padma reminds that a part of the river, society and human mind are known but most of those are unknown. We the human beings should not exploit the rivers for the interest of the society driven by selfish mind through our little knowledge, rather we should extend our love and emotion for rivers through we can be able to perceive the ethics and doctrine of rivers as an integral part of ecology and society.

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Rivers in Distress: A Geo-Ecological Consideration

Arun Kumar Singh, Prakriti Das, Shatarupa Dey Neogi, Tanushree Ghosh, Abarna Mukhopadhyay, and Atanu Sarkar

Abstract Rivers are considered as major resources of our country. Beside the geo-ecological aspects, rivers have also become social entities that reflects considerable influence on the life of the people from the beginning of civilization. But man, driven by their developmental needs, have over-exploited the rivers to such an extent that has caused irreparable damage to the ecosystem of the rivers. Many rivers are at the verge of dying affected by pollution, erratic flow and even dropping level of water in the river system in various seasons specially during the summer session. Construction of river embankments negatively impacts the river as well as the agricultural productivity. This paper deals with factors which have been responsible for the deterioration of our country's rivers by taking example of three rivers: The Ganga, The Narmada and The Cauvery by taking six parameters: deforestation in the catchment area, planting of exotic tree along the river banks, dumping of residential and industrial waste, obstructions, diversions of river flow, sand mining and pebbles collection from river beds, unbridled constructions and lastly climate change. The selection of these three rivers are not based on any serious statistical exercise but is based on author's convenience and the availability of data.

A. Kumar Singh
Foundation of Practising Geographers, Shree Ranjani Housing Society, 662 Picnic Garden Road, Kolkata 700039, India

P. Das (✉)
Department of Geography, Victoria Institution College, Kolkata, India
e-mail: victoriacollege1932@gmail.com

S. D. Neogi
Department of Geography, Sarojini Naidu College for Women, Kolkata, India

T. Ghosh
Department of Geography, Sailajananda Falguni Smriti Mahavidyalaya, Kharyrasole, Birbhum, West Bengal, India

A. Mukhopadhyay
Department of Geography, Ranaghat College (Under Kalyani University), Nadia, West Bengal, India

A. Sarkar
Department of Geography, Deshbandu College for Girls, Kolkata, India

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1 Introduction

Rivers are a large natural stream of water that flows into a lake, ocean or into another river. Apart from this geo-ecological definition, river also has a social entity and is considered as a life line of a region or a country. This is the importance of a river and India heavily depends on its river to meet its water requirement. Rivers in India have also been worshipped by its vast population of different castes and creeds even though they are not primarily dependent on agriculture for their sustenance. As per geographical estimates India has about 400 rivers with a total length up to nearly 2 lakhs kilometers. If we take all the rivers together it will come to nearly 1870 billion cubic meters of water every year enough to submerge whole India in about 2 feet height of water. Indian rivers support 1.3 billion people and provide a strong pillar around which diverse cultures and societies have developed and flourished. The importance of river again can be naturally understood by the fact that they are life giving and life supporting force to the people of this vast country. Rivers are also important from the ecological point of view because it provide sustenance to all the living organism of various forms and nature. In India rivers have been worshipped by its population on different occasions of rituals. Rivers are also important because it carries nearly 47% or more of rain water which are used again in diverse ways and means by all living species.

But irony of the fact is that with the growing population and its various demands of development, rivers of India are paying a heavy price with great pains like pollution, erratic flow and even dropping level of water in the river system in various seasons specially during the summer session. Thus rivers of India are in distress and also in a dying state. On the rivers itself in recent times terrible transformation has come. This paper will try to deal with factors which have been responsible for the deterioration of our country's rivers by taking example of three rivers: The Ganga, The Narmada and The Cauvery by taking six parameters: deforestation in the catchment area, planting of exotic tree along the river banks, dumping of residential and industrial waste, obstructions, diversions of river flow, sand mining and pebbles collection from river beds, unbridled constructions and lastly climate change. However, one constraint in analyzing the above factors is inadequate comparable data. However, let us explain the parameters which are killing our rivers.

A. Forests are extremely important from ecological point of view. The air over the forests absorb moisture from the trees and undergrowth which helps in bringing rains. Loss of forest due to various developmental activities lead to less rain and less percolation of rain water to the underground because lack of forest cover helps the rainwater to drain quickly. Deforestation increases the soil erosion.
B. Planting of non local trees along the river banks have become a major problem because change in local species of vegetation cover leads to loss of biodiversity.

C. Dumping of waste in the river is an acute problem faced by our rivers today whether it is Ganga or Cauvery. The uncontrolled untreated industrial effluents and domestic sewage are being released in the rivers making the rivers highly polluted resulting in great loss of its biota (plant and animal both). The living components of the river are vanishing at a faster rate.
D. Obstructions, diversion of flow is becoming a regular phenomenon in river management system. Excessive damming prevents minimum flow needed to sustain river ecosystem. Diversion of water from the main river channel in the form of canals for irrigation purposes, pumping of water from the river for industrial purposes effects river badly leading to drying up.
E. Sand mining and pebbles collection from river beds is becoming a big menace. These activities are destroying the river natural flow and also affecting the ability of the river to retain water.

Unbridled construction specially construction of embankments in the riparian tract may for some time prevent overflow of river during the flood period but in the long run it will rise the river bed making it unsuitable for holding water specially during the flood resulting in more acute flood (Rudra, 2010). Construction of embankment has prevented the flood water which contains fertile soil to get spread into the floodplain. This is harming the agricultural productivity. The way of controlling the river by embankments are still very much prevalent in free India.

2 Statement of the Problem

Before we go into the analysis of the selected three river's condition by taking the above parameters; let us define river scientifically or even as it is conceived by the people surrounding it. Let us consider the following definitions first because these two definitions have tried to define river epistemologically. Corfield (2007: 1527) in the Encyclopedia of Environment and Society, defines river as a large natural waterway that define civilization, that nourished great cities along the bank, demarcate political boundaries or provide transportation routes, and carry symbolic meaning, even offering their names to countries (like Gambia). In Encyclopedia of Geography, Plewa (2010: 2472) defines river as a physical landform that conducts (primarily fresh) water sediments and nutrients down slope under gravity from topographically higher land towards depressions at lower elevation, most often into bodies of water. In these two definitions, river is a part of river science and is a part of earth's hydrosphere. This is how geomorphologists define river as it traverses in its journey from the mountains to the plains. But let us see how a common man considers river. According to them, it is the very stretch of the river which they occupy or make use for them. Rarely they think that the river which they are occupying has an upstream and a downstream and also it has several tributaries which join the main river on its way from the source to the ocean or to the end point (Gopal, 2015: 14–15).Thus river is a natural ecological system which is unique and dynamic, has a living component, and is ever changing at every point (Misra, 2015: 29).

River are treated as holy as a mother or sometimes as a goddess but that is an unimportant belief because even who believe river as holy, treat the river badly in the name of rituals and traditional cultural practices which at present are badly driven by commercial interests. For some people, river is only a channel which drain the run-off water and so it should be dammed and barrages or reservoirs may be constructed for storing water for various uses. The communities who live on the river bank or its flood plain think rivers as a menace due to its unruly behavior like flooding. Thus, the river must be made to flow within the space provided by man. Here the conflict starts. Man forgets that rivers are life supporting systems and a habitat for more than 15% of all living organisms on this planet.

The above analysis has given a more detail account of the river per see. However, in the Hindu mythology it has been a place of holiness, where you can bath yourself and then pray. But our rivers throughout the country are in a pathetic state, perennial rivers have been turned into seasonal ones, biodiversity has declined and water quality has been heavily degraded and after a certain point, there is no return. At many places they have become merely a conduct to transfer heavy loads of pollutants in the form of garbage and various types of wastes.

3 Analysis

Now let us explain the causes of this degradation of our rivers by taking example of three major rivers of our country: The Ganga, The Narmada and The Cauvery by taking into consideration the parameters more or less by which these rivers can easily be said that they are in a distress and require immediate serious remedial measures or their survival will be at stake. The selection of these three rivers are not based on any serious statistical exercise but is based on author's convenience and the availability of data.

The Ganga: The Ganga is the most vital life line of the alluvial agricultural plains of north India, one of the most notable geographical dominants in the political history of the region and one of the most important elements in the religious, social, cultural and linguistic wealth of the area (Ahmad, 1971: 39). The approximate area of the Ganga basin is 905,000 sq. km which is about 28% of the total Indian territory. The Ganga is a young degrading river in the Himalayas above Hardwar. It is more or less stable, neither prominently degrading nor aggradational process is conspicuous by the dry-point levees which are mostly above high flood levels.

The length of the Ganga is estimated to be 2586 km or 1600 miles. The length is important for any river in shaping its gradient, pattern of drainage, the navigable length, its hydrological and biotic regime and extent of its uniting forces in respect of culture and civilization, areas liable to floods or habitable sites for settlements etc. Due to these factors the significance of the Ganga from Gangotri to Ganga Sagar is immense. So, the Ganga is the most sacred river of India, probably also of the whole world because so much sanctity does not appear to be attached to any other river. While the physical characteristics of the Ganga has influenced the national life of the Indo-Gangatic plan, its sanctity has enriched the religious and spiritual life of the whole nation (Ahmad, 1971: 43).

Ganga which has been recognized as a divine body—the holiest of rivers and purifier of mortal beings—a living Goddess, very aptly she is personified in the Indian consciousness as 'Mother Ganga' or Gangaji (Banerjee, 2020: 30). But all these personifications have not helped her by getting polluted by its own people and government. The degradation of the Ganga's environment has reached to such a level that Government of India has to set up 'Ganga Action Plan', but all the effort has failed to a great extent to clean the Ganga. The reasons have been many folds—such as the diversification of human activities in recent decades specially the changing anthropogenic activities have taken the river into a critical state of degradation (Sarkar et al., 2017). The situation has become worse by the fact that the region is vast and having socio-culturally complex civilization of over 300 million people with large population living in densely populated cities directly on the banks of river Ganga. Population pressure, lack of investment in water quality infrastructure, governance problems and non-empowerment of people, all these factors contributed to the deteriorating state of the Ganga (Tare & Ray, 2015: 55). The ecological conditions are given in Table 1.

Other facts about the Ganga:

a. 1800 Gangetic dolphins remain today from 5000 dolphins in 1982 in just 32 years.
b. 11 mn.trs. of human excrements is discharged into the Ganga every minute.
c. 40000 bodies are cremated on the bank every year.
d. 1500 tons of ash released into the water year every year.
e. 140–200 tons of incompletely cremated bodies dumped in the river every year.

Now let us look into pollution in the 4 major towns located on the bank. Data for Kolkata is not available.

a. **Haridwar**: Around 89 MLD of sewage is released into the river. There are 12 municipal towns upriver from Haridwar.
b. **Kanpur**: Kanpur is one city which is polluting the Ganga maximum. Several industries and number of tanneries are polluting the river. 425 MLD of domestic sewage and 50 MLD of tannery wastes flow in the Ganga untapped. World Bank

Table 1 Ecological condition of the Ganga

States	Uttarakhand	Uttar Pradesh	Bihar	West Bengal	Others
Location	North	North	East	East	–
Length (km)	450	1000	405	529	150
Sewage generated (MLD)	61.3	937.4	407.2	1317.3	–
Treatment capacity (MLD)	213	468.9	169.4	548.4	–

Based on *Sunday Hindustan Times* (2014) has suggested that 450 leather tanneries have to be shifted and relocated but till now nothing has been achieved due to various court cases.

c. **Allahabad or Prayag**: Domestic waste disposal in the Ganga directly is the main polluting factor in Allahabad. As per the Ganga Pollution Board, nearly 58 big drains release waste in the river untreated.
d. **Varanashi or Kashi**: This city is also known as a city of salvation where millions of Hindus arrive every year to wash their sins which has become the major source of polluting the river. The city generates 350 MLD of sewage every day which accounts for 95 percentage of pollution to the Ganga in Varanasi. Out of the 350 MLD, 250 MLD is being discharged in the Ganga every day without treatment. Thus release of sewage directly into the Ganga is a major source of pollution of the river in Varanasi. The other facts are that the two cremation grounds—Harish Chandra and Manekarnika Ghats dump 33,000 bodies, 300 tons of half burnt bodies and nearly 1500 tons of ashes annually into the river. In Uttar Pradesh only till Varanasi there are 12 dams and reservoirs on the Ganga and each of them takes a toll on the river. More and more water is being diverted from these dams and reservoirs for agricultural, industrial and domestic purposes. Thus climate change and melting of the glaciers are not the only threats facing the river. At least 1109 polluting industries discharge toxic waste in the river. Arsenic, cadmium, chromium, copper, lead, mercury and pesticides plague the river, not to mention microbes more than 3000 times the prescribed limit (Banerjee, 2020: 14).

To conclude about the distress state of our national River Ganga, time has come to think seriously how to save it from its death which River Saraswati has faced possibly during the Vedic era. Dying of River Saraswati was a major event in the evolution of Indus civilization and thus disappearance of The Saraswati River, which was known as mother of all rivers, have played a defining role in making the end of Indus Valley civilization. As the Saraswati dried, the Vedic people moved eastwards to the fertile and sparsely populated Gangatic plains, where they started growing rice, 4000 year ago, much of the Saraswati's sacred imagery in the Vedas was later transferred on to the Ganga. But if the Ganga were to falter (which we are causing the river to do), then the food supply of India would also falter and there would be nowhere eastward for the people to move (Banerjee, 2020: 19). However the River Ganga may be revived if we follow the four interwoven concepts of 'aviral dhara', 'nirmal dhara', 'geologic entity', and lastly 'ecological entity'. Further anthropogenic activities must have to be regulated and controlled so that indirect damages such as loss of basin fertility, geological disruptions can be stopped. To achieve this goal some suggestions:

a. Stoppage or curtailment of pollutant discharges from urban/industrial activities.
b. Recycling of waste waters and minimization of fresh water withdrawals.
c. Promoting sustainable agricultural practices.
d. Re-evaluation of river—based projects as well as water resources and infrastructural projects and land-use norms should be done strictly maintained through comprehensive environmental resource management (Tare & Ray, 2015: 73–74).

The Narmada: The River Narmada is also called the Reva and previously also known as "Narbada" or "Narbudda" is the 5th longest river in India, the largest west flowing and the largest flowing river of Madhya Pradesh. Narmada flows through the states of Madhya Pradesh (1077 km), Maharastra (74 km.) and Gujarat (161 km).

Narmada is one of the most sacred river referred in the Vedas and Puranas. As per Matsya Puran all the sins get washed/absorbed even by seeing Narmada. Accounting to local legend Narmada is believed to be more sacred than the Ganga because even Ganga comes to Narmada to wash her sin. With such an iconic heritage of the Narmada, it is pity to see Narmada, one of the most holy river of India is being destroyed by towns and cities which are located on its bank and are emptying untreated sewage into it and industries are sucking fresh water, but discharging effluents into it, thus making it polluted. Deforestation in the surrounding Satpura and Vindhyan ranges has dried up 60 out of 101 tributaries that used to feed Narmada. Ground water levels has fallen to 300 feet or more in the vicinity. Some crude facts and figures about how Narmada is being killed slowly.

a. At Amarkantak, the source of the Narmada, 0.72 MLD sewage flows into the river untreated every day.
b. In Dindori district, out of 25 tributaries of Narmada, 5 are dead and 12 are nearly dead. Dindori town discharge 10 MLD sewage directly into the river everyday.
c. In Mandla district, among 4 tributaries, 1 is dead and another 1 is dying. Ground water is down by 200 feet. The whole bank is marked by heavy sand mining.
d. In Jabalpur town which is the biggest town on the bank of Narmada, 200 MLD sewage goes into the river without treatment everyday.
e. In Narsinghpur district there are 9 tributaries, 6 dried up and 1 has become non-perennial and will get dried up in near future. In Golegaon and Narsinghpur towns, nearly 26 MLD sewage are generated and are directly discharged into the river, but there is no STP. This is supported by 6 sugar mills which also have no plant for treating their effluents.
f. In Raisen district, all the five tributaries have dried up. Mechanized sand mining in 5 places are being operated illegally.
g. In Sehore district, all the 3 tributaries dried up as sand mining is a common feature. There is no STP in any town, so wastes are being pumped into the river directly.
h. In Harda district, all the 4 tributaries have dried up. Harda town generates 10 MLD sewage which goes into the river without treatment.
i. In Dewas district there are 7 tributaries out of which 6 are dried up. There is no STP in its urban centers.
j. Khandwa district has 7 tributaries, all are chocked as flow of water is getting dried up.
k. Kargone district has 10 tributaries out of which 9 tributaries have dried up. From Kargone town, 5 MLD sewage directly flows into the river.
l. Dhar district has 2 tributaries, both are dried up. No STP in its town.
m. In Badwani district, 8 tributaries dried up. No STP in its town.

Source Modified after Vichar Madhya Pradesh 2017, Subodh.varma@timesgroup.com. *Times of India*, Kolkata, Wednesday 21, 2017. (MLD = Million liters per day, STP = Sewage Treatment Plant)

> Narmada and its basin is facing unprecedented degradation due to deforestation, uncontrolled sand mining, discharge of untreated domestic waste. Sucking water through reservoirs and canals is taking the river to a dying state. Narmada once the iconic river, the most loved daughter of Lord Siva and whose every pebbles are so holy and at the same time life line of Madhya Pradesh and Gujarat is fastlosing its status as a living entity. If the governments of these two states fails in implementing the existing laws and regulations, Narmada will continue to die a thousand deaths.

Cauvery—The Jewel of South: Cauvery, once the Jewel of South or lifeblood of the people of Karnataka and Tamil Nadu, has experienced showdown of its glorious past due to being dammed extensively, polluted abundantly by industrial and urban waste, mined heavily for sand and lastly drowned by court cases between the states of Karnataka and Tamil Nadu. Thus the story of Cauvery is the story of overexploited river, over developed basin and over ambitious political followers. The excessive dependence on dam-centric irrigation had led to the neglect of the traditional methods of irrigation like ponds and tanks. Industrialization and urbanization has a devastating impact on the river health and ecology. These anthropogenic consequences had/has led to water dispute between the two states Karnataka and Tamilnadu since 1882. The successive governments of both these states have fought judicial as well as political battle in the court as well on the streets to get more and more water from the River Cauvery, but served least for the upkeeping of the river's health and natural flow. The sacred river of the people of Karnataka and Tamilnadu is today a matter of dispute and thus Cauvery is losing fast it economic and cultural glory. More and more data are available on the court disputes but there are fewer holistic study on the river itself. We will take one or two examples to narrate the health of the river, naturally one will be urbanization and secondly expansion of agriculture and change in cropping pattern. This misery lies in her mythological story because Cauvery always tried to serve the humanity. Her father Lord Vishnu was not happy with his daughter's desire and married her to Sage Agasthya. Sage did not allowed her wife to wonder and chase her desire to serve the people, so he turned her into waters and kept her in his Kamandala and thus caging Cauvery. The cries of Cauvery for freedom reached in the ear of Lord Ganesha who took a form of crow and toppled the Kamandala, thus releasing the Cauvery from bondage. Cauvery joyfully escaped and graced the people of her region with high level agricultural and horticultural productivity, filling granaries year after year feeding millions and spreading prosperity. Temples and towns sprung up along its banks. These towns have now developed as a great metropolitan city such as Bangalore. But in return these big cities and industrial centers heavily polluted this pristine flow of natural water into a polluted water raising serious worries about her fate. People and governments are interested only to extract more and more waters from her and none are worried for her up keep.

Bangaluru: Karnataka has an allocation of 270 thousand million cubic feet of water from Cauvery per annum. Bangalore metropolitan area alone consumes most of the water allocated for drinking purpose leaving no water for other villages, towns and cities. The extended areas do not get water supplied by Cauvery which forced the people to depend on ground water putting lot of pressure on ground water level, thus dropping the aquifer level.

Agricultural Extension: With such a water crisis there has been a large expansion of wetland and agricultural areas with water loving crops of paddy and sugarcane. So, such a development continues in the river basin of Cauvery, the river in very near future will be failing to give service to humanity and even it will not be able to sustain the web of life as she has done for millennia (Saldanha & Rao, 2015: 291–313).

4 Concluding Remarks

Rivers of India in general and the three rivers explained above, in particular the Ganga, the Narmada and the Cauvery are in distress due to various factors which are based on their ecological condition and cultural history. However, two important causes have come to light.

One is the excessive use of water from the river by constructing major and minor dams, reservoirs and barrages and then channelizing the river water through canals to irrigate the agricultural land, establishments meeting water requirements of industrial and urban centers.

Second important factor which is causing the death of these three rivers are industrial and urban waste being discharged mostly without proper treatment causing chemical pollution in the rivers.

Other factors are deforestation in the catchment region and uncontrolled sand mining in the river bed. What is the way out by which these rivers can be saved ecologically and at the same time it can support the livelihood of the vast population dependent on it. It is strongly felt that man's relationship with water must be changed. Water is not only a chemical compound or has a ritualistic importance or it has a sacred nature, but we have to think and visualize that it is a life force in itself. It is a living entity and when its takes a shape of a river and it becomes life support system. So its survival is necessary for the sustainable survival of every species on this earth in general and its basin in particular. If necessary, man must have to change its ecological and cultural values.

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Incorporating Hydromorphological Assessments in the Fluvial Geomorphology Domain for Transitioning Towards Restorative River Science—Context, Concepts and Criteria

Sayoni Mondal and Priyank Pravin Patel

Abstract Almost every civilization has seen rivers from an utilitarian perspective, resulting in a series of irreversible hydromorphic changes that have disrupted all former balances between the human use of rivers and their natural flow dynamics. Rivers have been dammed, channelized and managed to meet societal developmental needs. However, with time the environmental costs of such river channel management was realised, which has led to the formulation of river restoration techniques, with the ultimate aim to bring rivers back to their pristine state. While traditional frameworks have always focussed on structural measures to restore rivers, they have invariably resulted in altering the natural stream functions, mostly by disrupting the channel longitudinal and lateral connectivity. Consequently, ecological restoration techniques with a greater emphasis on river health aspect, have been put forth that consider the interactions between river biota and the hydro-geochemical environment as the key parameter to promoting overall stream management. This concept of river health was slowly mainstreamed with the introduction of the term Hydromorphology by the European Union Water Framework Directive, which tried to combine the three elements of morphological functionality, hydrological regimes and river continuity to assess stream health. This paper provides a brief review of such ideas that are embedded into the concept of hydromorphology, focussing on the various methods and frameworks devised to assess stream health. Such methods have been conveniently classified into four categories depending on the major stream functions that are usually targeted to restore stream health. A few case studies where such frameworks have been successfully used to examine stream health are also discussed. As the human footprint becomes ever larger across the Anthropocene, it is contended that such holistic, hydromorphological assessment based restorative river science can provide the curricula needed for future river scientists and a collaborative platform for investigations by different disciplines.

S. Mondal · P. P. Patel (✉)
Department of Geography, Presidency University, 86/1, College Street, Kolkata 700073, India
e-mail: priyank999@hotmail.com

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1 Introduction

Rivers have almost always been viewed from an utilitarian perspective—as something that needs to be dammed, diverted, channelized, developed and controlled to meet societal demands (Behbahani et al., 2017). In many ways, it was the development of rivers and their adjacent lands that spurred on economic growth in a country (Anderson et al., 2019). However, until relatively recently, there was scant realisation of the environmental costs of such development and thus rivers have turned into exploitable physical entities, without life and soul. Any former balance between the human use of rivers and their natural flow dynamics is thus now considered quite lost, owing to the ever increasing pressure on land and water resources (Kline et al., 2009; Patel et al., 2020). Hence, traditional frameworks of river channel management need re-evaluation due to such increasingly adverse effects on the channel and floodplain environment (Boulton, 1999; Brookes, 1985; Ko et al., 2020; Mondal & Patel, 2018). The rising concerns of managing these adverse effects on fluvial ecosystems have led to a steady development of comprehensive river regulation systems that have several ecological elements, with such frameworks deliberately focusing on stream corridors as the unit of management and restoration since these are the storehouse of almost all ecosystem resources and services and play a vital role in the river recovery process (Graham et al., 2010). This paper outlines the gradual adoption of an ecogeomorphic approach (Kaya et al., 2020) for stream restoration, moving away from the traditional fluvial geomorphological focus of such studies. In doing so, the subject domain potentially transforms in to what can be broadly termed as 'River Science', with a holistic focus on the abiotic components of the entire watershed (encomapssing the reach to basin scale) and their interlinkages and governance frameworks, while also incorporating numerous ecological elements that would otherwise often be less touched upon when the focus was primarily just on water, sediments and channel form.

How human activities alter river courses and directly cause loss of connectivity in the fluvial landscape has been explained explicitly by Gregory (2006) and Wohl (2012, 2017a, 2017b). Such direct/indirect activities mainly occur in and around the channel, concentrated along the riparian zones and the extended floodplains (Brierley & Fryirs, 2012; Chatterjee & Patel, 2016). Therefore, the idea of taking rivers back to their natural settings, to a phase without (or with minimal) human impacts, and making them physically, biologically and ecologically healthy has become one of the most important aims of any river management programme, also being included as one of the targets within the Sustainable Development Goals (SDG6), which seeks to "*ensure availability and sustainable management of water and sanitation for all*" (Yu et al., 2019). The assessment of the overall channel condition and the river corridor at the reach level to gauge its site-specific present ecogeomorphic status (by combining its hydromorphological and ecological aspects) is therefore the first step to decide the required restoration strategies to better the river health.

In order to explain this approach, it is crucial that first, the different concepts that are linked to such river assessment and management frameworks are documented and explained succinctly. The subsequent portions of this paper therefore highlight why river restoration has become increasingly important and denotes its various types. It then delves into why older, structural methods of stream restoration are now being increasingly replaced by eco-engineering/ecogeomorphic and hydrogeomorphological approaches and details these two concepts. As part of these discussions, we highlight some notable frameworks adopted across the world and particularly in India, on river restoration overall and especially from the ecogeomorphic viewpoint (using hydrogeomorphological methods). Also explained are the two main concepts of the riparian zone—the *river corridor* and the *riparian buffer*—that are central to the evaluation, framing and implementation of such ecogeomorphology based restoration ideas. The scarcity of relevant studies in the Indian context, especially from the holistic perspective of integrative hydrological, geomorphic and ecological components, is also highlighted in the context of which backdrop, the existing research gaps that can be examined via future research are detailed.

2 The Growing Need for River Restoration

With the number of people living in close proximity to rivers steadily increasing and the alteration of river corridors for food, water supply, agricultural productivity, irrigation, waste disposal and infrastructural developments accelerating at an even faster rate (Fang & Jawitz, 2019), the need to control, manage, rehabilitate and restore these high value ecosystems continues to grow. One of the most direct alterations caused to river corridors are the flood defensive measures of damming and embankments, which have caused chronic changes to riparian environments (New & Xie, 2008). Altered and degraded stream corridors have, in turn, further enabled floods, and flood-related damages have risen by around 3.45% per year, even in the face of expensive flood control programmes (Cartwright, 2005). In view of the damages already caused and the continuation of significant and unsustainable water use, action is needed to eliminate such economic and ecological crises through rehabilitation of afflicted water courses via river restoration programmes (Xu et al., 2021). Ideally, the extent and intensity of use of rivers to meet sustained societal demands should be commensurate with their ecological regimes and natural replenishment. In this context, proper restoration measures applied to such degraded lotic ecosystems can to a large extent, bring back this lost balance (Addy et al., 2016).

River restoration is therefore, simply, any attempt to improve the health of a river and re-attain/rejuvenate its impaired functions, thereby returning a degraded river to its former (or as near as possible) pristine state (Logar et al., 2019). It seeks to modify the present structure and functioning of a river and its riparian corridor for greater catchment benefits (Pedroli et al., 2002). The International Union for Conservation of Nature (IUCN) in its report on ‘River Restoration and Biodiversity’ has defined river restoration as, “*the re-establishment of natural physical processes (e.g. variation of flow and sediment movement), features (e.g. sediment sizes and river shape) and physical habitats of a river system (including submerged, bank and floodplain areas).*” and this in turn should, “*assist the recovery of ecological integrity in a degraded watershed system by re-establishing natural, hydrologic, geomorphic, and ecological processes, and replacing lost, damaged, or compromised biological elements*” (Wohl et al., 2005). Thus stream restoration helps in improving the ecological status and environmental health of a river to achieve a self-regulating and self-sustaining natural system, that can either surmount or be devoid of any periodic disturbances (Palmer et al., 2005). While precisely defining all aspects that such *restoration* can entail is a difficult task, terms like rehabilitation, reconnection and reconfiguration (though each word has a separate connotation) have been included within the broader purview of restoration, based on the holistic approach of river management and sustainable water use (Beechie et al., 2010; Wohl et al., 2015).

Despite the absence of a meticulous theoretical foundation and well-tested, proven principles (Thomas, 2014), river restoration is considered as one of the founding stones of river management and its science is built upon two guiding hypotheses: that natural biophysical variability is inherent in all river systems and that the ambient physical, hydrologic and biological processes and functions are entwined across the entire watershed and also over a wide range of timescales (Wohl et al., 2005). Consideration of these two principles while formulating any restoration programme would help in successfully achieving the targeted goals (Wheaton, 2005). A review of the guiding principles and scientific discourse of river restoration has been critically discussed by Wohl et al. (2015).

2.1 Types of River Restoration

River restoration usually takes two different forms: structural restoration and non-structural restoration. Historically, river restoration has been initiated and controlled mainly by hydraulic engineers and hydrologists (Sammen et al., 2019), where the main purpose was to modify degraded rivers structurally, i.e. by either regulating meanders to create straight channels through channelization, by riprapping and revetting unstable banks using concrete structures to provide bank stabilisation or by grading river beds to reduce downstream erosion (Olokeogun & Kumar, 2020). Such restoration methods evolved out of the rising concern to control flood waters and thus river engineering structures (artificial levees, floodwalls, dams, reservoirs and weirs) were progressively promoted to increase the flow capacity of channels by either deepening or straightening them (Bechtol & Laurian, 2005). These were mainly based on the principles of hard engineering and popularly termed as structural river restoration techniques (Palmer & Bernhardt, 2006).

However, structural flood mitigation measures, while providing protection up to a degree from floods, are expensive endeavours that often fail to provide long-term security (Molla, 2011). These are also not environment-friendly as they tend to alter the natural hydrology and morphology of streams, thereby disrupting natural channel functions (Bechtol & Laurian, 2005). Especially, river straightening and cemented embankments as flood protection measures have often failed to provide the desired results (Pan et al., 2016). They increase the river's carrying capacity by reducing its flow-path and also raise the channel gradient, thereby increasing flow velocity and enabling accelerated erosion. Consequently, the water clarity and quality decreases and contains less hydrological and biological diversity, with aquatic habitats remarkably reduced by as much as 60% (Bechtol & Laurian, 2005). Restricted rivers, within embankments, that are disconnected from their floodplains (Looy et al., 2003), cause in-channel deposition, raising their beds. This leads them to overtopping or breaching the embankments and more such measures are usually repeatedly required to further rein in the stream (Chaudhuri et al., 2020). In a lowland tributary channel of the River Severn in Great Britain, the channelized segment of the river reported only juvenile and small fishes compared to its non-channelized natural segments, while the River Soar in Leicestershire reported a marked decrease in total fish density and biomass after channelization (Oscoz et al., 2005).

Channelization also decreases riffle-pool sequences in downstream segments, affecting in-stream habitats and causing loss of fish species (Congdon, 1971; Lau et al., 2006). It isolates rivers from their adjacent riparian corridor, disrupting linkages and interactions between terrestrial and aquatic faunal assemblages. The average density of macroinvertebrates was 50% lower in channelized sections of the Rio Grande, with a noticeable reduction in the taxonomic density and richness of predatory macroinvertebrate species, while nutrient exchange rates were also markedly low (Kennedy & Turner, 2011). Similar results (of reduced freshwater species and water quality) were observed in the Gomti Riverfront Development Project, together with the lowering of groundwater levels and a resultant decrease in the baseflow (Dutta et al., 2018; Wilcock & Essery, 1991). Channelization also causes detrimental effects on bankline vegetation, which alters energy flow in the aquatic ecosystem and thus has further implications on stream morphology and ecology (Oswalt & King, 2005). Other detrimental effects of channelization on the ambient stream ecology have been analysed in detail by Brooker (1985) and Horsak et al. (2009).

Another important and probably the most common structural restoration features are dams and reservoirs. Dams have been an important part of the twentieth century development landscape, providing a means to tame rivers (Liaghat et al., 2017). They provide direct economic and societal benefits via flood protection, supplying water for irrigation, drinking and domestic purposes and power generation (Dwivedi et al., 2010). However, their environmental effects have scarcely been taken into account during the design and construction of most dams, resulting in devastating ecological consequences (Brandt, 2000).

Dams are a principal threat to freshwater biodiversity, and a prime reason behind the hydrologic modifications of rivers and the fragmentation/loss of natural aquatic habitats (Silva et al., 2020). Dams obstruct fish movement/migration, impede their growth and lifecycles and limit their natural dispersal rate (Granzotti et al., 2018). They also disrupt the longitudinal connectivity of rivers. For example, the habitat fragmentation degree of non-diadromous fishes has been found to range between 28 and 73%, with the United States, Europe, South America, India and China, reporting the highest values worldwide due to dams. The potential increase in habitat fragmentation due to future dams is likely to be greatest in the tropics where dams are still considered as the best flood protection measure (Barbarossa et al., 2020). The hydropeaking effect of periodic water release from dams also causes changes in the original biotic makeup of a riparian zone, while disruptions of the river's morphologic and hydrologic functions and their impacts on flow and sediment regimes cause downstream hungry water effects, exacerbating erosion and channel instability and affecting the water quality (Tahmiscioglu et al., 2007; Zheren, 2008; Soja & Wiejaczka, 2014). Though some deleterious downstream effects can be mitigated by changing dam operations, most are long-lasting and these have been critically reviewed by Collier et al. (2000).

The futility of structural techniques in managing rivers was soon realised and design based hard engineering approaches are being progressively replaced by soft non-structural methods that are grounded in geomorphological and hydroecological principles, which allow rivers to imitate natural channel forms (Palmer & Bernhardt, 2006). Restoration methods have specifically started focussing on ecosystem functioning and services and rivers are increasingly seen as natural systems that need their own routes and spaces to function properly (Gann et al., 2019). Thus, newer methods/frameworks of ecological restoration have come into being, focussing on eco-engineering techniques. As an emergent concept during the early 1960s, eco-engineering uses ecology and bioengineering to manage degraded ecosystems, thereby helping to integrate human society with the natural landscape for the benefit of both. It is a combination of sustainable ecological best practices with innovative environmental engineering to restore and realign ecosystem functioning and balance (Habersack et al., 2016).

3 The Changing Science of River Restoration

Over the last decade, river restoration has progressed from the enhancement of fish habitats mostly through structural modifications of channel forms to now encompassing a variety of management scopes designed to improve river functions and processes (Wohl et al., 2015). The vast scale of restoration programmes have conveniently divided watersheds into a hierarchy of various spatial networks, ranging from catchment to geomorphic and hydraulic units, to successfully address targeted goals (Brierley & Fryirs, 2005). This includes a wide array of activities that comprise modifications of river channel and floodplain zones to improve the physical, hydrologic and ecological functions of degraded streams for the replacement/rehabilitation of lost and damaged elements and functions (Wohl et al., 2015). Restoration activities can sometimes be focused within stream channels, like channel modifications through changes in meander characteristics, channel cross-section and longitudinal profile, which all impact stream velocity, sediment size and volume and its distribution, water surface elevation and several other hydraulic aspects. The installation of cross-vanes, culverts, log jams, weirs, dams and other similar crossing structures are examples of in-stream restoration methods that tend to bring about channel adjustments. Such programmes are also focussed on restoring the floodplains and more specifically the riparian zone, which is an ecosystem in itself, supporting a large array of biota (Gurnell et al., 2016).

Another change in restoration science has been the increasing stress on process-based approaches rather than on form-based ones. Beechie et al. (2010) have preferred the use of process-based restoration plans that aim to restore the prescribed rates and intensities of the ambient physical, chemical and biological processes forming and sustaining river ecosystems as against those restoration plans that merely focus on recreating physical habitats. Process-based systems thus lay emphasis on the intricate interactions between erosion and sediment transport, the storage and movement of water, energy and nutrients through the system, surface–subsurface interactions and biota growth and succession and tries to alleviate the impacts of anthropogenic pressures so that channel-floodplain continuity persists with minimal artificial intervention.

Proponents of process-based restoration techniques further opine that focussing on the processes that cause degradation rather than just the form the river attains, is more effective in meeting/maintaining restoration goals (Walters, 1997; Wohl et al., 2005). This view negates form-based approaches that design specific channel geometries and dimensions to recreate fish habitats that are not only artificially constructed but more often herald altogether new channel forms and stream adjustments, making it more unpredictable to plan for (Baird & Klumpp, 2012). These have been increasingly replaced by process-based approaches that prioritise river functions and thus include restoration of channel longitudinal and lateral connectivity, restoration of the desired flow, sediment fluxes and ecological productivity and acknowledge the importance of bio-physical feedbacks in channel systems (Wohl et al., 2015).

While process-based approaches require higher start-up investment and research to understand channel processes and their linkages, they are more sustainable in the long run and yield greater ecological benefits. Their methods include active riparian vegetation establishment, flow enhancement that supports better and diversified fish habitats, strategic sediment storage and removal to optimise downstream aggradation, floodplain re-connectivity and removal of dams and other transverse structures, removal of structural bank protection measures and infrastructure relocation, meander renewal and a multitude of other techniques that help to restore the lost channel processes back to its former mechanism (Baird & Klumpp, 2012).

3.1 Significance of Ecological River Restoration

With this change from form-based to process-based principles, restoration methods and techniques have also shifted focus towards ecological perspectives and processes rather than just examining the morphological form of channels (Johnson et al., 2020). The importance of the ecosystem services provided by stream corridors are well understood and divided into four main categories: *Physical services*, which includes attenuation of high flood flows, local storage of water and sediments and recharge of groundwater systems; *Chemical services*, which include the movement and retention of nutrients within the system; *Biological services*, that intend to conserve a rich biota and diverse habitats; and *Social services*, which provide zones of aesthetics, recreation and education (Shields & Brooks, 2014).

Thus ecological river restoration frameworks are accorded higher status as these seek to rehabilitate the ecological integrity and natural functioning of degraded watersheds (Wohl et al., 2015), with special emphasis on re-establishing connectivity between the key riparian zone components, habitats and existing land uses (Wheaton, 2005). This ecologically dynamic state is one in which the in-stream and floodplain biota excels in composition and richness over time and space and the channel configuration and dynamics also change in response to the natural flow variability, thereby augmenting the resilience of the watershed to external perturbations (Palmer et al., 2014). Thus, a science that initially started with hydraulic engineers and river managers, and was carried forward by geomorphologists and hydrologists, has now been taken up by ecologists as reconditioning/developing the various biotic communities/linkages along a river has been identified as the standout aim of restoration projects (Palmer & Bernhardt, 2006).

In this respect, the various relevant hydrological and morphological principles should ideally guide ecological restoration principles. Therefore, a thorough understanding of the stream hydrologic and geomorphic connections with its associated land use dynamics is crucial in providing effective restoration designs (Palmer & Bernhardt, 2006). Ecological restoration now focuses on the utilitarian concerns of replenishing/provisioning ecosystem services and thus rests on three dominant pillars of channel reconfiguration and design, functional assessment and stream hydrogeomorphological evaluation (Palmer et al., 2014). With the steady progress of the science, realisation has dawned that true restoration of the river back to its former pristine position is almost impossible, due to the inherent channel dynamicity and the marked degree of alteration that most riparian zones have undergone. Therefore, the term *restoration* has been replaced by related concepts like *rehabilitation*, *reclamation* or *naturalisation*, all of which seek to return the system to its former pre-degraded trajectory, rather than to some specific previous state (Shields & Brooks, 2014).

In light of the above discussion, it becomes apparent that a complete synthesis of the bioengineering, hydrogeomorphic and ecological methods to address degraded riparian ecosystems should help in achieving the desired restoration objectives through an adaptive management approach. Almost all such approaches/frameworks are primarily concentrated on evaluating the constituents, structure and functioning of the *river corridor* and propagate the use of *riparian buffers* to aid in stream restoration. Thus, these two terms are crucial towards understanding the stream ecological/hydrogeomorphic assessment and rehabilitation process. The next section is thus devoted to examining these two concepts in detail, how they are both identified and demarcated in the landscape and their inherent functions and importance.

4 Restoration Components—Stream Corridors and Riparian Buffers

A river or stream corridor is in effect, a diverse area extending from the active channel zone to the outer extent of the floodplain, connecting the aquatic ecosystem to its terrestrial counterpart. It possesses distinct vegetation belts, fertile arable soils, wetlands, aquatic and terrestrial habitats and also provides recreational zones (Burt et al., 2013). These tracts are also among the most altered physical landscapes by human interventions (Gregory, 2006). Such corridors function as a critical watershed unit, connecting numerous other smaller ecosystems that are multi-dimensional, dynamic systems having characteristic soil and vegetation assemblages (Harvey & Gooseff, 2015) that in an integrative manner perform the major functions of a stream channel (downstream transfer of normal and peak flows and the transportation of sediments and nutrients), maintaining a dynamic equilibrium (Dissanayake, 2020; Ward et al., 2017).

The spatial structure of a stream corridor is in essence a special patch (often linked to other similar units) within the broader and wider setting of the regional watershed scale, which can be classified further into hierarchically smaller stream or reach scales (FISRWG, 1998, 2001). Their structure has two different aspects—longitudinal and lateral. The corridor longitudinal profile can be divided into the headwater, transfer and depositional zones. Within and across each of these segments, the ongoing geomorphic and hydrologic processes shape distinctive river and floodplain forms and patterns while biological communities simultaneously evolve, develop and change. Although streams vary widely in dynamics and character, the lateral corridor profile can generally be divided into three main components (Fig. 1):

a. ***Stream channel***—the active channel which carries water for the greater part of the year.
b. ***Floodplain***—the most dynamic, complex and variable zone of the corridor, found on one or both sides of the stream channel and which is frequently inundated by floodwaters, being home to a wide variety of plant and animal species assemblages. Lateral channel migration across the valley floor forms the floodplain and the continuous working/ reworking of its sediments creates meander scrolls, ox-bow lakes, levees, back-swamps and wetlands, all of which provide dynamic habitat niches to a host of plant/animal communities.

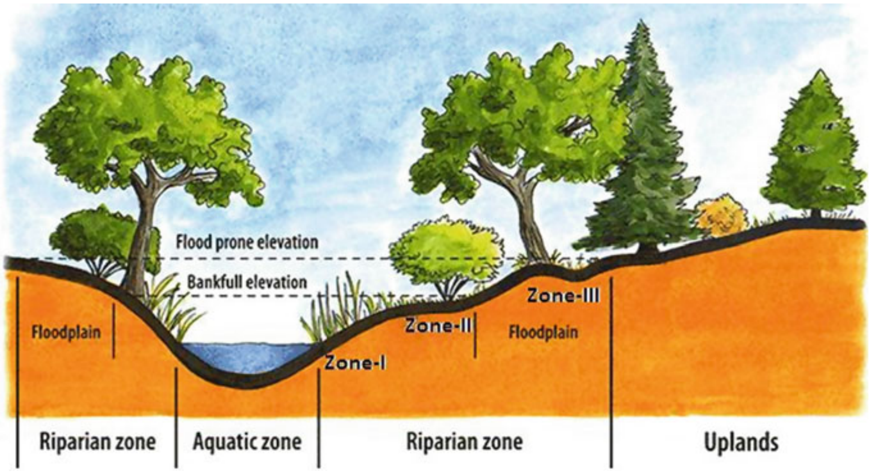

Fig. 1 Structural and ecological elements of a river corridor and its riparian buffer (*Source* Modified from Watershed Planning and Restoration, Salt Lake County, Utah [available at: https://slco.org/watershed/streams-101/the-riparian-zone/])

c. ***Transitional upland fringe zone***—the buffering zone on the landward side of the floodplain which serves as the connecting link between the floodplain and the adjacent upland tracts. Since it is not usually affected by current stream behaviour, land use activities tend to concentrate heavily within it and impact the overall corridor functions significantly.

Stream corridors are thus interweaved, multi-functional ecosystems and any changes in the river's longitudinal profile (due to alterations in channel length or gradient) get reflected through structural and connectivity changes in its lateral components. In this regard, the River Continuum Concept (Vannote et al., 1980) intricately details the links between these spatial units, and how biotic communities evolve and adapt to its various stages (Wohl, 2017a, 2017b). Situated adjacent to the channel, within the river corridor's floodplain component, is the *riparian buffer*, which is essentially an undisturbed, naturally vegetated or replanted strip (composed of both grasses and trees) of land that provides critical and valuable ecosystem functions (Vigiak et al., 2016) such as abating streambank erosion, enhancing water quality, supporting wildlife, intercepting runoff and pollutants and providing flood storage (Mondal & Patel, 2018, 2020, 2021; Verry et al., 2000). The installation and continued maintenance of riparian buffers is a crucial component of ecogeomorphic river restoration frameworks, with these providing the lateral connectivity between the stream and its floodplain (Agouridis et al., 2010). Riparian buffers experience sustained exchanges between the existent soil, water and vegetation components and thus have high physical, structural and biotic functionality. They withstand frequent perturbations including annual inundation, transport and deposition of sediments and the erosive forces of water, in turn creating the habitat diversity essential for an ecologically versatile and self-sustaining ecosystem (Verry et al., 2000). A typical riparian buffer consists of three sectors (Fig. 1)—Zone I: which is located just beside the river and is composed of fast and slow-growing water tolerant species; Zone II: located next to the trees and contains shrubs; and Zone III: occupied by grasses and forbs and positioned next to shrubs (Agouridis et al., 2010).

4.1 Demarcating Stream Corridors and Riparian Buffers

While delineating stream corridors is a cumbersome task, the success of river restoration programmes often depend on their scientific and precise demarcation. Ambiguities in river restoration approaches and objectives have caused much problems in delineating the exact width of riparian buffers, with this often depending on the resources being protected, even though ideally this should be decided based on the soil type, land use pattern, slope and other similar physical factors. Usually, for water quality enhancement, the recommended width varies between 5 and 30 m, for stream stabilisation it is 10–20 m and be a mix of trees and shrubs that support diverse habitats (Lind et al., 2019), for flood attenuation widths range between 20 and 150 m and for riparian habitat conservation, widths can be between 30 and 500 m. Fixed-width corridors for smaller streams is the standard practice (Richardson et al., 2012), being specified at a fixed distance of 60–150 m from the banklines. While the minimum base width of a riparian buffer can range from 6 to 60 m on either side of the stream, a minimum median width of 30 m is usually recommended (Hawes & Smith, 2005). Minimum buffer widths of 60 m are required for habitat conservation and ecological restoration (Agouridis et al., 2010).

Corridors can also be demarcated based on physiographic units and be of variable width. This is often based on the lateral extent of the river's meanders and the meander belt width, which is governed by the channel length and gradient, sub-surface lithology and valley structure (USDA, 1999). Generally, channels in equilibrium create a meander belt width that is equal to six times the channel width (Williams, 1986), which helps in achieving maximum channel stability (via balanced downstream transfer of water and sediment) and reduction of fluvial hazards. Based on the degree of confinement of the channel and the floodplain extents already developed, such corridors may then be narrow vegetation strips separating the active channel from its upland fringes or a wide and complex floodplain composed of diverse landscape units. However, as river channels are dynamic and characterised by meandering, riverbank erosion and creation of new distributaries, all of which can alter channel/floodplain widths, physiographic features are not always suitable for delineating stream corridors. Forest tracts, wetlands and other such landscape units are often considered during corridor demarcation. Corridors are also governed by local political and public interests which reflect land use planning and developmental control in delineating riparian buffers. Thus, while the variable width approach considers pertinent site-specific factors like bank and channel slope, bank erodibility, local geomorphic units, infiltration rates and land-use patterns, the fixed width concept for active stream corridors and especially riparian buffers is comparatively easy to apply and administer from a management perspective (Banerji & Patel, 2019).

GIS-based tools developed under the River Management Programme within the Stream Geomorphic Assessment Protocol enable corridor demarcation based on stream network, valley toe wall and meander centreline information (Bear Creek Environmental, 2012). A fixed corridor width of 2.5 times the channel width or 30 m on either bank or a user-specified value is taken. Alternately, the use of similar accumulation thresholds or slope breaklines and terrain attributes to delineate upstream riparian corridors from high resolution digital elevation models allows better extraction of stream networks to identify the present geomorphic units and valley configuration (Gilbert et al., 2016; O'Brien et al., 2019; Wheaton et al., 2015) and assess the scale and magnitude of the ambient riparian stressors and their concomitant effects on the local ecosystem (Bhowmik et al., 2015). For stream restoration in urban locales, the Minimum River Corridor concept considers the multipurpose benefits that stream corridors provide (Asakawa et al., 2004). This is an area of no disturbance (typically a vegetated strip/riparian buffer on either side of the channel) that aims to preserve the minimum flood corridor, acting as a protective shield between the city infrastructure and the channel itself (Augusta Hermida et al., 2019). Such green corridors enhance property values by improving aesthetics and allowing recreational facilities in addition to reducing erosion and flood hazards, while enabling biological conservation to enhance species richness and diversity (Kondolf & Pinto, 2017; May, 2006; Spackman & Hughes, 1995).

5 Why Focus on Stream Corridors and Riparian Buffers for Ecological River Restoration?

The foregoing sections have explained the need for ecological river restoration measures and highlighted the composition of the stream corridor wherein these efforts are mostly concentrated, while explaining the demarcation of the riparian buffer, which is the principal soft engineering or bioengineering method to bring about stream rehabilitation. Why so much focus is accorded to the stream corridor and the vegetated riparian buffer zone is discussed next, with the combined ecosystem functions and services they provide underpinning the need to identify and evaluate these components as vital pieces of any ecogeomorphic stream restoration plan.

Stream corridors are in essence circulatory systems wherein water, energy, sediments, nutrients and organisms dynamically interact in a self-regulatory and self-sustaining manner (Sardi-Caromile et al., 2004). Its critical ecological functions relate to two main attributes: connectivity and width (Arif et al., 2021). *Corridor connectivity* is its spatially continuous upstream–downstream linkage with the adjacent stream channel, with greater connectivity providing more valuable ecosystem services and instilling greater stability (Harvey & Schmadel, 2021). The *corridor* *width* is the distance from the stream to its adjacent land use. This width varies along the channel length and often has sudden gaps or interruptions (Feld et al., 2018), caused by landscape fragmentation due to environmental disturbance gradients or human interventions. These two attributes are interrelated (e.g. a diminishing width impairs the connectivity) and provide valuable insights for designed restoration goals.

The inherent and explicit functions performed by a stream corridor and the riparian buffer positioned within it range from the physical and ecological to the economic and social (Mondal & Patel, 2018). These can be combined into the following categories:

a. ***Habitat***: Undisturbed, continuous corridors connect smaller habitat patches and help create larger niches. Corridor stability may also be judged by the continued richness, composition and genetic diversity of its floral and faunal communities in both edge and interior habitats (Harvey & Schmadel, 2021). They also enable safe wildlife passage (Jeong et al., 2018). Diverse terrestrial habitats are best conserved using riparian buffer widths of > 100 m while buffer widths of 10–30 m are suitable for protecting aquatic habitats (Arif et al., 2021; Luke et al., 2018). Such buffers should ideally consist of native tree species and grasses and be preserved in their natural form for much of the stream length (Arboleya et al., 2021). These provide nutrition in the form of leaf-litter and twigs while large woody debris provide suitable in-stream habitats. Shading from riverside trees reduce the water temperature and elevates dissolved oxygen levels for fishes. Riparian forests also enable baseflow maintenance during drier periods (Wenger, 1999).
b. ***Conduit and Barrier***: Corridors are passageways for water, energy, nutrients and biota movement, both laterally and longitudinally within the watershed (Harvey & Gooseff, 2015). Riparian buffers act as flood storage reservoirs and excess overland runoff or overbank flow infiltrators, thus reducing potential damage from floods and recharging the local groundwater table. The above-ground biomass of riparian buffers increase the channel and floodplain roughness coefficients, which retards flow velocities and also abates streambank erosion by dissipating stream energy and reducing channel scour (Abernethy & Rutherfurd, 1999). The roots of grass buffers have substantial tensile strength and engender greater cohesion within soil particles, thus reducing the streambank erodibility (Mulyono et al., 2018).
c. ***Filter and Sink****:* Forested riparian buffers are excellent sediment filters that effectively retain sediments by inhibiting and retarding overland flow rates (Feld et al., 2011). The amount of sediment retained depends on the buffer width and slope, soil type, vegetation character and density of vegetation. Alongside retaining sediments, these buffers effectively trap excess nitrogen and phosphorous from agricultural runoff, which would have otherwise entered streams and accelerated eutrophication, causing harmful algal blooms (Klapproth & Johnson, 2009). Studies show that about 65% of the phosphorus in runoff can be retained by buffers along with trapping 50–100% of the inflowing sediments (Vigiak et al., 2016).

d. ***Recreation and aesthetics***: Riparian buffers also have economic values (Rempel & Buckley, 2018). For urban streams, buffers enhance water quality by absorbing excess sediments and contaminants and keep them out of rivers, thereby reducing expenses for drinking water treatment plants. Riparian buffers influence property values, which are much higher within healthy corridors, as they provide better environmental benefits. Buffers also promote hiking, camping and other recreational activities. Large forested buffers have a visual aesthetic appeal (Saha et al., 2020), which adds to the tourism potential (Shafer et al., 2013).

Having established the need and significance of ecological river restoration and the importance of stream corridors and riparian buffers in this context in the foregoing sections, the forthcoming sections shall highlight the emergent inter-linked hydrogeomorphic frameworks and methods that have been devised recently to link together the different hydrological, morphological and ecological components that are central to evaluating the overall *stream health* at the catchment and reach level in a holistic manner.

6 Linking Ecogeomorphic Principles, River Health and Stream Corridor Restoration

Merging ideas from ecology and sustainable river management, the term *river health* provides a broad framework for managing lotic ecosystems, encompassing the interactions between river biota and the hydro-geochemical environment (Baruah et al., 2011). Although initially criticised for being too subjective and ambiguous, the concept was mainstreamed using quantifiable indices embedded in holistic methods and frameworks, which can be easily applied to any river with slight case-specific modifications (Johnson & Beardsley, 2015).

The shift from a 'command and control' approach to a holistic 'ecosystem' based approach to assess river health became more acceptable based on the 'near to nature' concept (Brierley et al., 2019). This is addressed from the perspective of the biological diversity and ecological functionality linkages that a stream should promote in the course of its flow (Baruah et al., 2011, GRBMP Report, 2014), while meeting societal needs of water use (Ma et al., 2019). Quantification of river health generally follows two approaches- the *functional approach*, which focuses on the ecosystem structure, its functional attributes and resilience to disturbances, while the alternate approach is grounded in aquatic ecology and directly assesses the integrity of the unmodified biotic assemblages (Karr, 1999). Ideally, river health assessment studies should enable holistic river management by examining and describing the overall ecogeomorphic/hydromorphic condition of the stream reaches, diagnosing and highlighting the cause of each impairment at the debilitated sites, communicating with stakeholders and policy makers on issues relating to their solutions and also setting the stage for implementing such solutions as part of river management programmes

(Johnson & Beardsley, 2015). Towards this, the basis of the hydromorphological assessment frameworks that are usually adopted is explained next.

6.1 The Emergent Hydromorphological Approach for Guiding River Restoration

The gradual acceptance of the science of river health and the need for a comprehensive framework for it led to the emergence of the term 'hydromorphology'. The European Union Water Framework Directive (EU WFD) was one of the most important acts of water legislation that spurred its member states to examine the ecological health of their waterbodies and promote sustainable water use. This milestone water policy was adopted on December 22, 2000, with a new set of water laws for European river basins. The Directive addressed new challenges in water resource management and aimed to achieve 'good ecological status' for all European surface water bodies that were either natural, artificial or heavily altered by 2015 (Ozcan et al., 2018; WFD, 2006). This 'ecological status' was viewed in terms of a waterbody's physicochemical, morphological, hydrological and biological characteristics as a whole (Ozcan et al., 2018), exactly what is entailed in river health assessment.

Towards meeting the above directive, *hydromorphology* was considered as a critical element affecting river ecological health and the assessment of hydromorphological parameters and their impact on other morphological, hydrological and ecological components was deemed important (Keogh et al., 2020) (Fig. 2). The term *hydromorphology*, thus combined the three elements of morphological functionality, hydrological regimes and river continuity to scientifically assess a stream (Ozcan et al., 2018) and this was considered central to any river health assessment analysis (Tanago et al., 2021). Successive Environmental Impact Assessments and pressure analysis reports revealed that by 2004, the majority of surface water bodies in Europe were either at risk or had become heavily modified because of alterations in their morphological characteristics and flow regimes. Furthermore, much of the hydromorphological alterations were directly associated with hydropower and flood control projects and navigation (WFD, 2006). Hydromorphology has thus been termed as the key element in understanding water conservation science (Boon et al., 2010), and encompasses the assessment and analysis of the physical, hydrological and biological elements of the aquatic ecosystem (Belletti et al., 2015).

6.2 Hydromorphological Assessment Frameworks: Concepts and Methods

Hydromorphology links stream hydrology and morphology and places due importance on the physical stream characteristics and processes (Vogel, 2011). The

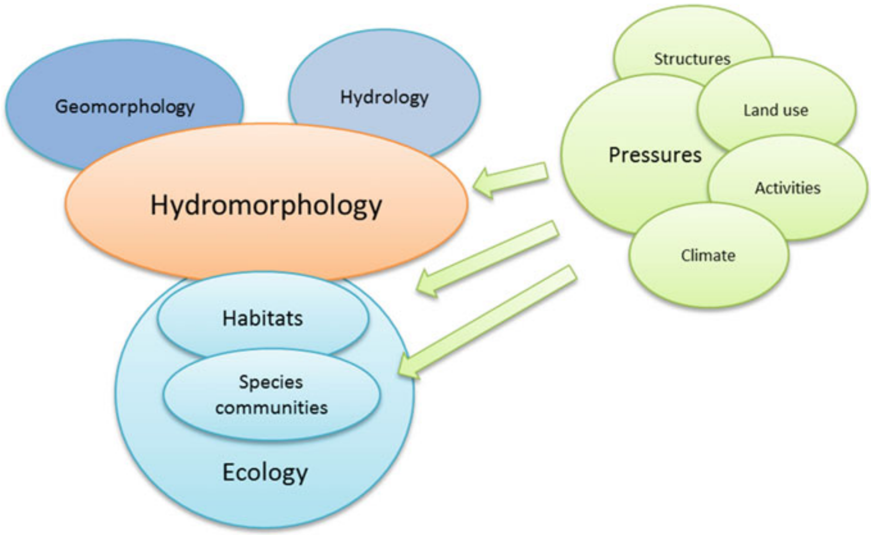

Fig. 2 The integrated science of Hydromorphology (*Source* Adopted from Riverdene Consultancy [available at: https://www.riverdeneconsultancy.com/our-approach/])

morphological properties of a river, i.e. its channel dimension, planforms and patterns and the processes creating them, the bed substrate and its calibre, the structure and dynamics of the riparian corridor and the lateral and longitudinal river continuity are intricately linked to its hydrological regime (the quantity, quality and regime of flow, which in turn depends on the local climate, lithology and valley setting) (Azlak et al., 2017). Any assessment of stream hydromorphology therefore must consider alterations to the flow and sediment regime, river planform and channel lateral connectivity (Rinaldi et al., 2013).

The stream's ecological setting is also central to its hydromorphological assessment (Boon et al., 2010). Hydromorphological conditions influence the biotic health of river courses, by impacting species diversity and habitat dynamics and also relate to other ecosystem functions like primary production and respiration of in-stream species, storage and circulation of nutrients, organic matter and sediments throughout the system (Hajdukiewicz et al., 2017). To achieve a good ecological understanding, evaluation of specific biotic communities like phytoplanktons, fishes and benthic invertebrates should ideally be incorporated (Keogh et al., 2020).

The EU WFD therefore mandated that all rivers should be classified based on their physical parameters and within each river type, the hydromorphological attributes should be examined to depict their overall status (Raven et al., 2002). Almost 40% of the alterations caused in rivers arise due to changes in their hydromorphological components (Keogh et al., 2020), with rapid urbanization, increasing agricultural practices, hard engineering flood control measures and the development of hydropower projects being its main drivers (Stefanidis et al., 2020). Usually hydromorphological functions tend to adjust themselves through feedback mechanisms as the river undergoes constant natural change (Hajdukiewicz et al., 2017). Thus evaluating the hydromorphological condition and the processes that govern it helps in understanding the stream stability (Boon et al., 2010) and these must invariably assess the stream's ecological status and ascertain the risks and pressures that exist on them (Boon et al., 2010).

A detailed review of existing hydromorphological methods by Belletti et al. (2015) identified that most of these fall in one of four categories: *physical habitat assessment*, *riparian habitat assessment*, *morphological assessment* and *hydrological regime alteration assessment*. Though the focus of such methods was the development of an all-inclusive and self-explanatory integrated framework, the hydromorphological processes that govern stream functions were generally neglected in most approaches. Earlier frameworks were mostly limited to assessing the physical habitat mechanisms for restoring streams, being localised, small-scaled attempts that were qualitative descriptions rather than quantitative measurements. It was only after the WFD came into being that greater emphasis was put on hydromorphological assessment via process-oriented methods that examined the hierarchy of spatial scales from the catchment to the reach level and within individual hydraulic units. A summary of these methods can be described as follows:

- ***Physical habitat assessment survey*** includes methods/frameworks that characterise and classify physical habitats in a stream channel. They primarily examine in-stream habitats but can be extended to floodplains as well. Also known as river habitat surveys, the heterogeneity and inherent complex structure of riparian physical habitats are examined by them, linking their morphology and ecology (Hooper & Hubbart, 2016). However, they only consider one hydromorphological component and are limited to reach-level examinations.
- ***Riparian habitat assessments methods*** particularly examine riparian habitats, which are an integral hydromorphological aspect. Crucially, these methods examine the riparian vegetation, based on WFD guidelines. Being primarily field-based, they can also incorporate remotely sensed datasets and examine larger spatial scales (Cornejo-Denman et al., 2018).
- ***Morphological assessment methods*** consider channel forms, patterns and adjustments and human modifications of river morphology at the reach level, which can then be related with physical habitat surveys (Rinaldi et al., 2013). The active physical processes are especially taken into account, aiming to quantify the ongoing pressures and responses in the system, with historical changes as well as future trajectories of channel processes being ascertained.
- ***Hydrological assessment methods*** measure the alteration of the natural hydrological regime of a channel and its impact on ecosystem functions. These methods are quite similar to and directly linked with morphological assessment methods, being highly data intensive and requiring longer duration data to compute. They are difficult to employ in un-gauged rivers while the identification of an unaltered reach to use as a reference condition is another challenge in such frameworks (Belletti et al., 2015).

With the WFD urging the attainment of a good ecological channel condition, about 300 different stream assessment methods to gauge river hydromorphological health are in use across Europe to fulfil the obligatory mandate (Meier et al., 2013). A detailed review of these eco- hydromorphological methods, their strengths and limitations, applicability and validity is provided by Rinaldi et al. (2013). Raven et al. (2002) compared three well-documented river habitat assessment frameworks [the River Habitat Survey (UK), SEQ-MP (France) and LAWA- vor-Ort (Germany)] in different setups, surmising that while these methods are broadly similar, the differences in defining the reference condition produces varying results. They also function at different spatial scales and differ in terms of data collection, survey procedure and analysis. Similar comparisons/validation of various hydromorphological assessment methods were also done by Wiatkowski and Tomczyk (2018). The suitability of the River Hydromorphological Quality (RHQ) assessment method for stream restoration was tested for the Biala River in the Polish Carpathians (Hajdukiewicz et al., 2017). The applicability, validity and potential of the German Field Survey method was judged in the Ruhr River Basin in western Germany, considering the river bed, banks and floodplain individually to assess the overall stream condition (Meier et al., 2013). In view of the ambiguities associated with the existing methods, standardised, holistic, scientifically sound approaches, with comparable outputs are desirable for assessing river health.

7 River Restoration Catchphrases

With ongoing research in ecogeomorphological approaches (refer to Hupp & Osterkamp, 2013; Jacobson, 2013; Pasternack, 2013; Rinaldi et al., 2013), its vocabulary has grown and incorporated aspects of fluvial geomorphology, flood mitigation and river rehabilitation (e.g. Giddings, 2011; Jones, 2017; Potter, 2013; Sayers et al., 2015). See Mondal and Patel (2018, 2021) for a detailed description of the focus areas and functions of riparian buffer implementation and keyword analysis of the studies conducted in this domain. The Google Ngram Viewer (Michel et al., 2011) was used to examine the frequency and publishing date of selected keywords across the entire Google Books repository. Six such catchphrases were charted (Fig. 3), with the steep rise in *river corridor* studies post-2000 being clearly discernible. In fact, all phrases related to river restoration, like *stream ecology* and *riparian buffer* displayed a marked rise post-1985 and especially since the turn of the millennium. *Flood mitigation* concerns have fluctuated markedly, with the 1970s–1980s (era of structural control measures) and the year 2000, recording peaks. Post 1995, *ecological restoration* has been the main focus of such studies.

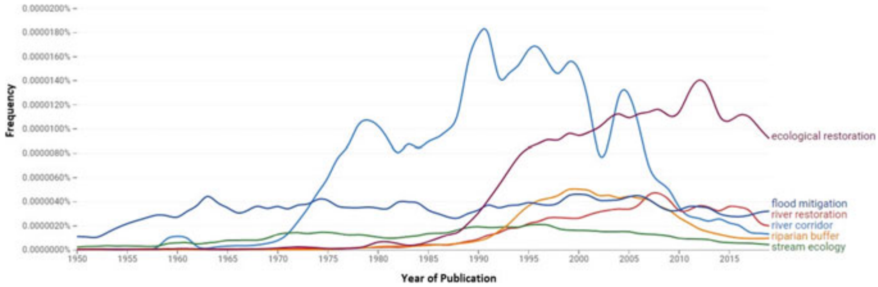

Fig. 3 Google Ngram showing the frequency of the selected phrases in publications archived in the Google Books Repository from 1950 to 2017

8 Challenges Faced in India for River Restoration

The growing (albeit slow) realisation that all water course related developments are not always beneficial and that society is best served by restoration of severely impacted rivers and lakes has led to river restoration efforts being thought about (so far) on a piecemeal basis in India. The Central Pollution Control Board (CPCB) has identified over 351 polluted river stretches in India, having a total length of 12,363 km. The Ganga River Basin, the most populated catchment within the country, has been the prime focus of restoration programmes, with a number of projects framed to rejuvenate its various degraded stretches. Although in dire need of a holistic restoration programme, most of the efforts have been limited to assessing just the water quality.

Initiatives like the Ganga Action Plan (GAP)- Phase I & II (1985), Yamuna and Gomti Action Plans (1993), modifying the National River Conservation Plan (NRCP) to include the Damodar and Mahananda, Ganga-Thames Twinning Programme (2010), Namami Gange (2015) and the Sabarmati Riverfront Development Project (2017), have slowly been forwarded to prioritise and restore impaired river reaches. The Ganga Action Plan (GAP) was the first ever restoration project of the country, based on integrated river management guidelines. Although the GAP had an initial objective of pollution abatement and improvement in river water quality, the other notable objectives also considered were revival of interactions between biotic and abiotic ecosystem components and conservation of ecological diversity, rehabilitation of soft-shell turtles to restore impaired stream functions, resource recovery and regeneration and the installation of sewage treatment plants for waste water treatment.

The Yamuna Action Plan, a bilateral project between the Governments of India and Japan and an extension of the GAP Phase-II, is one of the largest river restoration projects in India. Despite having a funding expenditure of US$172.7 million, the project only facilitated enhancement of water quality with special attention to waste water treatment. In addition, the Hon'ble Supreme Court of India in 1999 directed that a minimum environmental flow (E-flow) of 10 m^3s^{-1} be present in the channel to ensure sustenance of ecological species, but the observed values are far below this stipulated level even after 20 years of implementation (Jain & Kumar, 2014).

The pioneering Sabarmati Riverfront Development Project, while framed with a three-fold objective of environmental improvement, social infrastructural development and sustainable development, failed to properly restore river reaches due to too much emphasis on the concretization of river banks to reduce erosion, which led to the disruption of ecological functions causing elimination of flora and fauna and completely changing the ecological character of the river (Rao, 2014). Channelization and diversion of river water from the Narmada main canal to the Sabarmati caused degradation of ecosystem functions. It has also been criticised on the grounds that this project has only facilitated riverfront development without taking into account the increasing probability and intensity of floods due to poor management of riverside lands, with little attention paid to the rehabilitation of flood affected residents (Bhatt, 2016).

Other scarce examples include the Vaigai River Restoration Pageant Project (Earth Celebrations, 2014), ecological management of streams afflicted by hydel power projects in the Himachal Himalayas and restoring the Kuttemperoor River in Kerala and in the Kali Bein River in Punjab (see Mondal & Patel, 2018 for further examples). An enhanced perception of rivers as ecological entities did emerge with the High Court of Uttarakhand denoting the Ganga and Yamuna rivers as living beings with full human rights in 2017 (though this order was subsequently overruled by the Supreme Court). However such instances are limited in spatial extent and administrative coverage and no nation-wide plan exists for overall riparian condition restoration, following globally accepted goals and principles of such projects.

What is obvious from the above discussion is that only a few river restoration programmes in India have been successful in terms of the actual scope of such plans and in their implementation. Often, such river restoration approaches have lacked an understanding of the scientific principles and objectives of restoration and have also meant different things to different stakeholders. Restoration activities have largely been focussed on improving the water quality and stabilising river banks through concretization by almost completely disregarding the ecological front. The few examples of what is seen as restoration in India today revolve around the improvement of water quality in a few selected reaches, rather than a basin-scale management of watershed resources. It is also seen as a one-time activity without proper monitoring and impact assessment of future implications. River restoration in India has thus mostly been an expensive activity leading to futile results.

The lack of effort to understand specific river stressors, absence of proper restoration guidelines, lack of ability to foresee rivers as ecological entities and absence of a holistic framework based on ecological principles have made these piecemeal restoration efforts ineffective and unsuccessful in most cases. Furthermore, the socio-economic costs of restoration have seldom been acknowledged in India. The wider connotation of restoration, i.e. recovery of the overall river health, has never been realised and thus restoration efforts focussing on only one aspect of rivers have brought about unsatisfactory results. The uniqueness of each river in terms of its particular geologic and geomorphic setup needs to be realised to apply watershed-specific restoration plans. Holistic metric-based approaches focussing on hydrology, morphology, water quality and ecology and founded on sound restoration principles is thus the need of the hour for Indian rivers (Bedarkar et al., 2018). Several non-governmental organisations (NGOs) like WWF-India, PEACE India, Toxics Link and India Rivers Forum have come forward in this grand mission of restoring rivers and programmes like India Rivers Week, Rivers for Life, Life for Rivers are now being celebrated to create mass awareness regarding such programmes. These are some slender rays of hope for the dying rivers of the nation.

8.1 Hydromorphological Framework Based River Health Studies in India

The use of ecogeomorphic approaches to address river health has only occurred recently in India. River habitat assessments in the country have been carried out on a piecemeal basis without any holistic hydrogeomorphic framework being taken into account. The Yamuna Jiye Abhiyan at Allahabad was the only instance where a few of the components of the habitat assessment frameworks were acknowledged. All other attempts to assess river health have been limited to mere assessment of the physicochemical water quality.

Water quality assessments and nutrient flux modelling was done for the Ramganga River to understand catchment dynamics during seasonal and temporal variations, revealing that high nutrient concentration during low flows threatened aquatic life and degraded the overall water quality (Pathak et al., 2018). Water quality assessment of the Swan River in Himachal Pradesh (Sharda & Sharma, 2013), Godavari (Chavan et al., 2009), ecological assessment of the Chambal (Yadav et al., 2015), status evaluation of benthic micro-invertebrates of the Kosi (Sharma et al., 2008) and E-flow assessment of the Chenab (Bhatti & Latif, 2011) are other sporadic examples of river health assessment studies in India. Except for the River Ganga, most studies are limited to testing of water quality by using fishes and aquatic insects as bio-indicators or analysis of micro-flora present in the bed sediments. Some studies have highlighted the negative impacts of dams and barrages on flow continuity and channel mechanics (Nandi et al., 2016).

Geomorphic diversity helps to distinguish different geomorphic classes of rivers for habitat suitability assessment, E-flow requirement and flood risk analysis, all of which comprise essential elements of stream health evaluation. Such a framework provides the baseline information required for understanding the complexities of geomorphic processes and functions. This assessment has been done for the River Ganga to develop sustainable river management techniques in line with the inherent character and behaviour of natural streams (Sinha et al., 2017). As part of river conservation measures under GAP-Phase I, soft-shell turtles were introduced into the river near Allahabad to enhance the genetic diversity of the population, improve ecological stability and conserve other in-stream species. While the Ganga's channel geomorphology within the Varanasi Turtle Sanctuary (VTS) has remained quite stable over the last 50 years, construction activities, sand mining and movement of large vessels have affected some geomorphological and ecological facets (Sonkar et al., 2019). Singh and Sinha (2019) revealed that the hydrological connectivity within a water stressed wetland in the Kosi-Ganga interfluve was crucial to its ecological and morphological status, with a need to minimise any future connectivity loss. The methods used by them can help identify areas with changing connectivity potential and thus have significant implications for restoration and improvement of wetland-catchment connectivity.

While some studies on river ecological health and hydromorphic assessments do exist on the River Ganga, rivers in other parts of the country have been largely overlooked, with sporadic examples from the western and southern parts. The ecohydrological footprint of the Kali River in the central Western Ghats of Karnataka was studied to gauge the vital ecological functions of the main and tributary streams and their current status. Computation of the relevant ecohydrological indices revealed that while the forested sub-basins showed higher footprints due to their pristine ecosystems, the plains had comparatively lower scores due to anthropogenic activities and also suffered from water stress (Ramachandra et al., 2018). Several ecological health improvement projects that aim to revitalise the self-purification capacity of rivers to convert—'no-species' zones to native multi-species ecosystems have been implemented under various policies/plans like Water Policy (2002, 2012), National Environment Policy (2006) and the National Action Plan for Climate Change (2008). Eco-restoration of the Ahar River in Udaipur (2010), the Medi Kuntha Lake restoration in Hyderabad and the Rasoolabad Stream Restoration Project in Uttar Pradesh (2011–2012) are a few examples of the efforts to restore India's rivers.

Another important aspect of river health is the determination of the required E-flow, since the discharge regime is the master variable that affects all other ecosystem components—from river connectivity to water quality to aquatic life (Kumar & Jayakumar, 2018). However, doing this is still challenging in India where rivers are viewed from the perspective of societal use (Tare et al., 2017). The National Water Policy (2002), mentioned the term *E-flow* for the first time, denoting it as the minimum flow to be released from dams and barrages for environmental sustenance in downstream reaches as against its popular definition, which specifies it as the amount of water needed for the survival of ecological species (Smakhtin & Anputhas, 2006).

While most assessments of E-flows are mainly focussed on the stream hydrology and employ hydraulics-based methods (e.g. Sharma & Dutta, 2020), the use of a holistic approach based on multi-disciplinary science is still recent in India. WWF-India (2012) has used the holistic Modified Building Block Method (BBM) to ascertain the E-flow for some stretches of the River Ganga, incorporating hydraulic models, flow-depth requirements of characteristic species and other geomorphological considerations. Results revealed that although the bare minimum ecological conditions were maintained, the studied sites were severely vulnerable to the impacts of dams and barrages, which often disrupted the longitudinal continuity and caused long stretches of ‘no water zones’ that eliminated sensitive ecological species (Tare et al., 2017). The effect of the Nagarjuna Sagar Dam on the hydrological regime of the Krishna and its E-flow conditions was studied by Kumar and Jayakumar (2018), who discerned that while an immediate decrease in high flow conditions was the direct effect, low flow conditions were sustained longer due to the associated hydropower project. The Central Water Commission (CWC), India has also conducted studies to evaluate E-flows in Himalayan rivers, while the Ganga basin was investigated by a consortium of the various Indian Institutes of Technology (Tare et al., 2011). It was observed that although these rivers have high flows in their upper reaches due to significant contribution from snowmelt waters, they often fail to carry the minimum flow in their lower reaches due to anthropogenic pressures (Smakhtin & Anputhas, 2006). Therefore, variations in the standards of minimum E-flows have been seen for such rivers in their upper and lower courses (Jain & Kumar, 2014; MoWR, RD & GR, 2015).

9 Existing Research Gaps

From the foregoing discussions and reviews of the literature, it becomes apparent that restoration-based river health assessment studies, emphasising the multi-disciplinary concepts of hydro-morphology and ecology are not only scarce in the Indian subcontinent, but also often lack the necessary scientific foundation and resources to be addressed properly. Based on this surmise, the gaps in the existing body of knowledge are stated below:

a. River corridor mapping and characterisation of channel hydromorphological properties using spatial hierarchical concepts (from catchment to reach-level analysis) has seldom, if ever, been attempted for Indian rivers, especially in West Bengal.
b. Reach level ecogeomorphic assessments of river health and e-flow requirements have seldom been done in the Indian context. While a few field trials have been conducted, any systematic analysis encompassing a comprehensive approach is very rare, often devolving into mere analysis of water quality.
c. The application of the stream corridor concept with special emphasis on vegetated riparian buffers to restore the ecological health of rivers is almost non-existent in India.
d. Specific vegetation based assessments to mitigate fluvial hazards like floods and riverbank erosion has seldom been investigated for Indian rivers.

10 Conclusion

What is evident from the above discussion is that a multidimensional, multi-metric framework, which addresses all major concerns of the fluvial ecosystem, is required in order to precisely ascertain the stream health, akin to the Stream Functions Pyramid (Harman et al., 2012) that has been adopted in some US states. The concept of river health that is embedded in the principles of hydromorphology brought forward by the EU WFD should be acknowledged while formulating a national river health management protocol that should examine stream health across the major rivers of India, which are critically designated as polluted and having impaired stream functions. While a draft legislation has been framed towards this, it differs on a number of critical aspects from the EU WFD (Lafaye de Micheaux, 2015), in not being legally binding but merely suggesting some governing principles, in placing far greater emphasis on the social aspects of rivers and being policy driven than being based on scientific principles, and in not being as objective oriented or target driven as the EU WFD. What this contextual paper thus attempts to do is set the scene for restoration-based river science studies in India by highlighting the new hydromorphic frameworks that have been proposed and adopted in this regard in other parts of the world and urging for their integration within other Nature Based Solutions (India Climate Collaborative, 2022). We hope that the foregoing brief discussion can spur on further reading in this domain by introducing the basic concepts in a succinct manner. The discerned research gaps are meant to nudge new research in these aspects, so that greater focus is given on the entire riverine environment rather than on only some of its abiotic aspects, as has traditionally been the case. We also contend that simply gauging the impact of human influence on the river system does not fully constitute such integrative studies, as these can be considered to fall within the broader ambit of applied geomorphology or even anthropogenic geomorphology. The greater need is to create university curriculum that integrates all components of the ecohydromorphic approach to river science so that going ahead, cross-disciplinary research may be adequately accomplished. Only then can rivers in the Anthropocene be studied on the basis of the distinct anthromes they occupy and how human society and other biotic components react to and reshape these water and sediment conduits and their connectivities, for targeted restoration and careful management.

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The Role of Rivers on Man and Society Reflected in Literature: A Critical Study of a Few Selected River-Oriented Popular Bengali Novels in Geographical Perspective

Uttiya Chattopadhyay

Abstract Greek philosopher Thales of Miletus believed that water is the material cause of all things. Civilizations all over the globe were established besides rivers which are truly considered as the cradles of civilizations. Rivers not only provide sustenance to the human beings but also influence the livelihood and perception of the riparian people in many ways. Irrespective of the size of the river, there is no exception of the above-mentioned role of the rivers. Apart from Geography, the very same role of river on man and society has also been meticulously articulated in some texts of Indian literature, especially in some Bengali writings. In this study, four literary Bengali texts which have been selected, are of such kind that express the intricate relationship between man and river in the passage of time. The selected texts, mainly written in twentieth & twenty-first century, are as follows – *Padma Nadir Manjhi* (1936) by Manik Bandopadhyay, *Hansuli Banker Upakatha* (1941) by Tarasankar Bandopadhyay, *Titas Ekti Nadir Naam* (1951) by Adwaita Mallabarman, and *Subarnarenu Subarnarekha* (2018) by Nalini Bera. These four novels are not only classic works of modern time's Bengali literature but also gained high acclaim for representing river's impact on man and society which can be best explained with the perspective of *Literary Geography* which depicts the response of human beings to environment and its effects on literature.

Keywords River · Society · Riparian People · Literary Geography

1 Introduction

In whole world, Bengali literature stands at a dignified position. In order to Bengal's (Before and after the partition of 1947 & 1971) rich biodiversity and the presence of uncountable number of rivers, it has become the milieu of plentiful literary texts by many of the great writers and litterateurs. Thus, Bengali Literature has a wide range of influence on Geography as well as on many other disciplines of our academia.

U. Chattopadhyay (✉)
Department of Geography, Bhawanipur Education Society College, Kolkata, West Bengal 700020, India
e-mail: uttiya.chattopadhyay@gmail.com

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Though both Literature and Geography may encompass almost all possible issues one can think of; but Literature especially deals with human emotions expressed in the writings of individuals, whereas Geography is concerned with practicality of issues in a pragmatic way of dealing it (Meyer, 1988). Literature has always been a source of *traditional indigenous geographical knowledges* (non-academic) basically found in folklore and tribal customs, which have developed over a great span of time in our civilizations (Dutta, 2016). This very inclination of Geography on Literature is somehow seemed to be missing in recent fiction and non-fiction literary works. The book *The Great Derangement: Climate Change and the Unthinkable* by Amitav Ghosh recognizes the explicit absence of the non-human voices (directly or indirectly) in contemporary literature (Ghosh, 2017). Here lies the importance of some of the classical river-oriented literary works of Bengali literature where rivers play a specific role in the lives of the people of those fictions, if not as a central character (Gope, 2016). In these kinds of fictions, River is not only appraised as an element of nature, but also is impersonated as the protagonist often having a way of expressing its metaphoric voice (which is the very voice of nonhuman in Ghosh's aforementioned book). Literature in its own way is very often silent on geographical facts of which we need to restore in our *ecumene* to make it more liveable and lovable one (Pinter et al., 2019). Geographical interpretation of the literary texts is the one of the best ways of accomplishing it (Brosseau, 1994). There are several commonalities on the basis of which study of the linkages between Geography and Literature has been started mainly from 1970s when holistic approach in geography got a boost. Those five typologies are—studies on the links between real and literary landscapes, understanding of the sense of place, the concepts of rooting and uprooting, the definitions of inscapes and territorial consciousness (Lando, 1996). This subfield of epistemology is often titled as *Literary Geography* which seeks geographical approaches to explore literary texts. This branch of geography encompasses a wide spectrum of human as well as cultural geography (Hones, 2008). The way of living of people often leaves an impact on the landscape (What is termed as *Cultural Landscape* coined by Carl O Sauer) reflected in Literature and those thematic foci like: realistic, socially critical, symbolic, metaphoric, and surrealistic interpretations of literary landscapes is often revisited by Geographers in its own systematic way (Meyer, 1988). This very approach in Geography and other related disciplinary fields give passage to the concept of *Ecocriticism* which analyses literary texts in an interdisciplinary point of perspective. This concept was first initiated by Joseph Meeker with a name of *Literary Ecology*. Later on, William Rueckert coined the term *Ecocriticism* in essay named *"Literature and Ecology: An Experiment in Ecocriticism"* (Mishra, 2016). The literary texts which involve Nature, particularly Rivers, are more prominent in describing space in relation with human's society and culture (Cutter, 2021). This attribute of Literature gives birth of many modern theories like *Ecocriticism*. Another of such like is *Geocriticism* which incorporates the study of space and time in literary items with geographical perspectives which eventually bring forth of the conceptualization of *Literary Cartography* in USA (Peraldo, 2016). Chinese-American geographer Yi-Fu-Tuan, who is believed to be the propounder of *Humanistic Approach* in the field of geography, has written in his essay *Literature and Geography: Implications for Geographical Research* that: "From time-to-time geographers have asked the question, what is the relationship between literature and geography? Relationship is a vague word, and answers to the questions have not been satisfactory. Answers tend to be of three kinds: Geographical writings should have greater literary quality, literature is the source material for geographers, and literature provides a perspective for how people experience their world" (Ley & Samuels, 1978). This present work advocates the endeavor of searching geographical facts in literary items in a meaningful way by choosing some widely acclaimed texts from Bengali literature.

2 Methodology

The entire presentation of this work is on the basis of cognitive and critical analysis of the selected texts. There are Four such texts, i.e., *Padma Nadir Manjhi* (1936) by Manik Bandopadhyay, *Hansuli Banker Upakatha* (1941) by Tarasankar Bandopadhyay, *Titas Ekti Nadir Naam* (1951) by Adwaita Mallabarman, and *Subarnarenu Subarnarekha* (2018) by Nalini Bera. It is noteworthy that most of the mentioned texts are fictions, nevertheless they carry a vivid description of the landscapes which is very genuine in reality till now. The main source of interpretation is the published books of those selected novels. The analysis of the whole work has been done on the foundation of corresponding ideas available in numerous research articles, books, magazines and other secondary sources. Scanning of the ideas has been accomplished through the perspective of social geography where comprehensible outcomes are not rigid, rather widens the horizon of arguments and further research. In the explanation of the selected texts, basically the internal subjectivity has been sought in terms of novelist's appreciation of the sense of the behavioral aspects of human and experience of the landscape. This work is not a mere articulation of the facts mentioned in the texts, rather an endeavor of focusing on the whole gamut of causal relationship between man and riverine ecosystem persisting through the history of Bengal regions and around. Many of critical and comprehensive assessments which happen to be common in intellectual arena of geography, are somehow overlapping in nature in the texts. Thus, this article sheds light on the conceptions in separate and organize them according their importance in those novels.

3 Brief Background of the Selected Texts

All the selected texts are novels by nature and they are originally written in Bengali language stretching a long span of time over twentieth and twenty-first century. Among these four novels, *Padma Nadir Manjhi* (1936) by Manik Bandopadhyay, *Hansuli Banker Upakatha* (1941) by Tarasankar Bandopadhyay, *Titas Ekti Nadir Naam* (1951) by Adwaita Mallabarman are much older fictions and are considered to be classical works in Bengali literature so far. A few of them have been adapted into films by some of the great directors in India and Bangladesh. So, these stories which cover both the territories of *Epar Bangla o Opar Bangla* (India and Bangladesh in either side of River Padma) as we call it, have impact on the lives of Bengalis in terms of its portrayal of standard of living of riparian people and society, particularly of *Jele Somaj* (Fishermen). A great deal of characterization of fishermen society has been articulated in *Padma Nadir Manjhi* and *Titas Ekti Nadir Naam*, which are incomparable with any other fiction in Bengali, if not in other languages also. Padma, on which *Padma Nadir Manjhi* is based on, is mighty branch of river Ganga. Padma, being a perennial river, has huge resource in it which can cater the livelihood of innumerable number of people living beside it. A little change in river's rhythm can cause a big change in lives of the people dependant on it. *Padma Nadir Manjhi* is a story of such uncertainty in the lives of fishermen. *Titas Ekti Nadir Naam* is based on a small river Titas which is basically an offshoot (often depicted as a branch) of river Meghna of Bangladesh and covers relatively lesser area than the other rivers mentioned here. *Hansuli Banker Upakatha* is a masterpiece in Bengali literature in terms of its beautiful rendition of the rural subaltern people in Birbhum District, who are always at the mercy of upper classes of the society. Tarasankar Bandopadhyay, a notable writer of Bengali literature of all times, has successfully interwoven the different perspectives of the subaltern people who are subject to the impact of river (*Hansuli Bank*, local name of a bend of the river *Kopai*) as well as utterly deprived by the negativities of caste system imposed on them. Not only that, the novel encompasses a wide range of tensional issues, hitherto disregarded by the then Government, like—conflict between upper class and lower class, conflict between science and superstition, conflict between tradition and modernity, conflict between feudalism and capitalism, conflict between profit and ecosystem etc. Author in this nice novel has given a crystal clear portray of the ecosystem of the river bend which has its own way of influencing the people living alongside. This novel ends with a mention of flood which swept whole set of the living what once gave birth of the fact known to be *Folk lore of the river bent*. The last text which is a very recent novel, *Subarnarenu Subarnarekha* is unique of its kind. This one is little bit autobiographical in nature where author describes about his own culture, the subaltern society around and way of life in his childhood days which has been shaped by the presence of Subarnarekha, an east flowing river crossing Jharkhand, Bengal and Odisha. Subarnarekha is a medium length river, originating in Chhotanagpur plateau, ultimately has its confluence in Bay of Bengal. In its journey through varied topographic expressions, the river alongside gives birth of multicultural societies with the people of West Bengal, Jharkhand and Odisha. Author has articulated some of the Folklore and regional history of this region where the river Subarnarekha has taken a pivotal role.

4 Discussion of the Contexts of Literary Expressions of Certain Facts Under the Purview of Geography

All the selected novels depict the story of the people who have extreme impact of river in their lives. Selected texts talk about the four different rivers, i.e.—Padma, Titas, Kopai and Subarnarekha which are situated over India and Bangladesh. According to the change of space and time on which the stories are based, the change of literary expression is very well noticeable. The authors are also coming up from different socio-economic background, hence, their perspectives are different in each case. Adwaita Mallabarman and Nalini Bera (the author of *Titas Ekti Nadir Naam* and *Subarnarenu Subarnarekha* respectively) are coming up from the *Malo* and *Behera* community of which they are talking about. On the other hand, Manik Bandopadhyay and Tarasankar Bandopadhyay (the author of *Padma Nadir Manjhi* and *Hansuli Banker Upakatha* respectively) are not the members of the people they are taking about. As a consequence, their way of expression is much philosophical and intellectual in nature. Despite all these differences, river-oriented stories, at least what can be comprehended from the selected texts, have some commonalities in them, as rivers play almost same sort of supremacy everywhere in our earth and those kinds of impacts of rivers actually come under the purview of geography (Mukhopadhyay, 2010). Here literature meets with geography (it is true with other social science disciplines as well) in its own way and augment the scope of *Literary Geography* (Ley & Samuels, 1978). There may be myriad points to be discussed in the context of *Literary Geography*, but the present paper confines its discussion within limit of a few.

4.1 Spatiotemporal Aspects of the Story Telling

Every story must be based on space and time, but according to the kind of plot, authors tend to conceive their own approach. In the river-oriented texts, authors while interpreting the story deploy a wide range of time, so that the impacts of rivers on the society and individual can be best understood. In *Titas Ekti Nadir Naam*, author has depicted the life history of two generations which have modified by the river Titas. River Titas is also changing with course of time. In *Hansuli Banker Upakatha*, the *niche* of the *Kahar* community is completely dilapidated with the course of time by a huge flood. At the end of *Padma Nadir Manjhi*, author captures an open-ended temporal frame of the uncertainty of *Kuber*, the fisherman, who is sailing towards *Maynadweep* (An island where survival is uncertain due to the lack of resource). It is a metaphor of uncertain nature of Padma River itself on which the fishermen depend for their sustenance. *Subarnarenu Subarnarekha* is a tale of whole childhood days which author spent at the bank of Subarnarekha River. Sometime Author, while illustrating the events, now and again goes back to historical folklore which prevailed at the banks of Subarnarekha. From long ago, Geography's one of the fundamental attributes of reality is interrelation between time and space. Though some of the scholars like Immanuel Kant (1724–1804) preferred to treat time and space separately. Again, in 1950s and 60s with seminal works of F. K. Schaefer (1953) and W. Bunge (1962), geography started to be emerging as a predictive science rather than being descriptive in nature (Rana, 2008). It started giving emphasis on temporal approach to be predictive in terms of interpolation and extrapolation (David, 2021). Michael Foucault once said (in an interview, 1976) that—*Space was treated as the dead, the fixed, the undialectical, the immobile. Time, on the contrary, was richness, fecundity, life, dialectic* (Mambrol, 2017). The river-oriented literary texts, especially the selected ones, are the prolific manifestation of space–time frame (with slight supremacy of temporal approach) which has been a fundamental tool of explaining geographical propositions.

4.2 Facets of Subalternity

In critical theoretical studies of postcolonial periods of the world, the discourse of Subalternity started emerging in twentieth century, though literature has reflected the voice of subaltern people from the time immemorial not like a normative theory but in a descriptive way as a harsh reality in our society (Singh, 2019). In contrast to the term *Proletariat* from Marxist philosophy, a section of social studies concentrated on the theoretical understanding of Subaltern people from 1970s. The term *Subaltern*, coined by Antonio Gramsci (1891–1937), denotes to the hegemony of power elite in society which leaves a section of society completely deprived or in distress (Jazeel, 2014). In India the ideology of subaltern studies got impetus by the works of Ranajit Guha, Erik Strokes etc. Much before the works of *Subaltern Studies Group (SSG)* or *Subaltern Studies Collectives* (as it is known in academia), Bengali literature, especially river oriented Bengali literature was bestowed on the narrative of marginalized people of our society. Most of the river-oriented novels are of that kind and the selected texts are no exceptions. Each of the selected novels conveys the reality of different marginalized groups. *Padma Nadir Manjhi* of Manik Bandopadhyay illustrates the miserable condition of the *Jele* (Fishermen Community). They are not only vulnerable by the social system but also by the river Padma which takes a big toll from them time to time. The main character of the story *Kuber* rightly remarks—"*Padda amago joto daay abar totoi loy*" (Padma gives us a lot, but in return it also takes a lot from us). On the other side, though the author of *Hansuli Banker Upakatha* is a member of upper caste hindu brahmin, but he represents the unique socio-cultural conditions of *Kahar* community whose ancestral occupation was *Palki* Bearing, but now they are engaged in cultivation as tenant farmers. In *Titas Ekti Nadir Naam*, readers get to know the real scenario of *Malo* community (fishermen community of Chatlapur and Nabinagar upazila of Bangladesh) of whom the author himself is a member. So, description of that people comes from the core of that community. In *Subarnarenu Subarnarekha*, author is describing about many other communities like *Nauria*, *Behera*, *Teli*, *Sadgop*, *Karan*, *Kaibarta*, *Khandayet*, *Dom* etc. with whom he had a socialization in his childhood days. These all communities have their special role in society alongside the Subarnarekha River.

4.3 Social Conflict and Integrity

In Marxist theories it is said that in a heterogeneous society, powerful groups tend to exploit groups with less power. Thus, social classes have a conflicting relationship rather than having a relation of consensus (Sinha & Varma, 2017). India (along with Bangladesh is a region where plurality is the salient feature of the society and class conflict, racial tension is a common scenario here (Basu, 2010). But most often, conflicts are seen to emerge on the basis of political and economic superiority of the upper classes over the economically poor classes. The selected texts of this work have also mention of exploitations of upper class, social stratification that limits the survival scope of these poor people whose sustenance entirely depends on rivers directly or indirectly. But due to the utterly impoverished situation, social conflict between exploiter and exploited in the stories, does not lead to the rebellion in mass scale. On the contrary, racial tension (between Hindu and Muslim) in these kinds of river-oriented stories, is almost absent. In *Padma Nadir Manjhi* and *Subarnarenu Subarnarekha*, no racial tension and caste conflict (among the people with same economic condition) is seen in spite of cohabitation of many castes and races. It indicates to the very common practicality of our life that affluence makes human isolated, whereas uncertainty makes human united and this indicates to the imperative evolutionary process of human race (Aurobindo, 1999). River-oriented literary works are best examples of this kind and shows another form of territorial integrity in small scale.

4.4 Personification of the River

In Geography, the ideology of *Lebensraum* has started long ago by Friedrich Ratzel in the year 1897. German word *Lebensraum* denotes to the notion of living space which is a metaphoric concept believing on living entity of non-human things like country, society, territory etc. Ratzel believed that state is like an organism which can grow with time. Later on, geographical concepts have been personified in many other theories, like Youth, Mature and Old stage of Landform evolution of W.M. Davis and few other Geographers, Snout of the Glacier, mouth of the river etc. Embodiment of the non-living thing into living things or organisms is a long tradition in geography (Park, 1981). Not only that, in our Indian mythology from the time immemorial, major rivers have been attributed to be the mother who cares for her children. This led to the heritage of worship of these non-living elements of nature as deity in a form of *Animism* which is a kind of religious activity still prevailing in different parts of our world. This perspective of personification has imbibed by literature, especially by the river-oriented novels which are full of illustrations where very often rivers are metaphorically supposed to be either goddess or mother or a little girl or a virgin etc. In most of the cases personification is feminine, but sometimes it is masculine also, as in India rivers are sometimes categorized in genders on the basis of its nature. In this work, all the selected texts have lots of explanations where the riparian people believe the river as living entity which has compassion, anger, pity etc. Even if River becomes violent and devastates the settlement that is taken as the expression of anger by the river to the sin which they think, they might have unintentionally committed. Then they try to please river and pray for her blessings. W. H. Herendeen rightly remarks in his *The Rhetoric of Rivers: The River and the Pursuit of Knowledge* article—"*The river has many voices: at times public, intelligible to the citizenry at large, and at other times private, audible only to individual or the lover and his mistress. But whether it passes through city or estate, the river is recognized as indigenous and as speaking in vernacular. A decorum regulates each river's voice, suiting to its landscape and local society*" (Herendeen, 1986). This perception towards river does not let the riparian people to leave the place and go somewhere else far from riverine tracts. That gives birth of a *way of life* (the concept of *genre de vie* coined by Lucien Fevbre) which is very identical in all riverine settlements in whole world. This again results in a special landscape what is known as *Cultural landscape* as Carl O Sauer termed it (Rana, 2008). *Padma Nadir Manjhi* and *Titas Ekti Nadir Naam* demonstrates unique bonding between fishermen society and the river which unfolds their way of living despite of all misery they have in their life.

5 Conclusion

Both literature and geography describe the earth and human in their own typical ways. Both can be enriched from each other with sufficient explanatory and interdisciplinary approach in common issues like landscape, river, culture, society and many other fields between these two. Literary expression of geographical things has a feeling and viewpoints what cannot be achieved by scientific explications (Noble & Dhussa, 1990). If we look to our recent past of Geography during 1970s when *Humanistic Geography* brought about people and human agency back to the core of the Geographical research which was somehow ignored and underestimated during the time *quantitative revolution* of 1950s. This rehabilitation of subjectivity was soon proved to be a valuable source of Geographical explanation and literature became associated with it in English and French speaking countries (Brosseau, 1994). In India, Geographical conscience has been much influenced by Vedic and Upanishadic literature (Rana, 2008). But recent literary works have not been incorporated much in Geography and Geographers have not borrowed much elements from recent literature to enrich itself. The lack of research items in this regard is the proof of this statement. Here comes the question of the significance of this present article which seeks the possible avenues of 'literal translation of earth description' (Pocock, 1988) (as mentioned by Douglas Pocock) through the lens of four selected Bengali Novels.

Some important inferences that this present article has identified as commonalities in the selected texts as their typical characteristics, are as follows—(1) River oriented literary texts have an orientation of illustrating the spatio-temporal transformation of the typical *niche* of riparian people and their unique livelihood which is uncommon in others parts of human settlements. It is identical with *micro-geographic* study of a region which reveals an intrinsic nature of dwelling in spite of all adversities. It is an attempt of explication of human conditions by those novels for which geography must owe to literature of such kind. (2) Such stories are the narratives of those marginalised people, who due to their nature of occupation basically, cannot help but living in the vicinity of the rivers which become the boon and bane for them at the same time. Their collective struggle against both poverty and nature has been best articulated in some of the river-oriented texts like selected ones than any other disciplines in our academia. For such vivid narratives of human struggle and backlash of class division of these subaltern people in river-side settlements, geography has many things to be benefitted from these. (3) Indian subcontinent (including Bangladesh) is a land of plurality, where racial tension and class conflict is a common scenario. In this regard, river oriented Bengali stories are exceptions where in spite of all plurality articulated by the writers, peaceful cohabitation is seen mostly due to the river-oriented sustenance/economy which helps people integrate together even in the untoward struggle of life. (4) Personification of inanimate things is a long tradition in human culture and has been going on from the dawn of human civilization. Later, this concept has been incapsulated in the form of a theory called *Lebensraum* in geography in a similar conception. In India and Bangladesh, from the time immemorial, river-side people have mostly considered the rivers as their dearest ones if not mother. This perception has been embodied in all forms of art and culture of this subcontinent. Due to this perspective towards river, people gladly accept all negative uncertainties coming from the rivers and never think to go away anywhere.

In this point, literature excels geographic explanations. The eternal relationship between man and river can better be encapsulated in a single novel by a successful litterateur than a dozen of geographic text books. Here comes the significance of studying river-oriented novels in a perspective of geographic evaluation which can lead to a more meaningful and alternative pragmatic way of evaluating things which geography alone cannot encompass fully.

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An Assessment of Human Impact on Bhagirathi River in Murshidabad District: From Reverence to Responsibility

Sucheta Mukherjee

Abstract The Anthropocene response towards fluvial systems has primarily been for sustenance (water & food) and gradually evolved to being as transit routes with progress in ingenuity—with demographic growth and spatio temporal progress of settlements, infrastructure and transport routes—habitable river banks have become more congested with urban growth progressing unplanned and unprecedented. The presence of dense population favoring this moribund deltaic region gives rise to problems of sanitization, improper disposal of sewage and deterioration of water quality of surface water units that are utilized by the populace. Lack of access to clean water is directly linked to poor quality of life and health. To assess the water quality status of the stretch of river Bhagirathi flowing through Murshidabad and the impact of discharge from settlements on its immediate banks, field analysis has been done using physico-chemical methods for DO (Dissolved oxygen), BOD (Biological oxygen demand), pH, salinity and nutrient load which show no significant or alarming decline in the self-purifying capacity of water. The quality of water impacts the utilization of water resources and vice versa. Upstream water quality at Jangipur is better compared to downstream at Jiaganj, Lalbagh and Berhampore which can be attributed to the disposal of increased soluble and non-soluble domestic waste like phosphates due to detergents and domestic effluents, near dense human settlements. The health of R. Bhagirathi is a matter of concern because primarily it is a breeding ground for Hilsa and groundwater reserves in this region are contaminated with Arsenic due to geogenic reasons. This makes it the most realible source of freshwater being available. This study analyzes physicochemical condition of the river water as a result of human impact leading to water pollution and suggests measures to help in the improvement of water quality to assist for planning and integrated management of freshwater resources and sustain river ecosystems.

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S. Mukherjee (✉)
Department of Geography, Sripat Singh College, Jiaganj, Murshidabad 742123, India
e-mail: sucheta.geo2012@gmail.com

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Keywords Water pollution · Rituals · Geogenic · Sustainability · Demography · Sanitation

1 Introduction

Rivers have influenced and nurtured civilizations since ancient times. The rivers and their floodplains have been preferred because of their ability to generate and regenerate crops for sustenance. The concept of river economies can be traced back to 3000 years when civilizations flourished on the banks of mighty perennial rivers like the Mesopotamian civilization on the banks of the R. Tigris and R. Euphrates, the Indus Valley civilization on the banks of the R. Indus, The Egyptian civilization on the banks of the R. Nile. The journey is from reverence wherein rivers are respected through civilizations, to the present being responsible for their cleanliness and not hamper their self-purifying capacity. The rivers were used primarily for the availability of fresh drinking water suitable for human consumption, inland transport to and fro from harbours which brought in tradeable goods and for religious rituals. A polluted river can paralyze the economy of fishermen communities (Sarkar & Islam, 2021) and constrict scope for livelihoods sometimes leading to occupational shifts where they are unable to accommodate themselves. The Ganga Padma region is one of largest biodiversity zone and at the same time is densely populated due to its fertile alluvial soil encouraging plant growth. The Bhagirathi River system endows the Murshidabad district with a rich network of drainage channels flowing over the moribund deltaic expanse, bringing in riverine silt and encourages agricultural activities throughout the year due to sufficient soil moisture. The region is intensely cropped and known for its rich agricultural produce through out the year serving urban metropolis like Berhampur, Krishnagar and Kolkata. The region is comprised of old alluvium soil and supports rich agriculture. In its geographical nature and as recorded historically the chief drainage channel the Bhagirathi river has been used for transport, for irrigation and fishing and has mention in historical records of being navigable upto Varanasi in Uttar Pradesh prior to building of barrage at Farrakka (Islam, 2011). The presence of about eighteen oxbow lakes also refers to its sluggish nature of flow due to elevation of less than 1 m for about a kilometer in the district. The other rivers flowing through the district are Mayurakshi, Dwarka, Bramhani, Jalangi, Bhairab to feed the river Bhagirathi and Ganga/Padma (Islam & Ghosh, 2022). They are of importance because they provide freshwater for consumption, supports biodiversity, supports livelihoods, brings down and distributes nutrients through its course for both biotic (plankton) and abiotic (silt, salts) elements from mountains, accommodates excess drained surface water from adjoining banks and hinterland, groundwater recharge in adjoining regions, breeding ground for the famed Hilsa fish, source for drinking water as it is seen that most drinking water sources in the region are tubewells or well which are arsenic contaminated due to geogenic reasons. The recent fluviatile sediments consist of succession of clay, silt, sand and gravel and are characterized by grey sediment aquifers containing high Arsenic, total Iron and low Manganese (Chatterjee, 2017).

The Bhagirathi- Hooghly river channel forms an important migratory path for the anadromous hilsa from Bay of Bengal waters to upstream of Ganga. The river system consists of upper Bhagirathi stretch, the middle tidal freshwater stretch of Hooghly and lower Hooghly Estuary (Sajina et al., 2019) and the stretch flowing through Murshidabad district needs conservation and restoration of water quality to sustain livelihoods and provide clean fresh water for consumption. This study has been carried out to identify in the study area—

i. the causes for river water pollution,
ii. the zones which are source of major anthropogenic pollution,
iii. the possible remedial measures that can be undertaken to assist for planning and integrated management of freshwater water resources.

2 Study Area

The district lies between 23°43′ N and 24°52′ N latitude and 87°49′ E and 88°44′ E longitude (Fig. 1). The Bhagirathi river system is spread over 25,830 km^2 including its sub basins (CWC 2015–2016). The district covers 5324 km^2 approximately is traversed by the R. Bhagirathi through its length dividing it into two physiographic zones: Rarh and Bagri i.e. west and east of the R. Bhagirathi respectively (Islam & Ghosh, 2022). The channel bifurcates from the Ganga about 40 km southeast of Farakka near Khejurtala village in Murshidabad district. ie the lower course of the Ganga. The average discharge is 257.78 m^3/s (9,103 cu ft/s) while the maximum discharge after monsoons is 3,800 m^3/s (130,000 cu ft/s). It flows through a region characterized by tropical humid climate, with distinct hot dry (March–June) and wet (July–September) seasons and cold dry seasons occuring in December–February temporal span (DSR GoWB 2020). The region experiences very cold winters (7 °C), very hot summers (40 °C) approximately and heavy rainfall (235 mm) during the monsoon, characterized by the tropical monsoon climate (Am type). Average annual rainfall is approximately 120 mm and 80% of this concentrated during the summer monsoon (June to August month) (Bag et al., 2019) The drainage network is organized within the Bengal basin which is of low relief and lies almost entirely on river floodplain. Relative humidity is high (80%) and high temperatures in summers and low and dry temperatures in winter.

The total population of the Murshidabad district is 7103807 numbers which is estimated to be distributed over 254 g panchayat as per District Survey Report of Murshidabad District 2020 (GoWB). River systems in the district are mostly meandering as well as braided in nature (Ghosh, 2015). The R. Bhagirathi and the other minor drainage channels caters to the district as floodplains for agriculture, fresh water for drinking, cleaning, fishing, irrigation water during dry seasons, course for navigation (R. Bhagirathi), ritualistic practices, retting of jute to extract fibres (Fig. 2).

Physiographically the region is marked into five zones—(1) The Nabagram Plain, (2) The Mayurakshi—Dwarka Plain, (3) The Ganga—Bhagirathi basin, (4) The

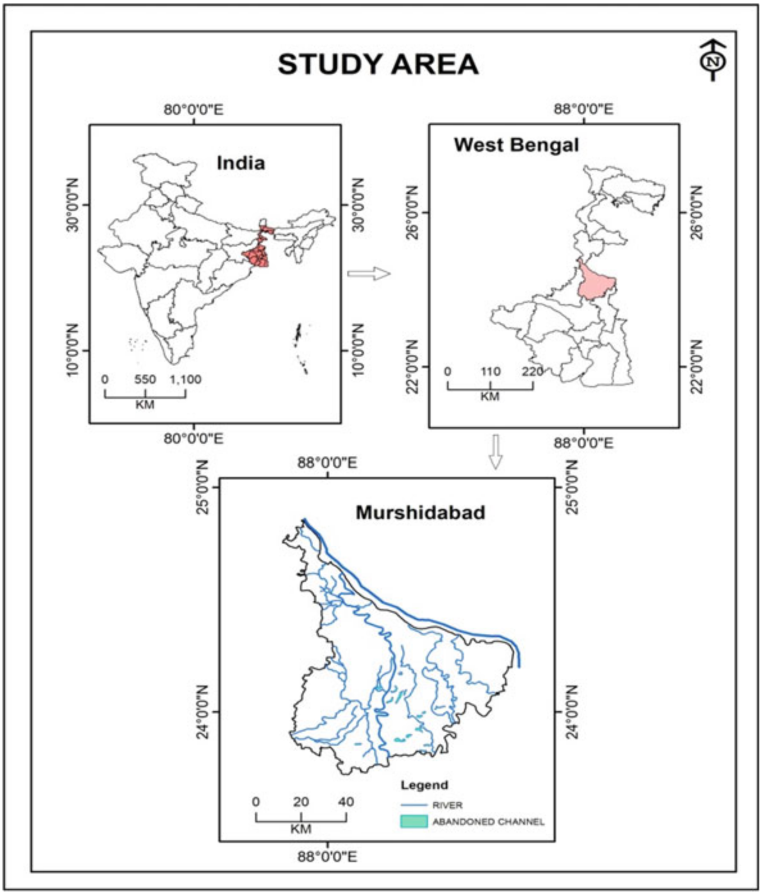

Fig. 1 The study area

Jalangi—Bhagirathi interfluve and (5) The Raninagar Plain. The Rarh region is part of the sub Vindhyan region and mostly made up of detrital laterites and clay (Ghosh, 2015). The eastern tract i.e. Bagri is an interfluve zone between the R. Bhagirathi and the R. Bramhaputra—R. Padma flowing south, characterized by rich alluvial deposited by them on both banks, inundation channels which have been abandoned as the R. Bhagirathi has changed its course over the ages. The eastern part of the river basin is more fertile than the western part. Geologically the district is divided into Recent—alluvium, Pleistocene-recent—older alluvium and lateritic clay and Jurrassic—Rajmahal Trap basalt. The Rajmahal trap is found in the northern part of the district according to the (DDMP 2016–2017 GoWB). A major part of the west of the river Bhagirathi is occupied by older alluvium and lateritic clay. The rest of the district is occupied by recent alluvium mainly composed of sands and clays brought down by the rivers. The soil character is of light texture, low organic carbon content

Fig. 2 Retting of Jute post-monsoon (near Jiaganj)

and the soil reaction ranges between slightly acidic to neutral (DDMP 2016–2017 GoWB).

The deterioration of riverine water quality is usually due to—(1) substances that harm humans or animals by causing disease or physical damage; (2) substances or situations that decrease the oxygen content of water, leading to anaerobic decay and the death of aquatic life (Fig. 3) and (3) substances that are indirectly harmful, by making water unpleasant to use or destroying the natural beauty and health of the rivers.

Fig. 3 Runoff from agricultural fields is a major concern (near Jangipur)

3 Methodology

The study has been carried out using satellite imageries (Google Earth 2021 & LANDSAT 8 Operational Land Imager or OLI) with 30 m resolution, Survey of India (SoI) topographical sheets (1968–1969 (79A/2, 79A/3, 79A/6 and 79A/7). The integration of the data set with a geographic information system (GIS) can help in illustrating the water quality status of river (Ali et al., 2021). Field survey for collection and testing of water samples collected at a 15 m depth mid channel on boat, for undisturbed samples and review of existing literature. Water quality was analyzed at four different stations (SCS1, SCS2, SCS3, SCS4) along the left bank of the river on field as well as laboratory for physico chemical investigations.

4 Field Samples

Water samples were collected between 0800 and 1700 h each sampling day, between winter (January) to post monsoon (October) in 2021. Physical parameters—air and surface water temperatures, nutrients and salinity were estimated on site. Water samples from the four selected stations for physical and chemical analysis were collected in one litre clean plastic bottles. Water samples to estimate dissolved oxygen and biological oxygen demand were collected separately using 250 mL glass reagent bottles with glass stoppers. Water temperature and pH were analyzed and recorded by using a mercury bulb thermometer and a digital pH meter respectively. Dissolved oxygen (DO) of the water samples were analysed by Sodium azide modification of Winkler's method following Panigrahi and Pattanayak (2020). The collected samples were put to laboratory test within 8 h of sample collection to minimize any change in water character. The presence of nutrients (nitrogen and phosphorus) in collected water samples were estimated using respective Nitrogen (LaMotte kit) and Phosphorus (Hach kit) water testing kits available. The Biologcal oxygen demand (BOD) from collected samples was measured using methods illustrated in American Public Health Association and American Water Works Association (APHA & AWWA 2005) (Fig. 4). The time period of measurement of BOD was 5 days to determine organic matter content. BOD and DO value were correlated with the water quality.

5 Results

The analysis revealed that majority of the pollutants are through six factors, that are organic and inorganic in nature. They are salinity (10.13%), organic pollution (dissolved and suspended materials) (10.31%), waste water pollution (37.19) from agricultural and organic load (20.18%) and erosional sediments from land (11.17%) that make up water quality and determine its fitness for consumption. According to

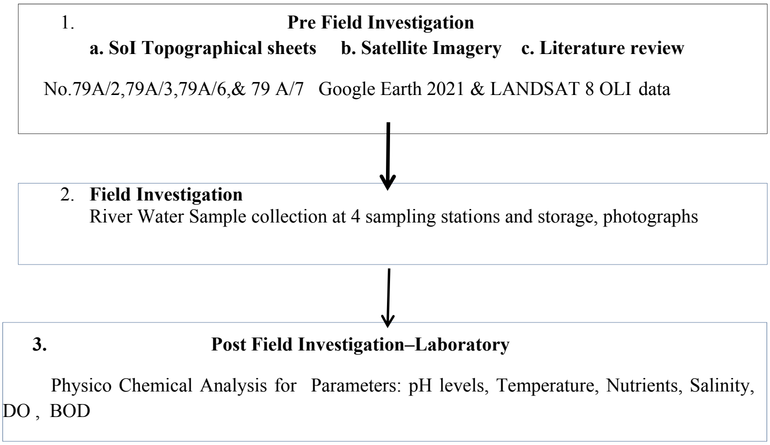

Fig. 4 Flow chart of methodology

Sener et al. (2017), Shil et al. (2019), surface water is affected by discharge from settlements and atmospheric air pollution deposits. Giridharan et al. (2010) also point out that the lithogenic structure through which the river flows affects the quality of water. Murshidabad district depicts the maximum average concentration of arsenic amidst its intrinsic complex geologic and hydro geologic set-up (Chatterjee, 2017) making river water much safer to consume than from ground water reserves. This necessitates the conservation of river water and maintaining water quality. Sampling stations for collecting water samples in the study area are (Fig. 5).

Jangipur (24°45′90″ N and 88°10′47″ E) **SCS1**—The river reaches maximum turbidity post monsoon after jute retting. This is the northern most station of the study area and semi rural in character. The river is used for irrigation, bathing, washing of utensils and cattle, disposing ash from pyres.

Jiaganj (24°24′41″ N and 88° 26′84″ E) **SCS2**—This settlement is the twin city of Azimganj on the opposite or right bank and contributes to major influx of polluted matter. Both banks are inhabited by dense settlements, agricultural and cattle markets. This leads to deposit of organic waste daily. The river is used for Irrigation, bathing, washing of utensils and cattle, disposing ash from pyres/crematoriums.

Lalbagh (24°17′33″ N and 88°27′65″ E) **SCS3**—The influx of urban waste and sewage is noticed here with chiefly deposit of chemicals from paint units and metal (bronze and copper) factories The river is used for bathing, washing of utensils and cattle, disposing ash from pyres/crematoriums.

Berhampore (24°45′90″ N and 88°26′84″ E) **SCS4**—The influx of urban waste, sewage and effluents from copper and bronze industrial units with municipal wastes. The river is used for bathing, washing of utensils and cattle, disposing ash from pyres/crematoriums, discharge of chemicals from paint units and metal (bronze and copper) factories (Table 1).

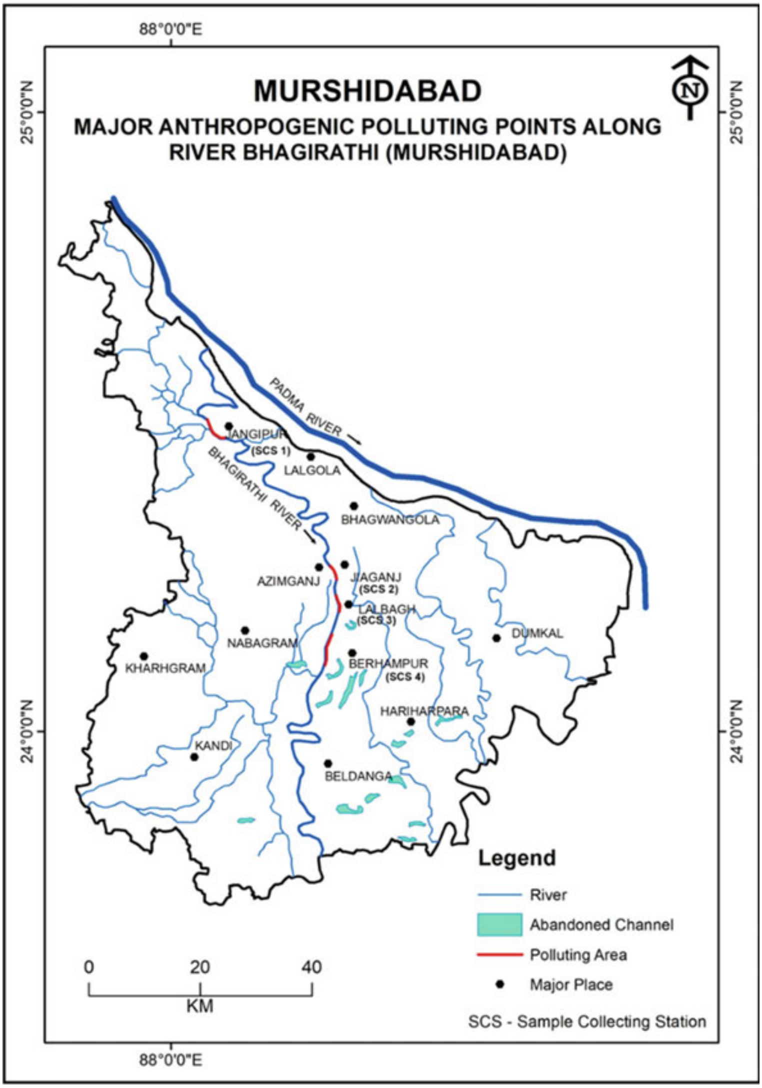

Fig. 5 Location of sample collecting stations along the R. Bhagirathi

The common reasons as found are use of excess fertilizers, herbicides upon agricultural lands and insecticides within residential areas. Oil, grease and toxic chemicals from motor boats crossing the river, urban industrial runoff from manufacturing units at Jangipur, Azimganj-Jiaganj, Berhampore, domestic sewage and runoff at settlements along the rivers contribute to river water pollution. Sediment from improperly managed construction sites, crop and forest lands, and eroding stream banks, all work together to constrict river flow and affect the quality of water.

Table 1 Percentage share of six factors of pollution in the study area

Sr. No.	Type of pollution	Percentage share (%)
1	Salinity	08.13
2	Suspended materials	13.02
3	Waste water	37.19
4	Agricultural fields runoff	20.18
5	Erosion from land	11.17
6	Organic load	10.31
	Total	100

Source Computed from field data 2021

The chief problem arises from improper disposal of waste and lack of awareness among locals regarding measures to maintain river health, with improper disposal of plastics being the predominant cause. The physico-chemical indicators that are water quality' indicators include dissolved oxygen, pH, temperature, salinity and nutrients (nitrogen and phosphorus) which are estimated to ascertain water health (Table 2).

Dissolved O_2 **(DO)**—Dissolved oxygen ranged from 7.71 to 7.01 mg/L, with a mean range between 7.43 and 8.25 mg/L post monsoon due to influx of sediments due to overland flow. Higher dissolved oxygen values were recorded during the dry winter months. DO is absorbed directly absorbed in river water from the atmosphere and increased through turbulence in the water. The presence of aquatic plants promotes DO in the water body. The amount of DO can be affected if degradation of excessive organic matter takes place which use O_2 for decomposition and breakdown. Also if the amount of aquatic animals are in excess to quantity of surface water (swamps, pools within the channel) there is an increased demand for DO (Sarkar et al., 2021). The settlements along the R. Bhagirathi though within permissible limits are impacted by discharge of human organic waste and sewage stations. The usual permissible

Table 2 River health of R. Bhagirathi flowing through Murshidabad—India

Station	Parameters							
	Dissolved O_2 mg/L	pH	Temperature		Salinity	Nutrients (mg/l)		Water quality
			4 am	2 pm		N	P	
Jangipur SCS1	7.71	8.14	23.1	24.7	0.61	0.69	0.67	Normal
Jiaganj SCS2	7.43	8.01	23.6	25.3	0.67	0.65	0.63	Normal
Lalbagh SCS3	7.57	8.03	25.5	26.8	0.63	0.58	0.60	Normal
Berhampur SCS4	7.01	8.10	27.3	28.4	0.66	0.59	0.61	Normal

Source Computed from field data 2021

range is 6.5–8 mg/L. The quantity of wastewater generated from the selected stations contribute to this factor. Untreated sewage should not be discharged in the drainage channels and should be strictly restricted.

pH—Alkalinity for all stations ranged from 8.01 to 8.14 mg/L with a mean.8.07 which is within the permissible limit as set by WHO (2011). There was no consistent trend in alkalinity. The pH range for irrigation water is 6.5–8.4 suitable according to Ayers and Westcot 1976. The pH level is controlled by various factors including human made waste (Omer, 2010). Water quality can be affected by pH as it can influence the alkalinity, solubility and hardness (Osibanjo et al., 2011; Panigrahi & Pattanayak, 2020).

Temperature (°C)—Temperature of water recorded early morning (4 A.M.) and late afternoon (2 pm) ranges between 23.1 to 27.3 and 24.7 to 28.4 respectively. The stretch near congested urban settlements record higher temperatures than those near rural settlements. The probable reason can be that high density of population leads to more use of amenities like transport, motorboats to cross the river and concretization of banks which contribute to urban heat phenomena chiefly and vice versa. The traditional bank protection works, concrete walls, cemented stone and brick, play a significant role in the modification of the hydraulic aspect of the discharge values and in the interference in the water dynamics of erosive and depositional phenomena both upstream and downstream (Bandyopadhyaya & Panda, 2011).

Salinity—The salinity is recorded to be negligible ranging between 0.61 and 0.67. The R. Bhagirathi is noted to have the Hilsa (*tenualosa ilisha*) fish during its spawning season travelling upstream from the Bay of Bengal to enter the Hooghly Bhagirathi river course to breed in waters with neglible salinity and steady flow. Already it is noticed that there is declining trend due to alteration of salinity.

Nutrients—Total Nitrogen (N) and Phosphorus (P) at selected stations followed the same trend of higher values during wet months compared to dry months. Nitrogen levels ranged from 0.58 to 0.69 mg/L with a mean of 0.63 mg/L. The low values may be due to utilization by phytoplankton and other primary producers (Ali et al., 2021). This influx of Nitrogen can be due to use of fertilizers on adjoining agricultural fields (Fig. 5) and subsequent surface flow during monsoon. Phosphorus levels ranged from 0.60 to 0.67 mg/L, with a mean of 0.63 mg/L. due to industrial waste near urban settlements especially Khagra near Behrampore known since historical times for its bronze and copper industrial units.

Water quality—The deterioration of water quality in rural localities is chiefly noticed after harvest of jute and its subsequent retting to extract fibre in ponds and oxbow lakes. These surface lakes and ponds overflow after monsoon contributing to surface flow) and brings down the quality of river water. Certain ritualistic practices which are religious also hamper water quality like immersion of idols which are painted with toxic paints and decorated with plastic flowers are not bio degradable. Rivers have always played a crucial role in shaping religious rituals of civilizations and the shift should be now towards responsible reverence. Hilsa fishery is by far the largest single species fishery in the Hooghly-Bhagirathi river system and has long been important to the economic and socio-cultural heritage of the people of the entire Gangetic plains (Sajina et al., 2019; Suresh et al., 2017). Thus a decline in

Fig. 6 Stressed flora due to influx of sewage and decline in water quality

water quality will have far reaching affect on aquatic fauna especially Hilsa fishing, as well as livelihoods. Environmental Impact Assessment (EIA) for adjoining industrial sites should be strictly carried out to regulate river health and maintain water quality. Rivers banks in the study area are encroached through construction and household liquid sewage drains are directed to the R. Bhagirathi which affects water quality in the bringing in a host of problems for aquatic flora (Fig. 6) and fauna (Table 3).

6 Discussion

The modern times have however seen a rapid shift in the method of utilization of rivers and river resources. In contemporary times it is more of shift for enhancing commercial gains as waterways (transportation), dumping effluents (sanitation), for multipurpose projects (energy), irrigation (agriculture and economy). This has considerably increased the levels of pollution of river water with the pollutants entering mostly point source pre monsoon and non point source post monsoon. Usually water pollutants enter the water body by two sources: point source (single source) or a non

Table 3 Analysis of water purifying potential of R. Bhagirathi (pre monsoon and post monsoon)

Stations which contribute to maximum point source pollution	Dissolved oxygen (mg/l.)			Biochemical oxygen demand (mg/l.)			Total coliform count (MPN/100 ml.)		Faecal coliform count (MPN/100 ml.)	
	March 2021	September 2021	Saturation %	March 2021	September 2021	Saturation %	March 2021	September 2021	March 2021	September 2021
Jangipur SCS1	7.71	4.1	88.62	3.3	5.6	42.71	6000	5000	2000	1000
Jiaganj SCS2	7.43	3.2	86.40	4.5	4.8	34.04	7000	5500	2400	1800
Lalbagh SCS3	7.57	3.1	92.32	4.4	5.7	32.98	6500	4000	2000	1400
Berhampore SCS4	7.10	4.3	87065	6.0	6.5	46.74	7000	4500	2600	2000

Source Computed from field data 2021

point source (multiple sources). The river water is fit for drinking only after organized conventional purification process and advanced treatment for disinfection. In preliminary sewage treatment, the sludge is partially digested, the water is extracted before disposal. The self purifying potential of the Bhagirathi river (Table 3) (Figures S1, S2, S3) (Table S1) is however not hampered but ecological stress can lead to dwindling of aquatic life and most importantly fish species. *Hilsa, Tenualosa ilisha*, is a popular fish in northern Bay of Bengal and Hooghly-Bhagirathi river system in India (Sajina et al., 2019) which for its breeding requires maintaining of normal water quality. This particular species of fish breeds in fresh water and the Hooghly-Bhagirathi and the Padma river systems. These river systems are noted around the world to be major breeding grounds from July to October. Fishing is a major source of livelihood and the chief source of dietary protein in the study area. Comparison of the estimated catch of hilsa with the earlier reported catches indicated that the commercial fisheries of the fish in the Hooghly-Bhagirathi river system have seriously declined, highlighting the compelling need for conservation of the species and managing its fishery (Sajina et al., 2019). The gradual decline in water quality, overfishing and juvenile fishing during breeding season are of major concern for scientists and environmentalists. Besides fishing, the river water is best suited for agriculture. Roychowdhury et al. (2002) investigated total Arsenic in food composites collected from Domkol and Jalangi blocks of Murshidabad district, where groundwater forms the major source of irrigation and have found that Arsenic content is generally high in the skin of most vegetables (Chatterjee, 2017) and hence groundwater use has serious health implications.

Challenges faced by the Bhagirathi river system due to increasing pressure of population in the study area and the factors that contribute to declining river water quality are enumerated as below—

i. Excess discharge of effluents from households and minor industries. Household chemicals (floor cleaners, utensil and laundry washing detergent residues).
ii. Defecation along river banks.
iii. Narrowing of channel and eventually being lost due to deposition of washed down silt from banks and cultivation (Fig. 7).
iv. Extraction of riverine sediments excessively for building materials etc.
v. Eutrophication - It is an increased level of nutrients in water bodies. This results in bloom of Algae in water. It also depletes the oxygen in water, which negatively affects fish and other aquatic animal population).
vi. Duress to aquatic life due to discharge of diesel or spills from motor driven boats, ferry.
vii. Bank failure during monsoon and post monsoon.
viii. Retting of jute post monsoon along the rural agricultural stretches (adapted from Khatun, 2017).

Despite the growing level of pollution, untreated water is still used for various purposes, which may impact human health. Therefore, water quality assessment is essential as the initial step towards generating public awareness and aiding the planners and government authorities to conserve and manage the water bodies (Ali

Fig. 7 R. Bhairab at Daulatabad—Silted banks are used for growing crops

et al., 2021). It has been analysed that sedimentary Arsenic contaminates through irrigation where groundwater is used on soil, plants, crops affecting "human well being of Murshidabad district of West Bengal and have found that food chain provides a significant pathway to get into the human system" (Chatterjee, 2017). The R. Bhagirathi hence is a reliable source for potable water as groundwater cannot be relied upon.

7 Implications of the Study

The drainage channels in the study area flow over a region of very low elevation, intensively cropped agricultural region. As per geomorphic description the region falls under the late mature to old stage of the fluvial cycle and thus a number of abandoned channels, meanders are noticed as the drainage channels have tried to adjust their flow in response to change in channel depth with increased volume load which has to be dispersed gradually over the alluvial terrain. The flood plain is characterized by oxbow lakes, meanders, distributaries and braided channels which contribute to an unique aquatic biodiversity of the region and contribute to surface /overland flow to the R. Bhagirathi during monsoons. The multifaceted anthropogenic influences (disposal of household waste around river banks) have impacted biota and the complex interaction between them has resulted in patch ecology. The water bodies are used for retting of jute after monsoons, thereby encouraging growth of mosquito larva and constricting water flow as bunds are created to hold water and rot jute stalks to extract fibre (Fig. 6). The region attracted a considerable number of migratory birds to its oxbow lakes during winters, but over the decade these numbers and varieties are dwindling. This creates a complex chain of events and may in future affect the bio diverse faunal population in the riparian and wetland ecosystems here. River water is not only used in drinking, irrigation and domestic purposes, but also used heavily in industrial set up (Shil et al., 2019). As hilsa is a fish in high demand in the region and its fishery involves huge population of fisher folks belonging to poor economic background, strict implementation of management measures can affect fishers' livelihood (Sajina et al., 2019). The administration should also raise awareness and river water quality may be managed through extensive land use management and controlling natural ecosystem disturbances which will not hamper livelihood scopes for fishermen in the region. The fishermen adopt few coping strategies like access to the nearby wetland for fishing, diversity in earning strategy and environmental movements (Sarkar & Islam, 2021). The river "pollution induces acute ecological stress concerning declining fish diversity" (Sarkar & Islam, 2021). The awareness among residents should be raised to maintain water quality and safeguard health for all (Ali et al., 2021) because a decline in self purifying capacity of the river water would bring in far reaching health effect and groundwater is not dependable being contaminated with Arsenic. The hydrostratigraphy of the Bhagirathi sub basin comprises clay/sandy clay of 20–30 m thickness followed by a shallow aquifer within 60 m depth containing sands of various grades. Below the sand impersistent clay lenses occur which is followed by sand and then by a thick clay. The shallow aquifer at places contains high Arsenic groundwater (Chatterjee, 2017).

Impact of polluted water on human lives, animals and plant—

i. affects health (spread of vector borne disease like malaria and bacterial infection like cholera, typhoid, jaundice, diarrhea),
ii. harms the aquatic food chain,
iii. agricultural produce is affected,
iv. releases stench from un decomposed and semi decomposed accumulated organic matter.

8 Scope for Development of River Systems to Service Societies

The SDG for 2030 has Goal 6 which aims to "Ensure availability and sustainable management of water and sanitation for all" whereby it also mentions - protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes and therefore it is mandatory to protect our water resources to ensure a better quality of life for society. The GoWB has taken initiatives under its Nirmal Bangla scheme to maintain river health. More awareness drives are required to increase sensitivity of people to realizing the importance of having clean and fresh water to benefit them in health and enhance their scope for sustainable livelihoods.

9 Conclusions

The restoration of river health depends upon a number of holistic measures that need to be put into practice at administrative level. Sensitization of common man is the foremost step that should be taken. Proper disposal of polyethene wrappers, ritualistic flowers, their recycling and reuse can generate livelihoods. Bathing, washing clothes lead to dissolution of detergents. The discharge of waste water directly into the R. Bhagirathi should be prevented with the solid wastes segregated, the filtered and treated water can be re directed back to agricultural fields, washing of streets or markets and other uses.

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Environmental Perception and River Rejuvenation: A Study of the Mithi River, Maharashtra, India

Meera Ranjith and Ashwathy Ravindra Sherla

Abstract This research article is the study about the condition of the Mithi River. It is located in the Mumbai city in India. The objective of the study is to find out the problems behind the degradation of the river and the possible remedies for Rejuvenation. Data analysis shows the toxic metal components and 80–110 metrics of plastic present in the river in year 2010–2011 and the current WQI of the river is below average even during the time of Covid -19 pandemic in the year 2019–2020. The average WQI of the river is 42 but the current WQI is 22 which says the river water is neither potable nor can be used for domestic or industrial use. There were initiatives taken in the past few years by various volunteers and authorities, yet the Pollution in the river did not decrease. The major concern is the Locality and people staying near the river that are one of the root causes for the trouble. There is also lack of serious Government intervention in the problem-solving which has generated a careless behavior in people towards the Mithi River. The study focuses on what all are the problems that caused the damage to the river, what steps can be taken towards the betterment from the root causes that don't let the river be cleansed in any way and the discussion for possible and practical improvement. The study also focuses on Environmental perception and River rejuvenation of Mithi river. The research approach used in this study is quantitative, and it collects both primary and secondary data. An online survey was conducted using self-administered questions. The survey rendered 73 responses. This survey, which was conducted, contained 30 questions. The evaluation of this survey was done electronically. Anthropogenic interventions, such as the dumping of industrial affluents and agricultural runoff from on bed to off bed landuse, have been identified as the primary sources of contamination in the current study. Natural forces such as neotectonic shifts and monsoon regimes have also exacerbated the problem. The findings show that the vast majority of people are aware of the river's state and are dissatisfied with it, while a small percentage believe it is in the worst possible condition.

Keywords Mithi River · Rejuvenation · Covid-19 Pandemic · Water Pollution · Locality · Government

M. Ranjith (✉) · A. R. Sherla
Mahatma Junior College of Education, Chembur, Mumbai 400071, India
e-mail: meeraranjith@mes.ac.in

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1 Introduction

The ecological study of rivers has become increasingly important in the Anthropocene epoch, since freshwater ecosystems are increasingly endangered by widespread human interference in the form of deforestation in river catchment areas (Toham & Teuguels, 1999). In the country India, the city having highest population is the Mumbai city, in which over 20 million people migrate from other cities and states looking for opportunities and employment. There is no systematic planning done regarding the sanitation and sewage management into the city according to the population. The sewage this city produces is over 2.371 million liters of sewage every day and out of it only 2.016 million liters are sent to the STPs (Sewage Treatment Plants). There are about 2 million people and over 1.5 million tenements residing on the sides of the river who tend to pollute the river with 93% of domestic waste leaving no scope for sewage management. With the River, a part of the city that can't be separated from the city life generated by the socio–economic system, we now have a river that is humanised in some ways (Hu, 2016). Due to overpopulation and related human activities such as industrialization, deforestation, and so on give a thought to their actions are an absolute threat to all the one's having access to such river water (Trivedi, 1989). Along the river's flow, illegal operations such as washing oil/chemical drums and dumping prohibited hazardous trash are also carried out. Cattle barns generate animal waste in various regions. Sludge oil, sewage, and debris are dumped in the river by barrel cleaners, scrap dealers, and others. The river's carrying capacity has been lowered due to the dumping of organic waste, sludge, and debris. Marine life is threatened by the water, which contains a mixture of sewage and industrial trash, and the river is displaying signs of total aquatic biodiversity loss. The level of human and animal excreta that is 'fecal coliform bacteria' is found to be 180 times more than the standard level.

Rivers are generally the source of clean and safe water for all the living beings to make use for different purposes like drinking, washing, irrigation, etc. but the Mithi river's condition alongside the residential and industrial area has been influenced and put under worst conditions to face. The Mithi River runs through the K (E), H (E), and L wards. There are numerous industrial, domestic, and other point sources of garbage that contribute to the river's pollution. The translation of 'Mithi' in Hindi is 'sweet'; the Mumbai's abused, polluted Mithi river is anything but sweet.

"Urbanization is the socio-spatial metabolization of nature, or the urbanisation of the environment." This fundamental understanding of the urban process as primarily concerned with metabolic linkages is a significant intrusion into both an environmental discussion that still ignores the city as an object of its activity and an urban debate that ignores the city as a material-ecological process (Swyngedouw, 2004). Over 1500 industries and more than 3000 illegal establishments are situated around the river which contributes to 7% pollution of the river and directly discharges the waste into it. These industries consist of the small scale including oil refining, automobile washing centers, textile and dye, tanneries, etc. They not only let the solid waste into the water but also the toxic chemical water, debris, cement and concrete and more such to be released into the river. Environmental degradation and major health risks are mostly caused by deterioration in water quality, which is primarily caused by human activities such as the discharge of industrial/domestic wastes, sewage, agricultural runoffs, and the disposal of dead corpses, among others (Meitei & Patil, 2004).

As rivers become increasingly contaminated around the world, researchers have focused their attention on ecological stress factors such as biocides, pollutants, and toxic metals (Wepener et al., 1992). The sewage, chemicals and plastics only are not the matter of concern, the river is also diseased with biology pests which overall affect the ecosystem. The mineral content increase in water due to the pollution in it increasing the algal content is called Eutrophication which is used to check the level of pollution. It is not surprising that the river has shown high levels of Eutrophication. Another plant species found in it is the Water Hyacinth which blocks it and is a breeding spot for the mosquitoes. Both Eutrophication and Water Hyacinth presence can lead to oxygen depletion which kills the aquatic life and increases BOD (Biological Oxygen Demand), one of the criteria that determine the quality of water (Center for science and environment). The trend of dumping sewage, wastes, etc. into the water continues into the Mithi river as it flows down to the Arabian sea. The river however now may be the sewer for people but is very vital for the city, if preserved it works as a natural storm drainage system that prevents flooding in the city and for the congested and over-concretized city like Mumbai, chocked river means a disaster during the monsoon. The people around it choke the river by dumping solid waste and have made concrete boundaries on the banks of the river, narrowing it and reducing its drainage capacity. For the rejuvenation of the Mithi River various committees were formed to study in detail the condition of the river and provide suggestions for the improvement (Natu Committee Report, 1974). This group investigated the causes of the 1974 floods and advised pumping stations be installed around the city, particularly on Mahim Causeway, Cleveland Bunder, and Love Grove, as well as electrically controlled sluice gates, desilting, and drain upgradation. Dharavi Storm water Drainage System Report (1988) Flooding in the Dadar-Dharavi watershed basin was investigated in the paper. Rainwater gathers in Dharavi when Mahim Creek swells. It proposed a pumping station, splitting catchment areas into four zones, and elevating drainage between Dadar and Dharavi to tackle the problem. After studying the causes of flooding in 1985, the (BRIMSTOWAD) Project recommended clearing encroachments along the Mithi and Vakola rivers, widening and deepening them, modifying drainage design for higher capacity, and pumping stations at Cleveland Bunder, Love Grove, and Milan Subway to increase storm water drainage for the Mithi river catchments. However, the recommendations were mostly ignored, with MCGM implementing only roughly 15% of the recommendations (Report of NEERI, Supreme Court Case, 1996). The report described about the impact of Mangrove removal and reclamation of land in BKC area that it will lead to flooding in the area. It was recommended that environmental assessment of the area should be carried out (IIT, Bombay Report, 2006) on “Development of Action Plan for Environmental

Improvement of Mithi River and along its bank The report comprises an assessment of all environmental issues for a 200-m stretch on either side of the Mithi river, as well as the formulation of an action plan for improving the river's bank. The IIT study also includes information on water quality assessments and pollution impacts on the Mithi River and Vakola Nalla at 55 different places. Mithi River and its Surroundings Development and Protection Plan (2006) by MRDPA the report summarizes that the state of the Mithi river and the Vakola nala in terms of pollutant load, legal aspects, suggested implementation plans, public awareness, infrastructural facilities such as water supply, sewerage, SWD, solid waste management, and ecological elements are summarised in the paper. It was suggested that the Mithi River, Vakola Nala, and their tributaries, including the lands around Vihar and Powai lakes, be proclaimed a "ECOZONE" right away.

Harvey (1996) theoretical scholarship sees the city as intricately intertwined with the environment, with the former being a component of the latter, and the two working together to create the urban environment, a new configuration of development with its own set of environmental circumstances (Latour, 2005). actor-network theory analyses links between many types of players (human, nonhuman, material, or immaterial) that impact social formations, thus bringing nature and culture into play (Hinchliffe & Whatmore, 2006) build on this by arguing that cities are interfaces where human and non-human; rural–urban; civic-wild, together result in a diverse form of ecology. This rejects spatial divisions that were presented in earlier ideas and this holds true where the human and non-human; rural–urban; civic-wild, together result in a diverse form of ecology.

By understanding the problems the goal of this study is to figure out why, in this Covid-19 pandemic, where water bodies have been observed being cleaned and water quality improving, with low pollution and harmful chemicals in it because there were no human activities such as dumping garbage, factory wastes, sewage, etc. that lead to water pollution, river Mithi is still polluted and degrading as it was pre-pandemic. As a result, the focus of this research is on environmental perceptions and river rejuvenation in the Mithi River, Mumbai, Maharashtra as well as potential solutions to the problem. The study examines the characteristics for the River zone that will provide chances to enhance and improve River-adjacent communities, thereby improving the environment, improving water quality, increasing water resources, and improving the River's ecological function. As a result, the current study will be a ground-breaking attempt to create a baseline that will allow policymakers to formulate plans for river restoration and envision new research directions. Keeping this view the present work will address the following objectives:

- To investigate the reasons why the river is getting polluted.
- To know what are the problems faced by the people staying nearby the river to not being able to keep it clean.
- To analyze the possible solutions to eradicate the act of people dumping garbage, sewage into the river and maintain it.
- To study environmental perception and river rejuvenation in the Mithi river.

2 Study Area

Mumbai, the capital of Maharashtra state and India's financial centre, has grown rapidly in recent decades, thanks to its concentrated industry, trading, transportation, economics, and administration. The Mumbai City drainage system consists of a combination of open storm water drains, nallahs, and rivers in the suburbs, as well as an underground box drain system on the island (FFC, 2006). The watershed of the Mithi River is located between latitudes 19°0′15″N and 19°15′0″N, as well as longitudes 72°45′0″E–73°0′0′E. The Mithi River is a 17.84-km-long river that flows northeast to west from the hillocks of Mumbai's Vihar Lake area and meets the Arabian Sea near Mahim Creek (CWPRS, 2006; FFC, 2006) (Fig. 1). The Mumbai City drainage system consists of a combination of open storm water drains, nallahs, and rivers in the suburbs, as well as an underground box drain system on the island (FFC, 2006). The confluence of two important reservoirs or fresh water lakes, Vihar Lake and Powai Lake, creates the source site for Mithi Nadi river (Fig. 2a), and so the name "Mithi," which means "sweet." The over flow of water from the weirs of the Powai and Vihar lakes (Fig. 2b), exacerbated by the strong rainfall during the monsoon season from June to August, is the primary cause of flow in the river. The pure waters were originally the lifeline of the then-settlements along the banks, but because to the growth of the city and the government's master plan, the river's natural channel was rumpused, leaving only a basic array of owing water. The river's hydrology, geography, and overall ecology changed throughout time, threatening the river's very life.

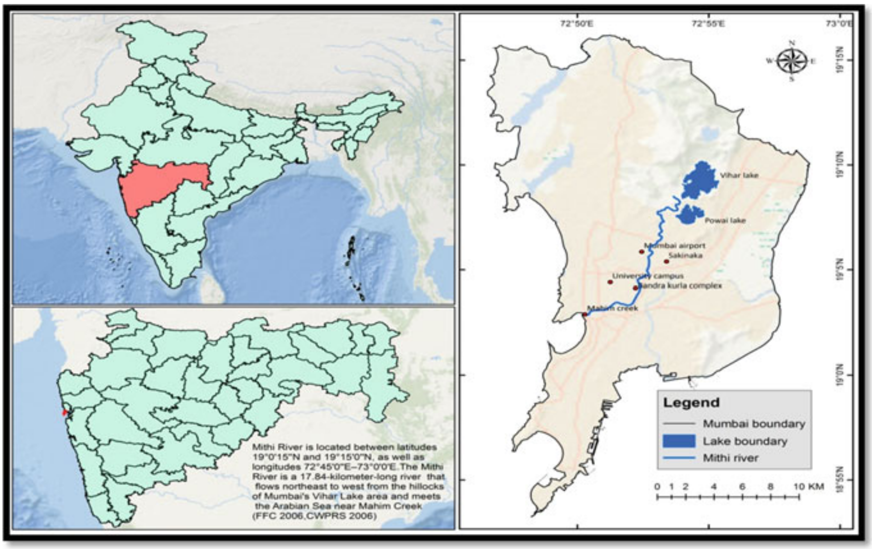

Fig. 1 Location of Mithi river on map (*Source* Urban Expansion Obsevatory, Mahatma Education society)

Fig. 2 a. Origin of Mithi river, b. Overflow of Vihar lake

Out of the five rivers (Ulhas River, Mithi River, Poisar River, Oshiwara River, and Dahisar River) that run through Bombay (Mumbai), only Mithi River has been fortunate enough to survive the turmoil of Bombay explicit, only to discover that the truth lies beneath the squander, while the others are all treated as noxious quagmire. The river flows through various industrial and residential complexes at Powai, Saki Naka, and around Santacruz airstrip, passing through densely populated and industrial areas such as Jarimari, BailBazar, old airport road, Kalina (CST road), Vakola, Bandra Kurla complex, and Dharavi, before meeting the Arabian Sea at Mahim creek (Kale Vishwas, 2006). In a battle for a sewer and storm water drain to the sea, it manipulates. The river's width is probably between 15 and 20 m in the beginning, but as it wriggles downstream, it widens to slightly more than 100 m, with a stream depth of 5.5 m (Ravi & Asad, 2006). The topography is given in Table 1 marked at four distinct segments.

The river basin includes the slopes of Borivali National Park, the Powai-Kanheri caves hill ranges, the open lands of Aarey milk colony, Bombay's suburbs, including Saki naka, the airport land, Kurla, Kalina, Andheri, Santacruz, Vile-Parle, Khar, Bandra, Dharavi, Sion, Kings Circle, Dadar, According to the BRIMSTOWAD report assessed in 1993, the river basin comprises 23 collecting systems and sub-systems, which include a group of diverse nallah3 (CWPRS, 2006). These sub-systems must be embraced because they contribute to the river's overall flow and pollutants, and they must be protected. and the most important Powai Lake, which also splurges water to meet the river at lower levels (Table 2).

Table 1 Topography of Mithi River

Sr. no	Segment	Slope	Type of Slope
1	Origin at Powai Lake boundary to Jogeshwari Vikhroli Link road	1:200	Steep
2	Jogeshwari Vikhroli Link road to Sir M.V road	1:450	Steep
3	Sir M.V road to CST Bridge	1:850	Moderate
4	CST Bridge to Mahim Causeway	1:4000	Flat

Source Ravi and Asad (2006)

Table 2 Mithi river sub-system

Sr. no	Mithi River sub-systems
1	Senapati Bapat road system
2	Industrial draining system adjoining Marol
3	Industrial draining system adjoining Saki Vihar road
4	Marol nallah system
5	Safed Pool nallah system
6	Airport north system
7	Airport south system
8	Thana cabin nallah system
9	Kalpana Kamran nallah system
10	Dadar Dharavi nallah system
11	Naik Nagar nallah system
12	Dharavi-Link road nallah system
13	Air India nallah system
14	Kolivery village nallah system
15	Sunder Nagar nallah system
16	Industrial draining system adjoining L.B.S road
17	The Vakola river system
18	The housing board nallah system
19	The Western Express Highway nallah system
20	The Kherwadi nallah system
21	The Boran nallah system
22	Industrial draining system adjoining the Bandra _yover-S.V. road junction
23	Vihar-Powai Lake system

Source Kale Vishwas (2006)

The river is a natural drainage waterway that carries excess water from overflowing lakes, storm water drains, and the catchment region during the monsoon. During the monsoon, the river swells due to rainwater entering from its catchment region. Despite the west coast's tidal influence, the river remains a drain with very low water quality. The river channel can be separated into 11 zones based on the various activities.

Because the Mithi River is exposed to tidal flows, the river's water level fluctuates significantly. Because sea water has a high specific gravity, river water swells upstream during high tide, and during low tide, the water level drops to a few feet at some points. This variance makes estimating the flow of water in such a short period of time challenging. Apart from tidal variations, flat gradients downstream of the Mithi river, and mud flats (in the eastern catchments, which cause excessive siltation), the most common causes of flooding are inappropriate levels of manmade outfalls, poor drainage channel placement, loss of holding ponds due to land development over time, increased runoff coefficient due to widespread development and paving of open areas, dilapidated drains, encroachments on drains, and enhanced siltation.

The Brihan Mumbai Municipal Corporation has split the city into 24 wards (Demographia, 2009) some of which are island districts and others are suburban districts. The Mithi River runs through all of the suburban districts, but only one island district.

Due to the change in landuse, the river course of Mithi reduced drastically. Mud flat areas which was earlier acting as holding pond, vanished completely due to infrastructural development, urbanization and unauthorized slums (Fig. 3a–c).

River course of Mithi encroached on the banks by unauthorized slums reducing the width of the river drastically.

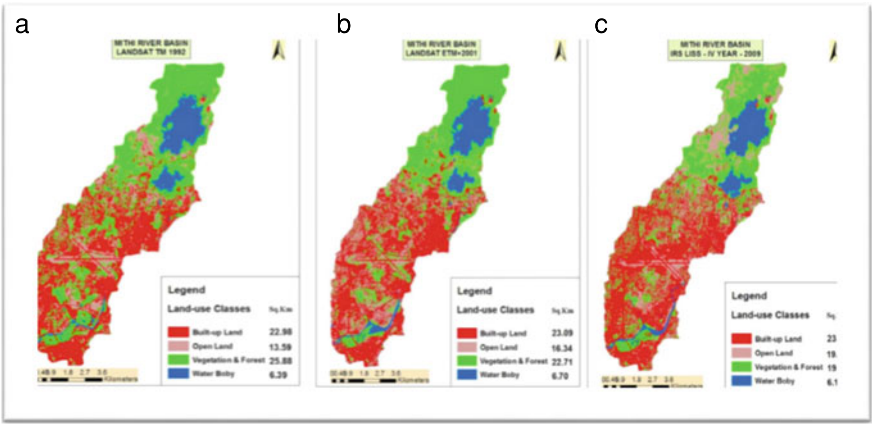

Fig. 3 Land use and Land Cover a. 1992, b. 2001, c. 2009

Fig. 4 a, b, State of pollution in Mithi river (Maharashtra Pollution Control board)

Over 1500 industries and more than 3000 illegal establishments are situated around the river which contributes to 7% pollution of the river and directly discharges the waste into it. These industries consist of the small scale including oil refining, automobile washing centers, textile and dye, tanneries, etc. They not only let the solid waste into the water but also the toxic chemical water, debris, cement and concrete and more such to be released into the river. As rivers become increasingly polluted around the world, researchers have focused on ecological stress factors such as biocides, pollutants, and toxic metals (Abdel-Satar et al., 2017; Qu et al., 2018; Wepener et al., 1992; Yarahmadi & Ansari, 2018) as well as strain factors such as energy flow and production, biomass, density, and diversity (Karaouzas et al., 2018; Smeti et al., 2019; Washington, 1984).

In 2012 a study was conducted to determine the level of heavy metals into the Mithi. And they found that all the heavy metals have exceeded the maximum permissible range (refer the below table). By this we can understand that the water is not safe for domestic as well as industrial use too, and need not mention the threat that it possesses towards the human and aquatic life. 80–110 metric tons of plastic waste is dumped into the city's drainage and water channels daily which leads to the accumulation of such solid wastes including concrete, mud etc. narrowing the banks of the river and demolishing the motive of the river which otherwise helps the city during the monsoon period.

The sewage, chemicals and plastics only are not the matter of concern, the river is also diseased with biology pests which overall affect the ecosystem. The mineral content increase in water due to the pollution in it increasing the algal content is called Eutrophication which is used to check the level of pollution. It is not surprising that the river has shown high levels of Eutrophication (Handa & Jadhav, 2015). The trend of dumping sewage, wastes, etc. into the water continues into the Mithi river as it flows down to the Arabian sea (Fig. 4a, b, Table 3).

Table 3 Water quality Status of Maharashtra 2019–20 (*Source* Water Quality Status of Maharashtra 2019–20 [Compilation of Water Quality Data Recorded by MPCB] February 2021)

Type	Station Code	Station Name	Apr	Dec/Oct	Average	District	Taluka	Village
SW	2168	Mithi River at near bridge	22	47	42	Mumbai	Bandra	Mahim
Saline	1318	Mahim creek at Mahim Bay	56	72	53	Mumbai	Bandra	Mahim
	2165	Sea Water at Gateway of India	45	57	53	Mumbai	Colaba	Colaba
	2166	Sea Water at Charni Road Choupathy	45	56	54	Mumbai	Mumbai	Girgaon
	2167	Sea Water at Worli Seaface	50	55	55	Mumbai	Worli	Worli
	2169	Sea Water at Varsova Beach	49	57	54	Mumbai	Andheri	Versova
	2808	Sea Water at Nariman Point	49	54	54	Mumbai	Colaba	Colaba
	2809	Sea Water at Malabar Hill	46	56	55	Mumbai	Mumbai	Walkeshwar
	2810	Sea Water at Haj Ali	46	54	53	Mumbai	Worli	Worli
	2811	Sea Water at Shivaji Park (Dadar Choupathy)	51	63	54	Mumbai	Dadar	Dadar
	2812	Sea Water at Juhu Beach	49	63	55	Mumbai	Santacruz	Juhugaon

Surface Water		Good to Excellent	Medium to Good	Bad	Bad to Very Bad	Dry	Not collected	No Data
Ground Water	Excellent	Good	Poor	Very Poor	Not suitable for drinking	Dry	Not collected	No Data

The above table shows the recent analysis done to determine the river water quality and we can understand by reading the table that in 2019–2020 which means that this was the time of Covid-19 pandemic and human activities like industrialization, hotels, offices, and other establishments were at pause as lockdown was imposed by the government of India. During this period many rivers and water bodies have been rejuvenated and cleansed but there is no positive change seen in the river Mithi.

3 Materials and Methods

The research approach used in this study is quantitative, and it collects both primary and secondary data (Fig. 5). Primary data is gathered by surveying residents in Maharashtra using a well-structured questionnaire created specifically for the project. There were 73 responses to the survey. Journals, books, and periodicals, authentic sites in addition to these, were considered for the study. The survey primarily focused on people's opinions, the importance of the river, and government actions, causes of pollution, initiatives by people, difference in the river in the pre pandemic and during Pandemic, contribution for the betterment of river and environment etc.

Secondary data are collected from Environment Status Report of Mumbai Metropolitan Region (MMR) March 2015, Report on Action plan for Mithi river, March 2019, Mithi River Development and Protection Authority, MMRDA. Maps and images are prepared by UXO observatory of Mahatma Education society.

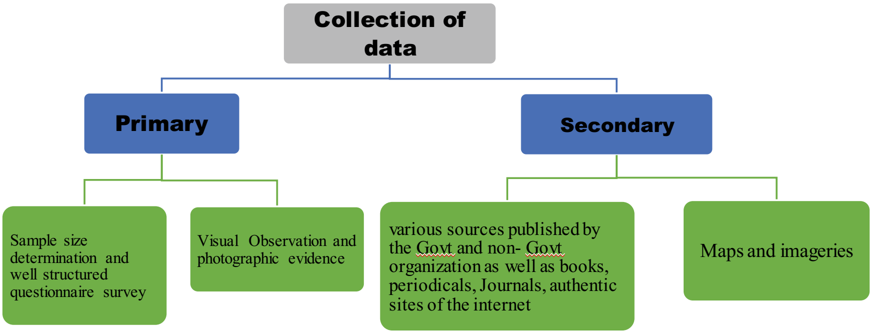

Fig. 5 Flow Chart of data Collection

4 Results

Eighty-eight percent of the 73 replies are from people aged 21 to 30. 9.6% of those between the ages of 18 and 20. The respondents are primarily from Mumbai, with the remainder from other regions of Maharashtra. Female respondents make up 53.4% of the total, while male respondents make up 46.6%. When it comes to the relevance of the Mithi river (Fig. 6a), 84.9% of Mumbai residents believe it is critical to the city's survival (Fig. 6b). 43.8% believe the river was contaminated as a result of polluting elements mixing in the air, 35.6% believe it was contaminated as a result of waste dumping, and 17.8% believe it was contaminated as a result of industrialization.

Source Online primary survey by the author, October 2021

Figure 6c 64.4% of people feel the river is contaminated because there are no rigorous rules in place to prevent it, yet 28.8% believe it is the citizens' fault, and 6.8% believe it is due to other factors. Figure 6d maintaining the river by avoiding throwing waste or sewage into it, planting trees near the river, and ceasing to live near the river are some of the actions that people living near the river can do, according to 46.6% of those surveyed. Figure 6e the majority of people (95.9%) believe that tough restrictions are necessary to safeguard waterways. Figure 6f the river was found clean during the epidemic, according to 46.6% of those polled. The statement is supported by 38.4% of respondents. Figure 6g 41.4% say there is a difference in the river during the pre-pandemic and pandemic phases, whereas 42.5% believe there is a difference between the pre-pandemic and pandemic phases. Figure 6h 67.1% are dissatisfied with the state of the river, believing it to be contaminated, and 26% believe it to be in the worst condition. Figure 6i 72.6% feel that harsh action should be taken against industries that settle near the river's bank, and 58.9% believe that large fines should be imposed on those who pollute it. Figure 6j 84.9% feel that visitors should never throw trash into rivers, 35.6% believe that raising awareness is important, and 37% believe that projects and pushes to clean up rivers should be undertaken.

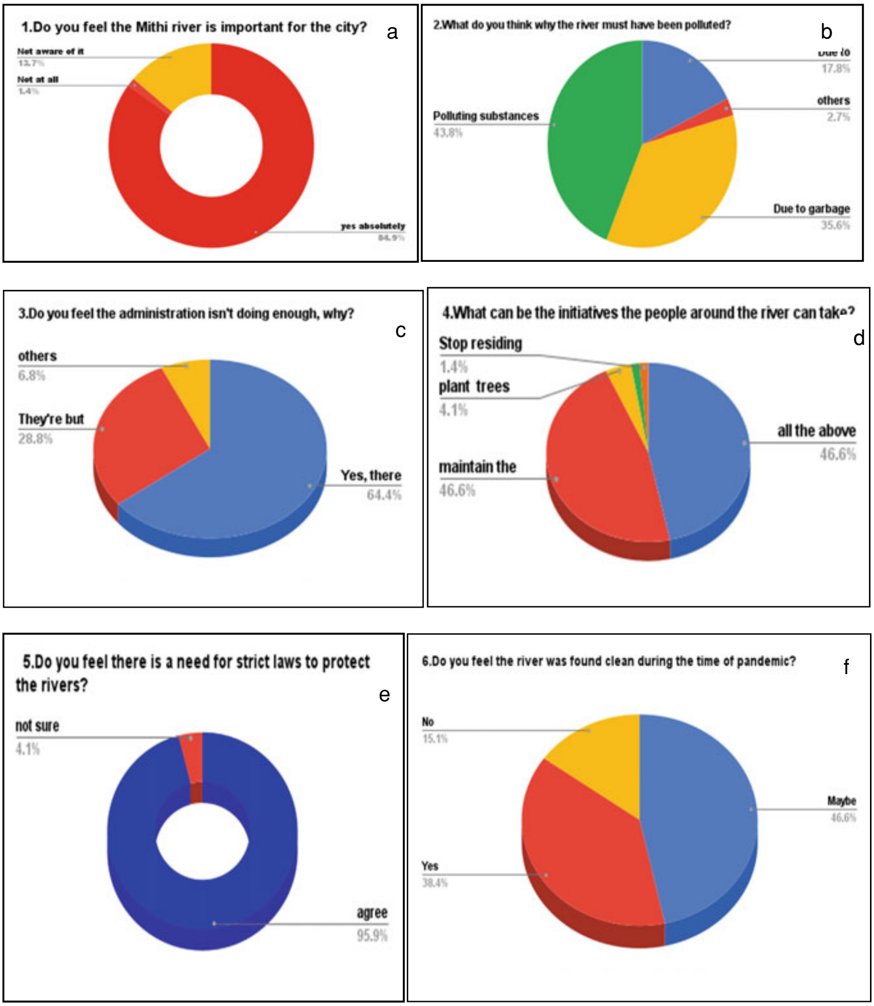

Fig. 6 a–j portray the results of online primary survey conducted in 2021 regarding the various geo-environmental dimensions of the Mithi River

5 Discussion

The phrase "River as the Soul of the City" should encourage people to help the river recover from its dangerous status and undeniably bad development. Because the functional harmony of all autotrophs and heterotrophs is largely dependent on water with all physicochemical characteristics within allowed limits, high-quality water is essential. Changing river courses to suit human needs may have resulted in a few positive developments, but it has also resulted in the eradication of the

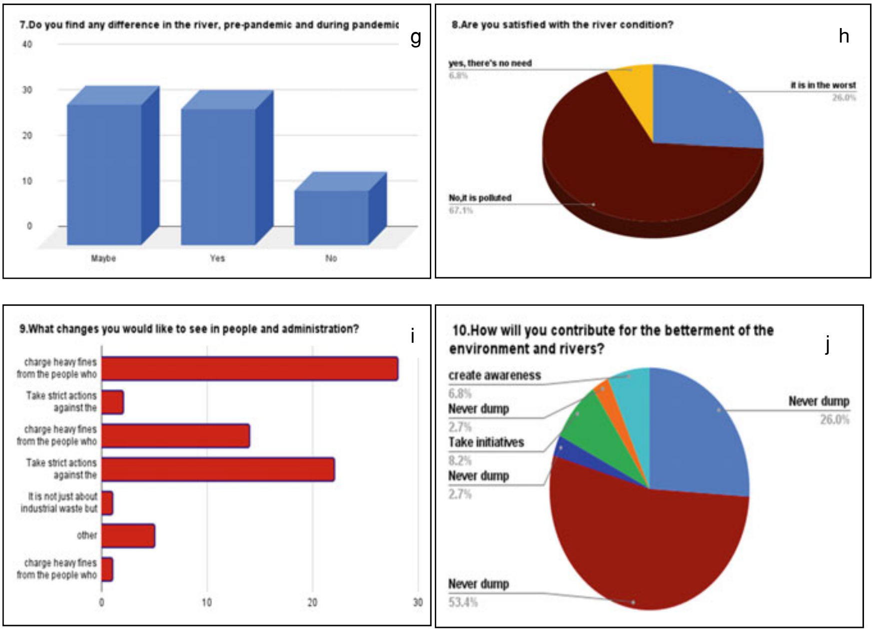

Fig. 6 (continued)

natural city system, the disappearance of aquifers, open spaces for people, and, most importantly, the extinction of numerous plant and wildlife species that help to balance the environment, which is true for all rivers. The presence of ecological functions indicates a stream's health and integrity, and restoring these ecological services in an urban stream with a changed syntax might result in serious consequences. The Mithi River has been abused and treated as a backyard atrocity, making headlines every year during the monsoons, yet the river has broken the barricade by sailing straight through, ensuring its survival. The river's dynamics have been disrupted by urbanisation, and the current pattern will make it difficult to restore Mithi's natural services.

Some of the attempts performed to clean up the Mithi river include the following: Afroz Shah, an activist and lawyer, is in charge of a group of volunteers who volunteer to clean the river. With him, the Dawoodi Bohra Community is actively involved in the deed. They also teach the people who live along the river about the dangers of dumping and the penalties of doing so, in addition to cleaning up. The founder of Beach Please, Malhar Kalambe, started a cleanup mission. This crew started working on the Mithi River in 2018 and has collected about 3800 tonnes of rubbish. In partnership with Beach Please, the NGO Project Mumbai organised a three-day campaign dubbed "Jallosh-Clean Coasts" to clean up Mumbai's waterways and beaches. The campaign drew participation from a wide range of people, organisations, and even corporations, resulting in the collecting of nearly 16 tonnes of trash. The goal of this project is to collect floating matter using a machine that will collect, sort, and recycle the garbage.

History of administration attempts: Following the 2005 floods and the resulting damage to the city, the Mithi River Development and Protection Authority (MRDPA) was founded to restore river conditions, as only then would it be useful during monsoons and floods. They spent nearly 12 billion rupees on its rehabilitation and decoration, although there were little visible changes.

Many schemes and plans have been introduced and implemented since then, including: In 2013, the National Green Tribunal ordered the closure of 239 companies that were contributing to river contamination.

In 2014, the MPCB (Maharashtra Pollution Control Board) issued closure notices to 100 industrial establishments. Around 700 small-scale industries have been instructed to close because the flow of their waste material is increasing pollution levels. Water and electricity were withdrawn for 200 industrial units operating near the Mithi in 2018. Former State Environment Minister Ramdas Kadam announced a proposal in 2019 to develop STPs and sewage pipes along the river to prevent sewage from entering the river by the end of two years, at a cost of 21 billion rupees.

6 Are There Any Areas in Which We Fail?

The Administration's Ignorance: Despite so many programmes, campaigns, and volunteer efforts to clean up and educate the community, as well as vast sums of money and resources spent on beautification, the river shows no signs of progress. This is due to ineffective administration and planning on their part, which failed to achieve the desired results. Only six meetings have been place since the MRDPA (Mithi River Development and Protection Authority) was established in 2005, the most recent being in 2010. This authority, which was created specifically to improve the river, was dormant. Because the work they planned to accomplish would take so long, people's dumping and polluting contributions would be much higher until then, resulting in the same or worse situations all around. There were no concrete activities or remedies proposed or planned to focus attention on the river in order to solve the problems at their source.

It's quite upsetting to watch a river that is so important to the city and contributes as one of Mumbai's key rivers become a sewer. It has been completely destroyed, not just as a river but also as a source of ecological destruction. If the government do not act responsibly now, we can expect the river to be lost and designated as a dangerous zone for anybody to enter.

7 The Role of Citizens

The citizens and industrialists along the river play a major role in polluting Mithi. On the daily basis there are tons of solid garbage, sewage, etc. added by them into the river. The lack of responsibility and knowledge in people about what conditions and ill-effects will be caused to the river because of them decrease the chances of the river getting to its desirable nature which impacts more than the administration's avoidance.

- The work of cleaning up the Mithi River should be taken seriously as it is the cause of floods in Mumbai, so it has to be prioritized.
- There must be STPs set up in all the industries. STPs should also be upgraded by polishing, installing quaternary treatment units.
- There must be actions taken over open defecation and solid waste dumping by building enough toilets and the concept of in-situ solid waste treatment facility should prevail in each stretch.
- In order to collect and transfer the sewage, industrial chemicals or waste water effective mechanisms must be implemented and connected for the treatment facilities.
- Cleaning and maintenance of the river on daily basis to collect fresh garbage can drastically improve the quality of water.
- The entire river including the river bed must be desludged and purified thoroughly to clean up the decomposition of garbage settled on the river bed to revive it and improve the odour.
- For the type of waste generators such as bottle washing units, laundry, scrap dealers, buffalo sheds, electroplaters particular areas should be allocated to work and dwell, equipped with environmental infrastructure facilities. The automobile and washing services should adopt zero discharge policy.
- On both sides of the river there should be a greenway developed for controlling of erosion, reducing pollution and also for beautification. The wall building along the river stretch must be avoided as it will have a rapid movement in the flow of the river causing flood.
- The action plans and movements must be discussed by the locals to make them aware and learn how to improve the conditions by monitoring and suggestions too.
- Illegal and unplanned settlements and industries up to 50 m on either sides of the river should be shut or shifted so that the river has an open space around it to revive decreasing the dumping and drainage and plant helpful plants instead, to improve the quality of the soil too.
- There must be a provision for decentralizing and segregating the solid waste, proper sewage and sanitation facilities, water network availability in slums are very crucial measures to take to provide an alternative for the people to avoid dumping. These measures are to be discussed by the concern authorities for effective implementation.

The administration is aware that the city has a huge population which is ever growing. Such a huge crowd won't think alike and have the time to make efforts or even aware about the river's situation so here the important role of administration will be to make rules and regulations in such a way that the citizen should follow those and if not done so strict punishments to be charged on people from which they cannot escape. Only then the people will be united, have the responsibility or at least out of fear of charges they end up doing nothing bad to the river. Not only imposing strict laws or rules but the administration should provide convenient facilities to dispose the trash as the area belongs to a poor socio-economic background so the administration can engage with people to help them and accordingly take initiatives against the pollution. For this the administration should work on timely basis and efficiently taking the seriousness of the matter in mind.

The citizens that stay along the river are the major source of pollution therefore the people should have the understanding of their actions and educate themselves and others and inculcate habits that are careful and positive for the river and it should be given utmost importance. The behavioral change in the community is essential to respect and maintain the river to attain sustainability. The people may even find cleaning up as a source of income so there is also a circular economy which will only develop and improve their conditions to better along with river.

It is high time to realize that the river badly needs a change and we as a responsible citizen should act quickly to get the situation under control. We are the city which has a growing population who at least should have access to a basic need which is potable water. If it doesn't happen now then we will simply be a major reason for the devastation that can happen in future, however we are already a cause of inefficiency in using our resources sustainably and disturbed our ecosystem. However this should be a wakeup call for the people to act towards conserving our nature and environment for our own well-being.

8 Conclusion

Mithi's governance is influenced by socioeconomic considerations that ignore River's natural ecological features. All of the expenditures earmarked for River revitalization have proven to be a fraud because they have failed to improve the River's conditions at any level. The Mithi River, its conservation and rehabilitation have been the focus of none of the BKC's development projects.

The nature and type of the recommendations put out reveal the meaning institutions attach with when they propose such initiatives. So, where does governance lag?

From the foregoing, we can deduce that the Mithi River is confronted with a serious and pervasive problem that needs to be investigated and addressed, not only on paper but also in practise. According to the results of the poll, 46.6% of people believe the river was clean during the pandemic. Despite the fact that many people live in the same city as the river, they are unaware of its importance, state, problems, and the threat it poses to us. So the first step toward river rejuvenation is to: (a) raise awareness of the river and its health b) explain the river's importance to the city. (c) how we, as responsible citizens of this city, should treat the river to reduce its toxicity. Then we may teach people about the numerous factors that contributed to the river's current state.

According to the survey, 67.1% of individuals are dissatisfied with the river's status, and 26% believe it is in the worst condition. We can deduce from this that the vast majority of people are aware of the river's state and are dissatisfied with it, while the remaining handful believe it is in the worst possible condition. 72.6% of people believe that harsh action should be taken against industries located near the river's bank, and 58.9% believe that large fines should be imposed on those who pollute it. Well, if we want any improvements, it should not just come from the residents' side, but also from the industries and administrations, who should take stern steps against people and industries that are endangering the river in any way. 64.4% of voters feel the river is contaminated because there are no severe rules in place to prevent it, while 28.8% believe it is the citizens' fault. To make a change in the river, we must first make a change in ourselves, so that we can recognise wrongdoings and stop them immediately, as well as consider the river as an important part in our living world and conserve it. 84.9% of respondents say they never throw trash in rivers when they visit, 35.6% believe it is important to raise public awareness, and 37% agree that projects and drives to clean up rivers should be undertaken.

The river must be considered as an ecosystem that is connected to other neighbouring systems, with diverse elements of the river—the wetlands, the edge, the floodplain, biodiversity, and other components linked to it—to be rejuvenated in its sacred approach. The assessment done for analysing the part of the river that the recommendation is assigned for showcased that some reports have highlighted or the governance machinery in the city has the knowledge which corresponds to the proper means of perceiving or imagining the river, but the UPE that tangles the process from conceptualisation to executions falls short in materialising this idea on the ground. No such considerations occupy the minds of Mumbai's bureaucracy, legislators, and courts, who have re-designated some areas in their wisdom. This difficult task can be completed by considering not only YOU and ME, but also US. The river supplies the city with drinking water, therefore this is not something that can be overlooked or changed. As a result, no single individual or organisation can bring about change; we must all work together to improve our future.

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An Integrated Assessment of Flood Risk Using Geospatial and Multi-Criteria Based Analysis: A Case Study from Mayurakshi River Basin, India

Anirban Kundu, Sayani Mukhopadhyay, and Sumit Panja

Abstract Flood is considered to be one of the most important and common hydro-meteorological events and cause damage to the social system. A heuristic framework to assess the distributive pattern of flood risk is, therefore, an essential need for policymakers. This study aims to delineate the spatial distribution of flood risk in the Mayurakshi River Basin (MRB) region using an inclusive methodological foundation of comprehending geospatial and multi-criteria techniques. Spatial distribution of 10 natural and 8 socio-economic factors contributing to flood in the MRB region have been attained to delineate the Flood Susceptibility Index (FSI) and Flood Vulnerability Index (FVI) of the MRB region using Remote Sensing (RS), Geographic Information System (GIS) and multi-criteria based Analytical Hierarchy Process (AHP). Finally, after successful inculcation of FSI and FVI, a Flood Risk Index (FRI) has been adopted to represent the spatial distinction of the intensity of flood risk in the MRB region. Results show that the lower basin region of MRB has comparatively higher FSI and FVI which in turn resulted in a higher degree of FRI concerning the middle and higher basins. The West Bengal part of MRB has 46.74% of the area consisting of very high—high flood risk compared to the 1.94% area of the Jharkhand part. This study thus tries to introduce a holistic methodological framework in the comprehensive apprehension of flood risk and after synthesizing all the results, it calls for some area-specific policy intervention for flood management in a more sustainable and radical manner.

Keywords Flood Risk · Mayurakshi River Basin · Flood susceptibility · Flood vulnerability · AHP

A. Kundu · S. Mukhopadhyay (✉) · S. Panja
Department of Geography, Asutosh College, Kolkata, India
e-mail: sayani.mukhopadhyay@asutoshcollege.in

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1 Introduction

The unprecedented nature of natural calamities has always been a concern for policymakers as it poses a direct threat to human life and disrupts the equilibrium within the social system. The degree and intensity of different types of natural calamities have become more common in recent years as a result of environmental degradation, climate change, rapid population increase, intensified and unsustainable land utilization etc. (Caruso, 2017; Dano et al., 2019). Flood is a very common hydro-meteorological calamity that causes several damages to life and properties all over the world (Adhikari et al., 2010; Das, 2020). Flooding can be described as a natural and continuous overflow of large amounts of water that happens as a result of excessive and prolonged precipitation and overflows the ground's absorption capacity as well as the capacity of rivers, streams, and coastal regions (Dano et al., 2019; Das, 2020) and over the last few decades, floods have caused significant environmental and social devastation in many places of the world (Dawod et al., 2012; Kron et al., 2012; Nied et al., 2017; Parsian et al., 2021; Rahmati, Zeinivand, et al., 2016). Therefore, a proper flood risk management strategy is indeed a profuse requirement for synthesizing a systematic blueprint to prevent flood-induced environmental, economic and social losses.

Flood risk management necessitates the collection of data on magnitude and frequency, as well as different flood conditioning variables that might induce rapid inundation during a flood (Mishra & Sinha, 2020). The term 'flood risk assessment' deals with three major aspects, i.e. risk analysis, risk assessment and risk reduction (Schanze, 2007) and this approach has gained huge popularity among researchers all over the world. The study of different natural conditions that exist within a natural system produces a considerably profound idea of flood risk within a riverine regime. Moreover, a study by White (1942) has significantly discussed the need for including human-centric conditionings within the flood management regime to distinguish the degree of vulnerability and resilience to flooding in any social system. Conversely, although, various studies have successfully implemented the flood risk assessment approach and prepared a flood susceptibility map considering different geophysical aspects (topography, lithology, hydrology etc.) of a riverine flood hazard (Janizadeh et al., 2019; Rahmati, Pourghasemi, et al., 2016; Tehrany et al., 2014; Wang et al., 2019), most of the studies have excluded the spatial distribution of human aspects and its contribution to this assessment technique. This creates a significant research gap in the discourse of preparing a holistic understanding of flood risk assessment. Furthermore, a generalized and gross idea of flood risk within an entire hydrological basin cannot depict the distributional differences of flood risk intensities due to spatial variations in flood conditioning factors. This necessitates the need for a methodological framework for a detailed analysis of spatial heterogeneity of flood conditioning factors, both geophysical and socio-economic, to depict the distributive sensitiveness of flood risk in a specific river basin area.

The Mayurakshi River Basin (MRB), located in the eastern part of India has a very long history of flooding of more than 200 years and has always been a major concern for policymakers with respect to a proper flood risk management strategy. It has been of utmost necessity to promote an integrated flood management strategy by analysing risk factors of humans, like estimated damage analysis, livelihood impact analysis, community-based perception analysis etc. (Juarez Lucas & Kibler, 2016; Okazumi et al., 2014; Osti et al., 2008) with a blend of detailed geophysical factors to apprehend a holistic flood risk management strategy in the region. Although, in India, different studies have tried to assess flood risk by considering both physical as well as human aspects (Das, 2020; A. Ghosh & Kar, 2018; Shivaprasad Sharma et al., 2018), no such detailed work been done yet in the Mayurakshi River Basin area. There have been either numerical modeling studies (K. G. Ghosh & Pal, 2015; Islam & Sarkar, 2021; Mondal & Pal, 2018; Pal, 2016) of geophysical and meteorological aspects or purely sociometric analysis of human perception (Mukhopadhyay & Mukhopadhyay, 2018). Therefore, this study aims to delineate the geospatial distribution of different natural and socio-economic conditions of flooding, which exists within the MRB region and tries to integrate them within a multi-criteria-based framework to apprehend a comprehensive understanding of flood risk in the region. The specific objectives of this study are as follows:

i. To depict the geospatial distribution of physical and socio-economic factors to flooding in the MRB region.
ii. To comprehend the different natural and socio-economic factors of flooding under a multi-criteria framework for a detailed understanding of flood susceptibility and flood vulnerability respectively in the MRB region.
iii. To systematically combine the idea of flood susceptibility and flood vulnerability into a heuristic foundation to synthesize an integrated idea of the distributive pattern of flood risk in the region (Fig. 1).

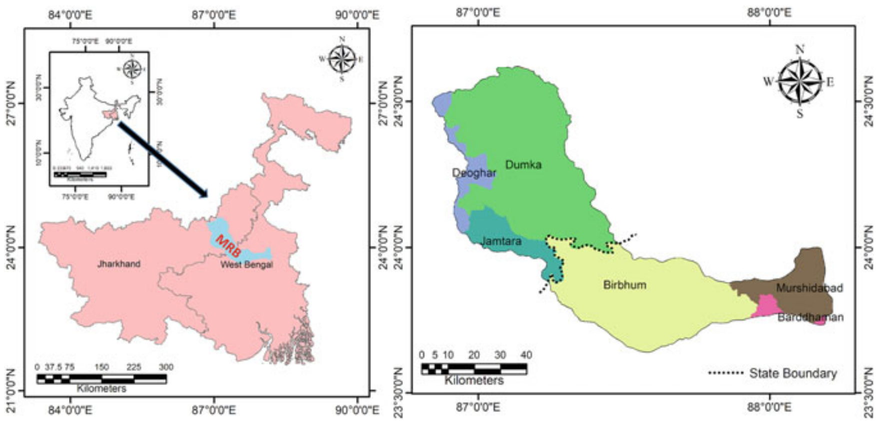

Fig. 1 The study area

2 Study Area

The Mayurakshi River Basin (MRB), extended within 86°50'E–88°10'E longitude and 23°30′N–24°35′N latitude, is one of the major river basins of eastern India. The major constituent river of the basin is the Mayurakhsi river, a 288 km long 5th order rainfed tributary (Pal, 2016) of Ganga-Bhagirathi River and is infamous for its long and widespread history of flooding (Mukhopadhyay & Mukhopadhyay, 2018). The western and north-western part which mainly consists of the upper and a part of the middle basin of MRB, is located in the Dumka, Jamtara and Deoghar districts of Jharkhand and the south-eastern part (consisting mainly the lower basin) is located in the Birbhum, Murshidabad and Barddhaman districts of West Bengal. The MRB region falls under the subtropical monsoon climate and the average annual rainfall is almost 150 cm. 80% of the rainfall in the region happens during the monsoon season, hence the rivers swell up and inundate the surrounding floodplains (Pal, 2016). Although the Massanjore Dam (constructed in 1954) and the Tilpara Barrage (constructed in 1976) have been developed as an engineering management measure to cope with the devastating floods, the situation has not been developed as it was estimated rather different scholars (K. G. Ghosh & Pal, 2015; Mukhopadhyay & Mukhopadhyay, 2018), in their work, have even adhered to the role of these dams and barrages as responsible elements of flooding in the MRB region in later decades. The major and noteworthy documentations of floods in the regions have been of the years 1870, 1885, 1890, 1904, 1907, 1924, 1931, 1932, 1933, 1934, 1951, 1956, 1959, 1961, 1968, 1971, 1978, 1986, 1989, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2003, 2004, 2006, 2007, 2013 and 2015 (Islam & Sarkar, 2021). These frequent flood events diminish mostly the primary economic activities (especially agriculture and animal husbandry) and benumb the socio-economic condition severely.

3 Materials and Methods

3.1 Materials

The entire study has been conducted by comprehending several causative factors (discussed in Table 1) responsible for flood in the MRB region. To assess the geospatial distribution of each factor, thematic layer of every individual factor was created. For evaluating topographical and hydrological parameters, Digital Elevation Model (DEM) of Shuttle Radar Topographic Mission (SRTM) has been acquired from USGS Earth Explorer repository (https://earthexplorer.usgs.gov/). SRTM-DEM has moderate (30 m) spatial resolution and they have been effectively used for depicting flood susceptibility in different studies (Das, 2020; Demirkesen et al., 2007). Average annual rainfall data for 30 years (1991–2020), at a spatial resolution of 30″ × 30″ have been downloaded from https://www.worldclim.org/. For delineating the Land Use Land Cover (LULC), global LULC dataset for the year 2020 has been extracted from https://www.arcgis.com/home/item.html?id=d6642f8a4f6d4685a24ae2dc0c73d4ac. This LULC dataset are of 10 m spatial resolution and the output has 86% overall accuracy (Karra, 2021). For assessing the lithological (soil) parameters, the soil map of South Asia has been downloaded from FAO Soils Portal (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/). For delineating different vulnerability parameters, village-wise socio-economic data has been accessed from https://sedac.ciesin.columbia.edu/ and major road network has been downloaded from Open Street Map (https://www.openstreetmap.org/#map=5/21.843/82.795) repository.

3.2 Methodology

3.2.1 Preparation of Thematic Layers for Flood Susceptibility

Most of the preparation of thematic layers of causative factors has been done in the ArcGIS 10.5 environment. Downloaded SRTM-DEM images were first processed using the 'Fill' tool and next the 'Elevation' and 'Slope' map was prepared. Thereafter, the drainage network in the study area was extracted using the 'Hydrology' toolbox and 'Flow accumulation' map, 'River density' map and 'Distance from river' map were prepared using the 'Flow accumulation', 'Line Density' and 'Proximity' tool respectively. 'Topographic ruggedness index' and 'Topographic wetness index' map were prepared using the 'Raster calculator' tool and the following Eq. (1) and (2) respectively (Table 2).

Next, the downloaded LULC maps were masked according to the study area and were resampled to 30 m spatial resolution. For generating the 'Average annual rainfall of 30 years' map, a new raster layer of average annual rainfall of 30 years was prepared using the 'Raster calculator' tool from the extracted rainfall maps and the newly prepared raster was masked and resampled to 30 m accordingly. The vector layer of the soil dataset of South Asia was also clipped out according to the MRB region and was finally converted to raster layer of 30 m spatial resolution using the 'Features to raster' tool.

3.2.2 Preparation of Thematic Layers for Flood Vulnerability

The village-wise socio-economic data downloaded earlier were of vector format and they were clipped according to the study area. Then, the vector layers for individual flood vulnerability parameters were prepared. All the vector layers were then transformed into raster layer of 30 m spatial resolution using the 'Features to raster' tool and finally the raster layer of each indicator of flood vulnerability was prepared.

Table 1 Different parameters used in the study for discerning flood susceptibility and flood vulnerability

Major realm of flood risk assessment	Sub-realm	Parrameters	Time
Flood susceptibility	Topography	Elevation (m)	–
		Slope (°)	–
		Topographic ruggedness index (unitless)	–
	Hydrology	Distance from river (m)	–
		River density (km/km^2)	–
		Topographic wetness index (unitless)	–
		Flow accumulation (unitless)	–
	Meteorology	Rainfall (30 year annual average) (mm)	1991–2020
	Land management	Land use land cover	2020
	Lithology	Soil	1980
Flood vulnerability	Exposure	Village-wise distribution of population density (person/km^2)	2011
		Distance from major road network (m)	2020
		Village-wise distribution of child (0–6 years of age) population (number)	2011
	Sensitivity	Village-wise distribution of people engaged in agriculture (%)	2011
		Village-wise distribution of ratio between non-working and working population (unitless)	2011
		Village-wise distribution of female literacy (%)	2011
	Adaptive capacity	Village-wise distribution of literate population (%)	2011
		Village-wise distribution of female work participation (%)	2011

Table 2 Equation used in the study to determine Topographic Ruggedness Index and Topographic Wetness Index

Parameter	Equation used**	
Topographic Ruggedness Index (TRI) (Riley et al., 1999)	$TRI = Y\left[\Sigma\left(x_{ij} - x_{00}\right)^2\right]^{1/2}$	(1)
Topographphic Wetness Index (TWI) (Sørensen et al., 2006)	$TWI = \ln \frac{a}{\tan b}$	(2)

[** x_{00} = elevation of the cell selected for calculating TRI, x_{ij} = elevation of each neighbourhood cell of x_{00}, a = local upslope area draining through a certain point per unit contour length, tan$b$ = local slope in radian]

3.2.3 Delineation of Relative Weightage of Individual Parameter of Flood Susceptibility and Flood Vulnerability Using Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), originally formulated by Saaty (1987), is a multi-criteria decision-making tool that incorporates the relative importance of all the factors responsible for a particular event and using a comparative prioritization technique, it discerns the relative weightage of the factors in the execution of the event. AHP model relies on all the criteria and is subjective to marginal input (Das, 2020). The AHP model incorporates all the causative factors, finds out the relative weightage of them and finally, using a weighted-aggregated system, it perceives the comparative ranking of all the alternatives. Therefore, it is considered to be one of the most important tools in the study of distinguishing spatial variability of hazard or disaster risk.

The implementation of AHP in this study has been done using the following steps:

First, all the 10 parameters responsible for flood susceptibility evaluation in the MRB region were tabulated in a 10 × 10 matrix. Next, the relative importance of each parameter with respect to another one was assigned (with the help of experts' opinions in the field of regional planning and hazard and disaster management) using the relative importance score formulated by Saaty (1987) (Table 3). Finally, after synthesizing the relative importance of all the parameters, the comparative weightage was generated. The consistency in the weightage scheme has also been calculated using Eq. (3) formulated by Saaty (1987) (Fig. 2):

$$\text{Consistency Ratio} = \frac{\text{Consistency Index}}{\text{Random Index}} \tag{3}$$

where,

$$\text{Consistency Index} = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

Table 3 Scale of relative importance of one parameter over other, after Saaty (1987)

Intensity of relative importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between two adjacent judgements

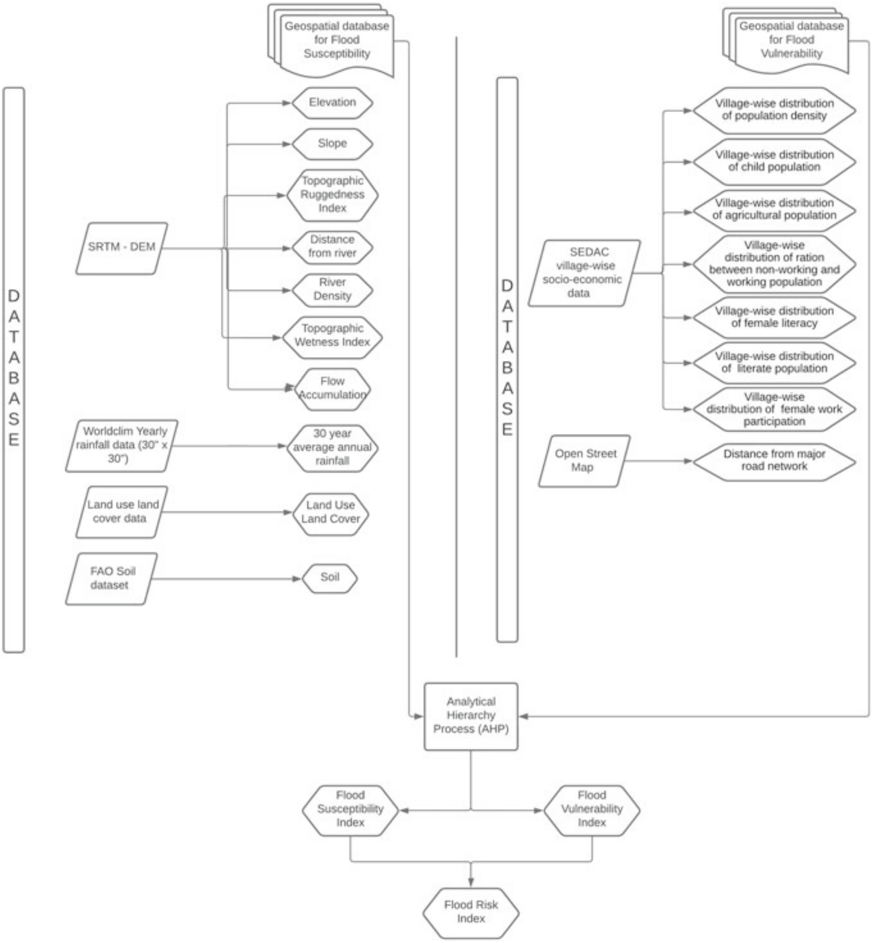

Fig. 2 Methodological framework of the study

Table 4 Random Index table propounded by Saaty (1987)

n	1	2	3	4	5	6	7	8	9	10
Random Index	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

where λ_{max} = the principal eigenvalue of the matrix and n = number of parameters. The random index has been defined by Saaty (1987) as a constant number specified for a corresponding number of parameters. In the AHP process for flood susceptibility parameters, the random index has been chosen as 1.49 due to the incorporation of 10 parameters (according to Table 4).

After acquiring the weightage of each parameter of flood susceptibility, the same process was repeated for the sub-classes of each 10 parameters individually. Thus the weightage value (W_i) for all 10 flood susceptibility parameters and the risk value (R_i) for all the individual sub-class of each parameter was generated. The same process was then applied and W_i for the 8 parameters selected for flood vulnerability and R_i for all individual sub-class of each flood vulnerability parameter were engendered.

3.2.4 Mapping of Geospatial Distribution of Flood Susceptibility, Flood Vulnerability and Flood Risk

After obtaining the relative weightage of individual parameter and individual sub-classes, the final objective was to prepare a flood susceptibility and flood vulnerability map in a weighted-aggregated manner using the formula (5) and (6) respectively (as mentioned by Das(2020) and IPCC (2007) respectively):

$$\text{Flood susceptibility index (FSI)} = \sum W_i^S \times R_i^S \tag{5}$$

$$\text{Flood vulnerability index (FVI)} = (\text{Exposure} + \text{Sensitivity}) - \text{Adaptive Capacity}) \tag{6}$$

where,

$$\text{Exposure} = \sum W_i^{\text{Exposure}} \times R_i^{\text{Exposure}} \tag{6.1}$$

$$\text{Sensitivity} = \sum W_i^{\text{Sensitivity}} \times R_i^{\text{Sensitivity}} \tag{6.2}$$

$$\text{Adaptive Capacity} = \sum W_i^{\text{Adaptive Capacity}} \times R_i^{\text{Adaptive Capacity}} \tag{6.3}$$

where $W^S{}_i$ denotes relative weightage for flood susceptibility parameter, $R^S{}_i$ denotes risk value of sub-class of flood susceptibility parameter, W_i^{Exposure}, $W_i^{\text{Sensitivity}}$ and $W_i^{\text{Adaptive Capacity}}$ represent relative weightage for flood vulnerability parameter depicting exposure, sensitivity and adaptive capacity respectively and R_i^{Exposure},

$R_i^{\text{Sensitivity}}$ and $R_i^{\text{Adaptive Capacity}}$ represent risk value of sub-class of flood vulnerability parameter depicting exposure, sensitivity and adaptive capacity respectively. This step was achieved using the weighted linear sum method in the ArcGIS 10.5 environment. The FSI and FVI maps were further normalized and rescaled to 0–1 for ease of understanding and were classified into five intensity zones ('Very High', 'High', 'Moderate', 'Low' and 'Very Low').

Finally, flood risk has been identified as the function of flood hazard to flood susceptibility by Das (2020) and it has been depicted as a product of flood susceptibility and flood vulnerability using Eq. (7):

$$\text{Flood Risk} = \text{Flood susceptibility index} \times \text{Flood vulnerability index} \quad (7)$$

Using the following equation, the flood risk map of the MRB region was generated using the 'Raster calculator tool in ArcGIS 10.5 environment and the spatial heterogeneity of flood risk in the MRB region was discerned.

4 Geospatial Inventory of Different Causative Factors Responsible for Flood Susceptibility and Flood Vulnerability

4.1 Flood Susceptibility Factors

For a detailed analysis of the geospatial distribution of flood susceptibility, it is quite important to determine the major causative factors that influence flood conditioning. Because of their dynamic nature, the influencing factors, that make a region susceptible to flood, tend to change from place to place and the selection of the proper causative factors under a definite hydrological regime is a major pre-requisite for a complete understanding of flood susceptibility. After a detailed analysis of several literatures, 10 causative factors, that try to encompass five major aspects of the physical environment responsible for flood susceptibility, have been selected for the MRB region. Selected physical factors and their corresponding environmental aspects have been discussed in Table 1.

4.1.1 Topographical Factors

Elevation

Elevation is considered to be the most influencing factor for flood susceptibility. Due to its intrinsic nature, water always tends to flow from the upper to lower elevated

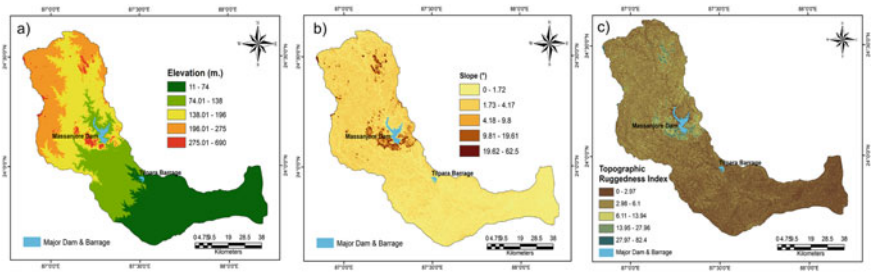

Fig. 3 Spatial distribution of a) Elevation; b) Slope and c) Topographic Ruggedness Index in the MRB region

region and finally accumulates in the lower elevated region causing flood. The elevation of the MRB region (Fig. 3a) generally extends from north-northwest to south-southeast. The extreme north and northwestern part of the study area falls under the elevation of 196.01–275 m, followed by the elevation of 138.01–196 m. Due to the presence of the Chotonagpur Plateau, the elevation of the upper course of the Mayurakshi river is generally high compared to its lower course, hence, most of the part of the lower course falls under the elevation range of 11–138 m.

Slope

The surface gradient thoroughly determines the nature of the flow of water. Flood susceptibility is largely determined by the velocity of water flow as well as the amount of infiltration rate, and these two factors have a positive and an inverse relation with the surface gradient respectively. Therefore, slope can be considered as an important indicator for flood susceptibility. In case of the MRB region, the slope map (Fig. 3b) shows that the lower gradient values (0°–1.72°) are mostly distributed along the south, south-eastern part of the region, whereas the moderate to higher sloping values (1.73°–9.8°) are along the north, northwestern part.

Topographic Ruggedness Index (TRI)

According to Riley et al. (1999), the Topographique Raggedness index is the square root of the summation of the squared difference of elevation of a specific DEM cell and its corresponding 8 neighborhood cells. TRI has an intrinsic relationship with the slope of the ground and lesser TRI implies a gentle slope with lesser fragmentation and vice-versa (Swain et al., 2020), hence it can be considered as a very good indicator for flood susceptibility. Figure 3 shows that the Slope map, as well as the TRI map, has a very close relationship within them and the lower TRI (0–2.97) can be seen mostly along the south and south-eastern part of the MRB region. Such a lower distribution

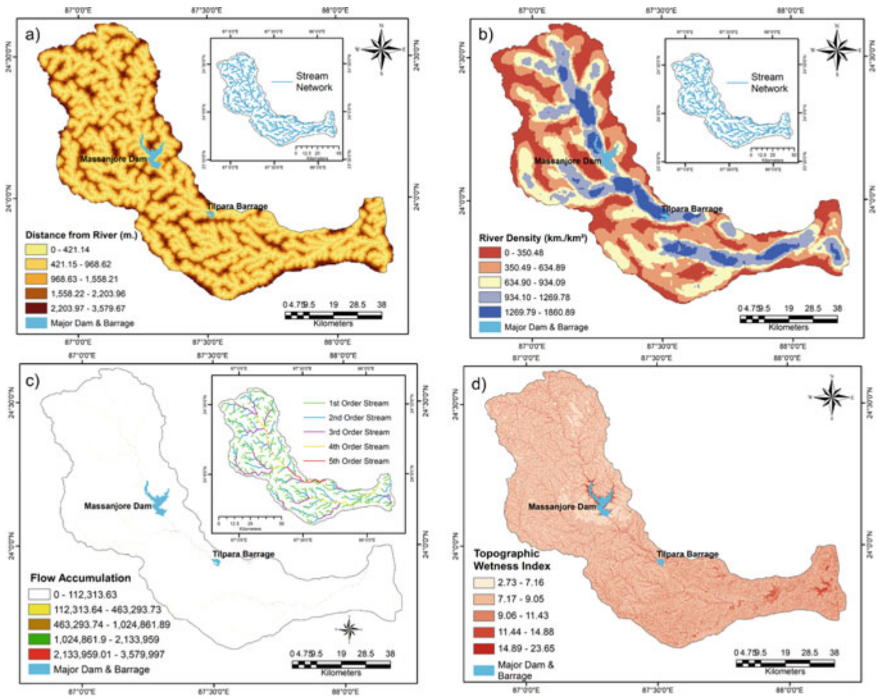

Fig. 4 Spatial distribution of a) Distance from river [Inset: Major stream network]; b) River density [Inset: Major stream network]; c) Flow accumulation [Inset: Distribution of different orders of streams] and d) Topographic wetness index in the MRB region

of TRI values makes the south-southeastern part of the region more susceptible to flood.

4.1.2 Hydrological Factors

Distance from River

There is a universally accepted fact that nearness to river always has a positive relationship with flood susceptibility. The expansion of a flood event is critically controlled by the nearness to river and the more any region is near to river, the more it will be susceptible to flood and vice versa. Interestingly, no universally accepted critical value of flood susceptibility, in case of distance from river has been still addressed. Das (2020), in his study, selected 500 m as the most vulnerable zone to flood susceptibility in the rivers of Western Ghat, likewise, we also have selected 0–421.14 m as the most vulnerable zone to flood susceptibility. Figure 4a shows the different regions situated at varying distances from the major stream networks in the MRB region.

River Density

River Density is the sum of all channel lengths in a unit area. Regions having higher River Density are already experienced by greater degree of surface runoff, hence they are more susceptible to flood events. The lower catchment area of a river basin has more amount of stream networks with varying orders. Therefore, the River Density in the lower catchment is higher compared to the upper catchment areas. The lower catchment, especially the south-eastern part of the MRB has a relatively higher River Density (634.90–1860.89 km/km^2). On the other hand, most of the upper catchment areas fall under the lower River Density classes (0–634.89 km/km^2) (Fig. 4b).

Flow Accumulation

Flow accumulation can be defined as the total flow received from upstream to a particular point of interest in the catchment area and it has been adroitly used in several studies (Das, 2020; Dou et al., 2018; Weerasinghe et al., 2018) to determine flood susceptibility. A higher amount of flow accumulation certainly indicates a higher tendency of accumulation of water within a specific point which in turn stipulates a higher probability of flooding. In the MRB region, maximum flow accumulation can be observed in the lower basin region (Fig. 4c). Due to the prevalence of two major reservoirs i.e. the Massanjore Dam and the Tilpara Barrage, the lower basin obtains more water compared to the upper basin. This makes the lower basin more susceptible to flooding.

Topographic Wetness Index (TWI)

TWI is an index for predicting areas susceptible to producing a higher degree of overland flow. As TWI is the ratio between local upslope area and local slope (Sørensen et al., 2006), it can significantly represent the hydro-geomorphology of landscape (Das, 2020). Therefore, it can effectively discern the tendency of flooding within a floodplain area and a higher amount of TWI will certainly indicate a higher susceptibility to flooding. Figure 4d shows that most of the higher values of TWI in the MRB region are concentrated in the south-eastern part which in turn makes this area more susceptible to flood.

4.1.3 Meteorological Factors

Among different meteorological factors, rainfall is the most direct and influencing factor that is responsible for floods in any region. A higher amount of rainfall certainly indicates a higher amount of overland flow as well as a higher chance of flooding. The 30-year average annual distribution of rainfall in the MRB region (Fig. 5a) shows the southern part of the region receives the most rainfall (>1293.01 mm) and there is

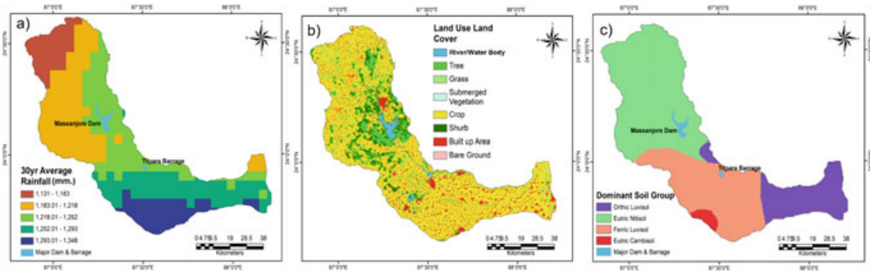

Fig. 5 Spatial distribution of a) 30 year average annual rainfall; b) Land use land cover and c) Dominant soil group in the MRB region

a continuous decrease in the amount of rainfall from the south to north. The north-western part receives the least amount of annual average rainfall (1131–1183 mm).

4.1.4 Land Management Factors

According to Yalcin et al. (2011), different land use land cover (LULC) have a different amount of control on several hydrological processes (i.e. infiltration, leaching, surface runoff, evapotranspiration etc.) and therefore, LULC of a basin is indeed a significant factor in depicting flood susceptibility. Waterbodies are mostly susceptible to flood followed by built-up areas (due to the adequate presence of impervious surfaces that increases surface runoff), agricultural land (due to moderate amount of surface runoff and evapotranspiration) and vegetative land (due to very less amount of surface runoff and high amount of evapotranspiration). The MRB region is mostly comprised of cropland with scattered built-up areas along the entire basin (Fig. 5b). The Mayurakhshi Dam and the Tilpara Barrage are the two most important water bodies. Several water bodies can also be observed along the southern part. Some amount of trees, grass and shurbs can also be observed surrounding the Mayurakshi Dam and along the northern part. Very less amount of submerged vegetation and bare ground can be observed.

4.1.5 Lithological Factors

Soil characteristics play a pivotal role in hydrological events that in turn control the extent and intensity of flood events. The texture and constituent elements of any soil group control the amount of infiltration and runoff, hence controlling water flow over it. The MRB region consists of 4 major soil groups (i.e. Orthic Luvisol, Eutric Nitisol, Ferric Luvisol and Eutric Cambisol) as propounded by FAO. The north-western part of the MRB is consists of Eutric Nitisol, the western and southern region is composed of Ferric Luvisol. The south-eastern part and a small patch of the middle part have orthic Luvisol and a very small patch of Eutric Cambisol is located in the extreme south. Nitisol has the maximum water drainage system compared to the others followed by Cambisol and Luvisol. Thus the areas with Nitisol are less susceptible whereas the areas composed of Luvisol is most susceptible to flood.

4.2 Flood Vulnerability Factors

Environmental factors contributing to flood hazards alone cannot depict a comprehensive understanding of flood risk. In the discourse of Flood Risk Management, the incorporation of different social and economic factors are essential for distributional justice (Johnson et al., 2016). Such inclusion of socio-economic indicators will amalgamate the dimension of the man-nature relationship in the sphere of Flood Risk Management, which will help to produce a socially just policy. From a generalized standpoint, vulnerability can be defined as the internal risk factors of any subject or a system that is exposed to a hazard and corresponds to its intrinsic tendency to be affected or susceptible to damage (Cardona, 2003). More specifically, IPCC (2007) has defined social vulnerability or inherent vulnerability of any system or society as the function of three major aspects or sub-realms (i.e. Exposure, Sensitivity and Adaptive Capacity) of the society that exists within the social system. After an extensive review of literature, 8 indicators have been chosen under the aspects of these three sub-realms to understand the socio-economic vulnerability to flood in the MRB region. The detailed analysis, as well as the spatial distribution of the selected 8 socio-economic indicators, have been discussed below.

4.2.1 Factors Affecting Exposure to Flood

Exposure, in the study of flood vulnerability, can be defined as the predisposition or the tendency of any system to be affected by flood. 3 major socio-economic parameters (i.e. population Density, Distance from Road and Number of child population) have been selected to indicate the exposure to flood in the MRB region.

In any flood-affected area, the most affected components are the people living in that area, therefore, areas with high population density are most vulnerable. Figure 6a shows that the highest population density (>743.89 person/km^2) in the MRB region is along the south-eastern part (mainly the lower basin area). Moreover, Fig. 7a shows that 29.27% and 26.82% of the West Bengal part of the MRB region falls under 'Very High' and 'High' population density. Therefore this region is more exposed to flood. On the other hand, most of the Jharkhand part of MRB falls under 'Low' and 'Moderate' population density classes, which makes this part comparatively less exposed.

Road network indeed augment accessibility and connectivity and therefore, it plays a crucial role in the development and expansion of human settlement. People always tend to built settlements as close as possible to roads. Conversely, during any flood event, road network gets inundatad, hence, areas located nearer to road

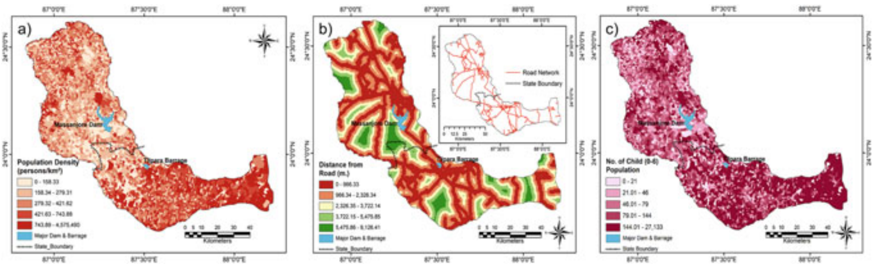

Fig. 6 Spatial distribution of a) population density; b) Distance from road [Inset: Major road network] and c) Number of child population depicting exposure to flood vulnerability in MRB region

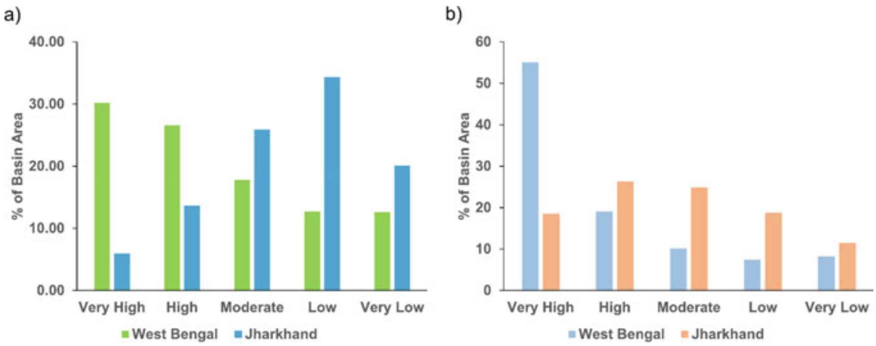

Fig. 7 Statewise areal distribution (%) of different classes of a) Population density and b) Number of child population

network are more vulnerable to flood. Figure 6b reveals the distribution of areas located in different distance classes from road networks in the MRB region and areas surrounding the Massanjore Dam and the Tilpara Barrage are located in the least distance class (0–966.33 m).

Finally, the third component depicting flood exposure is the number of child (0–6 years of age) population. The population of the age group of 0–6 years is the most dependable one and they can't make their own decisions during any disaster event. Moreover, biologically they don't have enough strength to adapt to any vulnerable situation. Such inability and dependency on elderly people make them more exposed to hazards. The village-wise distribution of the child population in the MRB region (Fig. 6c) depicts that villages in the lower basin area (south and south-eastern part) have more child population. Even, more than 50% of the villages of West Bengal part of MRB falls under the 'Very High' Child Population class (>144 childs), hence, this area becomes more exposed to flood vulnerability.

4.2.2 Factors Affecting Sensitivity to Flooding

Sensitivity of any social system to flooding is the degree to which the system is either detrimentally or propitiously affected by flood events. 3 parameters (i.e. People engaged in Agriculture, Ratio between Non-working and Working population and Female Literacy rate) have been selected to determine the spatial diversity of sensitivity to flooding in the MRB region.

The most important economic activity in the MRB region is agriculture and its been well depicted earlier in Fig. 5b. Therefore, during any flood event, when croplands get inundated under flood water, people engaged with agriculture become most vulnerable. Hence, villages with more percentage of agricultural workers are more adversely affected. The villagewise distribution of the percentage of people engaged in agricultural activities (Fig. 8a) is more in the upper basin part (Jharkhand part in the north-west) of the MRB region and they are most sensitive towards flood events. On the contrary, the West Bengal part falls in the 'Moderate' to 'Low' class which makes them more economically diverse and less sensitive to flood events.

Economic wellness and economic dependency is the next important factor that reflects the ability of the population to overcome the distressing situation of any hazardous event. Per capita income is the most suitable parameter to reflect such economic soundness and it has been used in several studies (Chun et al., 2017; Saleem, 2013) to depict the sensitivity to flooding. Due to the lack of spatial data in per capita income along the MRB region, a proxy parameter i.e. ratio between non-working and working populations has been chosen for depicting sensitivity to flooding. More the ratio between non-working and working populations, more the economic dependency, more the sensitivity to flooding. Figure 8b shows that the extreme eastern part of the MRB region (West Bengal part) lies in the 'Very High' (>2.05) class, hence this part is more vulnerable compared with other areas.

Women empowerment is another key social factor that enhances the sensitivity of any society toward hazard management in a propitious manner. In a patriarchal society like India, key decisions in the family is mostly taken by men. On the other hand, the academic ability of the female in the family makes them more robust and purposive in decision-making and a conscious decision taken by both the men and

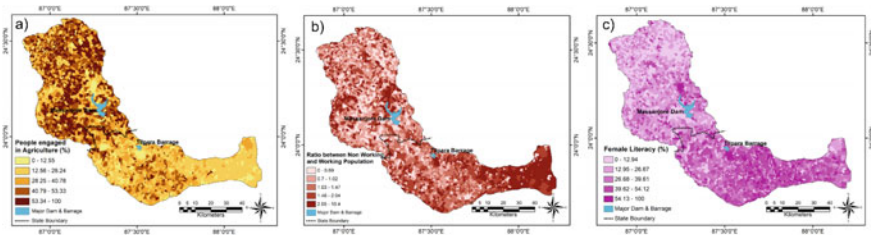

Fig. 8 Spatial distribution of a) People engaged in agriculture (%); b) Ratio between non-working and working population and c) Female literacy rate (%) depicting sensitivity to flooding in MRB region

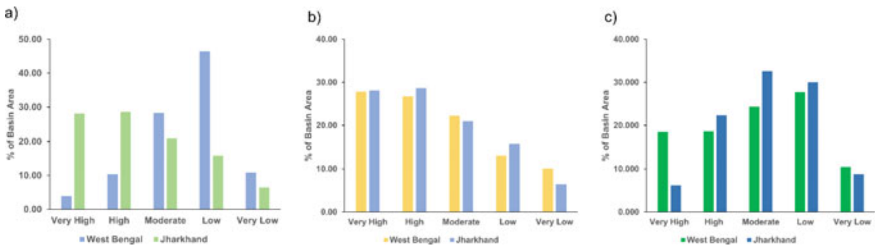

Fig. 9 Statewise areal distribution (%) of different classes of a) People engaged in agriculture (%); b) Ratio between non-working and working population and c) Female literacy rate (%)

women in the family can be considered as more rational in managing any precarious event. The village-wise distribution of the percentage of female literacy in the MRB region Fig. 8c shows a larger portion of the Jharkhand region lies in the 'Moderat' and 'Low' classes. Moreover, the amount of the 'Very High' class is also more in the West Bengal part compared with the Jharkhand part of the MRB region (Fig. 9c).

4.2.3 Factors Affecting Adaptive Capacity to Flood

In the process of delineation of hazard and disaster vulnerability, adaptive capacity is the third important sub-realm that should be considered. Adaptive capacity is described as the ability of a system to counteract the induced adverse stimulus to cope better with the subsisting or foreseen stresses (Adger et al., 2004). Therefore, adaptive capacity to flood duly represents the ability of the social system to manage any flood event most efficiently. 2 social parameters (i.e. percentage-wise distribution of literate population and percentage-wise distribution of female work participation) have been chosen in this study to depict the spatial village-wise distribution of adaptive capacity in the MRB region.

In the discourse of hazard and disaster management, disaster literacy is one of the important components that play a crucial part. Several litertures (Bouchard, 2007; Mohebi et al., 2018) have suggested ensuring a community-based disaster literacy framework for better disaster management practices. The most important underlying factor to achieve better disaster literacy in a society is the level of preliminary education. Education enhances decision-making ability as well as develops skills that in turn help to acquire purposive knowledge. The village-wise distribution of the percentage of the literate population (Fig. 10a) in the MRB region shows that 18.68% of the West Bengal part lies in the 'Very High' class whereas in the Jharkhand part this class acquires only 6.23%. Moreover, the major part of the 'Very High' and 'High' classes belongs to the lower basin (West Bengal part) which makes this region more resilient to flooding (Fig. 11a).

Contemporary literatures have duly addressed the role played by women in building disaster resiliency. Ear (2017) has considered women as 'natural social marketers' as they convey their experience and knowledge regarding disaster to their

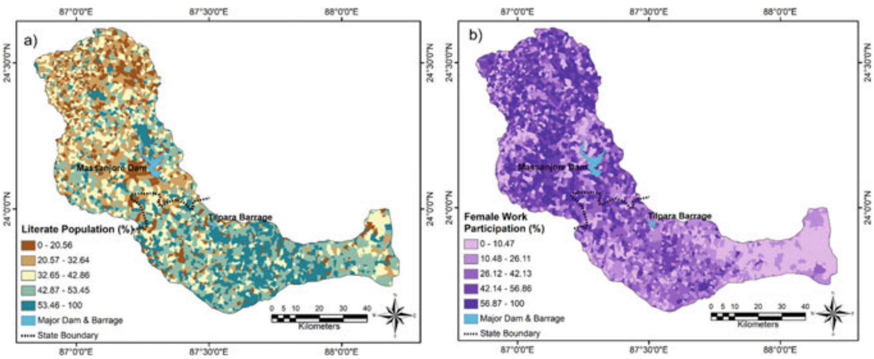

Fig. 10 Spatial distribution of a) Literate population (%) and b) Female work participation (%) depicting adaptive capacity to flooding in MRB region

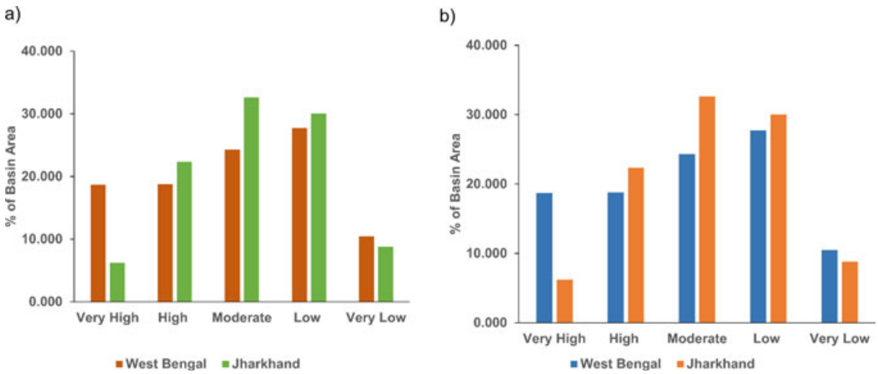

Fig. 11 Statewise areal distribution (%) of different classes of a) Literate population (%) and b) Female work participation (%)

family, friends and neighbours. Moreover, working women possess more social status as well as they are less dependent on the men of the family. Such self-sufficiency encourages them to take more part in the management of disasters and take more reasonable decisions during calamitous events. The village-wise distribution of the percentage of female work participation in the MRB region (Fig. 10b) shows an interesting scenario. Despite the Jharkhand part having a lesser amount of female literacy (Fig. 9c), it has more female work participation compared to the West Bengal part (Fig. 11b). This can be corroborated by the study of Kanjilal-bhaduri and Pastore (2017), where they found a 'U' shaped relational curve between women literacy and women work participation. Figure 11b shows that 2.33% of the 'Jharkhand part lies in the 'High' class whereas it is only 18.80% of the West Bengal part. This makes the Jharkhand part bit more resilient to flooding from the perspective of women work participation.

5 Results and Discussion

The MRB region is one of the most flood-affected regions in eastern India and flood is the most frequently occurring natural hazard in this region (Islam & Sarkar, 2021). The documentation of flood events in this region is more than 200 years old and they have been well documented by O'Malley (1910). In this regard, the Massanjore Dam and Tilpara Barrage were built as hard management measures to alleviate the devastating impact of flood. Interestingly the trend of flood has continued and 25 major floods have been documented in the area from 1920–2019 (Islam & Sarkar, 2021). Several scholars have tried to investigate the nature of flood in the MRB region from different perspectives. In their study, Islam and Sarkar (2021) have used a numerical modeling approach to analyse the nature and frequency of flooding in the region coupled with a future simulation of flooding. Ghosh and Pal (2015) and Pal(2016), in their study have mentioned the hydro-geomorphological impact of the Massanjore Dam in the lower basin of the MRB region and have criticized the dam itself for flooding. These studies are extremely technocratic, lack geospatial information about flood risk and also lack the incorporation of a socio-economic standpoint, which is essential in the discourse of disaster risk management. Although, Mukhopadhyay and Mukhopadhyay (2018), in their study, have used peoples' perceptions to perceive the spatial distinctiveness of flood intensity in the upper, middle and lower basin of the MRB region, the study lacks systematic analysis of flood risk. Therefore, this study tries to consummate such research gaps and aims to contemplate the geospatial distribution of flood risk zones of varying intensity in the MRB region combining several natural as well as socio-economic factors prevailing in the region and tries to structurize a holistic idea of flood risk in the MRB region.

5.1 *Geospatial Distribution of Flood Susceptibility Index (FSI)*

For a systematic analysis of the geospatial distribution of flood susceptibility induced by several natural parameters, a proper multi-criteria based decision-making tool is needed and the AHP model has effectively succeeded to do so in this study. Using the AHP model, the underlying factors controlling flood susceptibility in the MRB region were given a weightage value ($W^S{}_i$) and elevation has got the maximum weightage of 0.213 followed by slope, distance from river, drainage density, flow accumulation, TWI, annual average rainfall (30 years), LULC, dominant soil group and TRI (details are in Table 5). Moreover, each controlling factor was classified into different sub-classes and each sub-class of each factor was also given a risk value ($R^S{}_i$), in the same manner, based on its tendency to instigate flood susceptibility. All the weightage schemes have a consistency index of <0.1 which can be considered as an acceptable and consistent scheme according to Saaty (1987). Finally, all the parameters with their weightage value and risk value were brought under a weighted-aggregated environment using Eq. 5 and after normalizing the values, a normalized flood susceptibility index (FSI) for the entire MRB basin has been attained.

The FSI map (Fig. 12) shows the south and south-eastern part of the MRB basin has high (0.53–0.67) to very high (0.68–1) FSI value. Most regions after the Tilpara Barrage (which is mainly the lower course of the Mayurakshi River) fall under these groups. The middle course (from Massanjore Dam to the Tilpara Barrage) mostly falls under moderate (0.38 – 0.52) FSI class whereas a substantial part of the upper course (north and north-western part) falls in the category of low (0.24–0.37) to very low (0–0.23) FSI class. Areas in the upper course, which are surrounding the major drainage networks have relatively higher flood susceptibility, hence, they have a moderate FSI value. The state-wise distribution of FSI value (Fig. 12a, b) shows 30.91% and 45.36% of the area of West Bengal have very high and high FSI values respectively. Only 4.30% area comprises of low FSI and no area in West Bengal comes under very low FSI class. On the other hand, 0.72% and 5.15% of the Jharkhand part of the MRB basin have very high and high FSI classes respectively, whereas 44.86% and 26.71% area comes under low and very low FSI classes respectively.

5.2 *Geospatial Distribution of Flood Vulnerability Index (FVI)*

Socio-economic vulnerability has been attributed as the function of three components (i.e. exposure, sensitivity and adaptive capacity) and an orderly combination of these 3 components yield vulnerability (IPCC, 2007). Using the AHP model, weight values (W_i^a) and risk values (R_i^a) were generated for different parameters shortlisted for depicting exposure ($W_i^{Exposure}$, $R_i^{Exposure}$), sensitivity ($W_i^{Sensitivity}$, $R_i^{Sensitivity}$) and adaptive capacity ($W_i^{Adaptive\ Capacity}$, $R_i^{Adaptive\ Capacity}$). Next, they were brought under a weighted-aggregated scheme to generate exposure index, sensitivity index and adaptive capacity index using Eqs. 6.1, 6.2 and 6.3 respectively. While applying the AHP model for all components, the consistency index has kept less than 0.1 for a better and more consistant weightage scheme (Table 6). For delineating the weightage of adaptive capacity ($W_i^{Adaptive\ Capacity}$), AHP model was not followed and a equal weightage of 0.5 was given to both the parameters as only two components have been selected under this sub-realm. Finally, using Eq. 6, flood vulnerability values were generated and after normalization, a normalized flood vulnerability index (FVI) was created for the entire MRB region.

The FVI map (Fig. 13) shows that 28.96% of the MRB region comprises of low (0.38–0.49) FVI class followed by 28.74% and 20.68% of area containing moderate (0.5–0.59) and high (0.6–0.71) FVI classes respectively. 12.06% area comes under very high (0.72–1) FVI class and only 9.57% area falls in the very low (0.04–0.37) FVI category. The state-wise distribution (Fig. 13a, b) also indicates that 18.68% of the West Bengal part of MRB falls in the very high FVI category compared to

Table 5 Delineation of relative importance of natural factors controlling flood susceptibility and calculation of weightage (after Saaty, 1987)

	Elevation	Slope	Distance from River	Drainage Densiity	Flow Accumulation	Topographic Wetness Index	30 yr Average Rainfall	Landuse & Land Cover	Dominant Soil Group	Topographic Ruggedness Index	Weightage
Elevation	1	2	3	3	4	5	6	7	8	9	0.213
Slope	1/2	1	2	3	4	5	6	7	8	9	0.202
Distance from River	1/3	1/2	1	2	3	4	5	6	7	8	0.163
Drainage Densiity	1/3	1/3	1/2	1	2	3	4	5	6	7	0.129
Flow Accumulation	1/4	1/4	1/3	1/2	1	2	3	4	5	6	0.099
Topographic Wetness Index	1/5	1/5	1/4	1/3	1/2	1	2	3	4	5	0.073
30 yr Average Rainfall	1/6	1/6	1/5	1/4	1/3	1/2	1	2	3	4	0.052
Landuse & Land Cover	1/7	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	0.034
Dominant Soil Group	1/8	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	0.021
Topographic Ruggedness Index	1/9	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	0.013

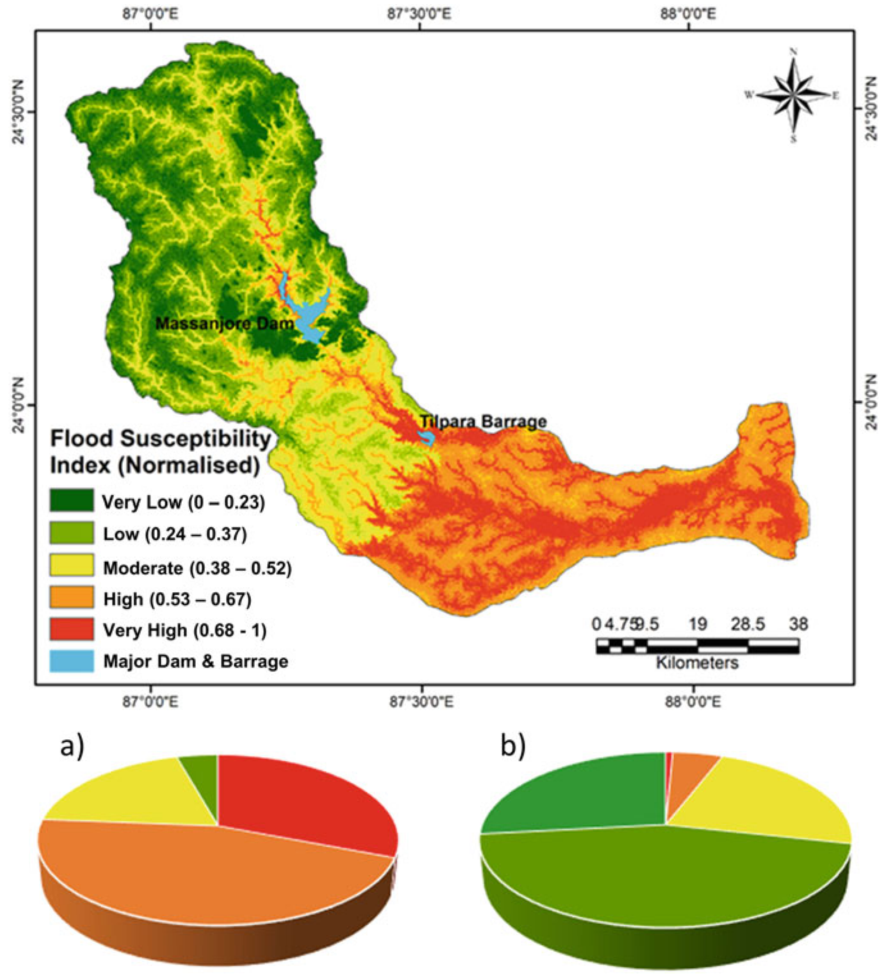

Fig. 12 Spatial distribution of flood susceptibility index (FSI) in the entire MRB region (top); state-wise areal distribution of different FSI classes in a) West Bengal and b) Jharkhand part of MRB (bottom)

only 6.23% of the Jharkhand part. Although the Human Development Report of 2018 states that West Bengal has a relatively higher HDI value than Jharkhand, the situation is completely different from the standpoint of socio-economic vulnerability to flooding. The comparative study of FVI, therefore, certainly depicts the importance of incorporating issue-specific socio-economic parameters in the realm of disaster management studies.

Table 6 Delineation of relative importance of socio-economic factors controlling exposure and sensitivity of flood vulnerability and calculation of weightage (after Saaty, 1987)

Parameters controlling exposure to flooding					
	Population Density	Distance from Road	No. of Child (0–6) Population	Weightage	Consistency Ratio
Population Density	1	4	5	0.633	0.033
Distance from Road	1/4	1	3	0.270	
No. of Child (0–6) Population	1/5	1/3	1	0.097	
Parameters controlling sensitivity to flooding					
	People engaged in Agriculture (%)	Ratio between Non-working and Working Population	Female Literacy (%)	Weightage	Consistency Ratio
People engaged in Agriculture (%)	1	4	6	0.623	0.029
Ratio between Non-working and Working Population	1/4	1	4	0.298	
Female Literacy (%)	1/6	1/4	1	0.080	

5.3 Geospatial Distribution of Flood Risk Index (FRI)

Flood risk can be described as a cumulative function of flood susceptibility as well as flood vulnerability and can be depicted in the form of a product between these two (Das, 2020). The flood risk index (FRI), in the MRB region, has been therefore attributed using Eq. 7 in the GIS environment.

The FRI map (Fig. 14) shows that the south and south-eastern parts (the lower basin area) of the MRB region are most risk-prone to flood. On the other hand, the middle and upper basin areas have comparatively lesser FRI values. Interestingly the overall areal distribution of different FRI classes in the entire MRB region (Fig. 14) shows 31.22% of the entire MRB region falls under low (0.15 – 0.23) FRI class followed by very low (0–0.14), moderate (0.24–0.34) and high (0.35–0.45) classes comprising of 24.04%, 21.74% and 15.08% area of the entire MRB basin respectively. The very high (0.46–0.86) FRI class includes only 7.93% of the entire MRB area. But, a detailed analysis discloses that the high and very high classes are mostly concentrated in the lower basin area. Even, the state-wise distribution of FRI values (Fig. 14a, b) shows that almost 46.74% of the West Bengal part of MRB falls

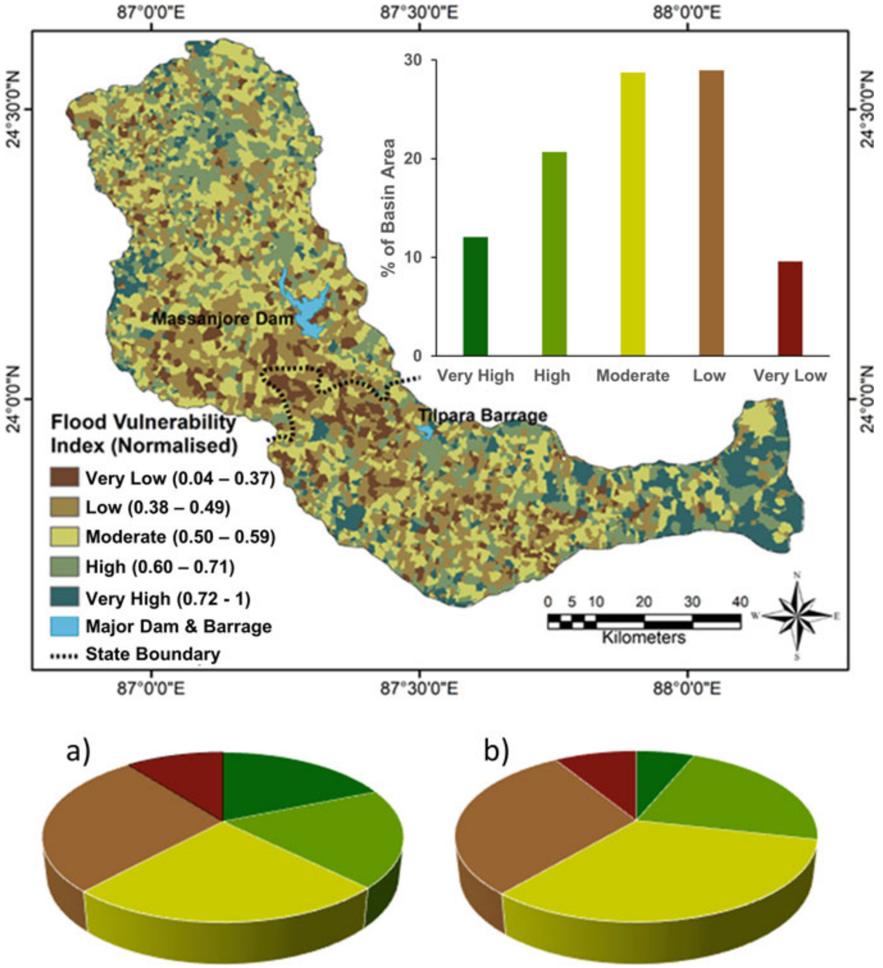

Fig. 13 Spatial distribution of flood vulnerability index (FVI) in the entire MRB region (top) [Inset: Areal (%) distribution of FVI classes in entire MRB]; state-wise areal distribution of different FVI classes in a) West Bengal and b) Jharkhand part of MRB (bottom)

under very high–high FRI classes whereas this amount is only 1.94% in case of the Jharkhand part. The lower course of river, due to its significant geomorphological characteristics, is always prone to flood and it is also true for the MRB region. Moreover, when corroborated with previous studies, it has been found that the Massanjore Dam and the Tilpara Barrage pose some hydro-geomorphic changes (i.e. attenuation of carrying capacity, narrowing of channel, generation of nested channels) in the course of Mayurakshi River that act as a tipping factor (Pal, 2016). The same results have been mentioned by Mukhopadhyay & Mukhopadhyay (2018), where the

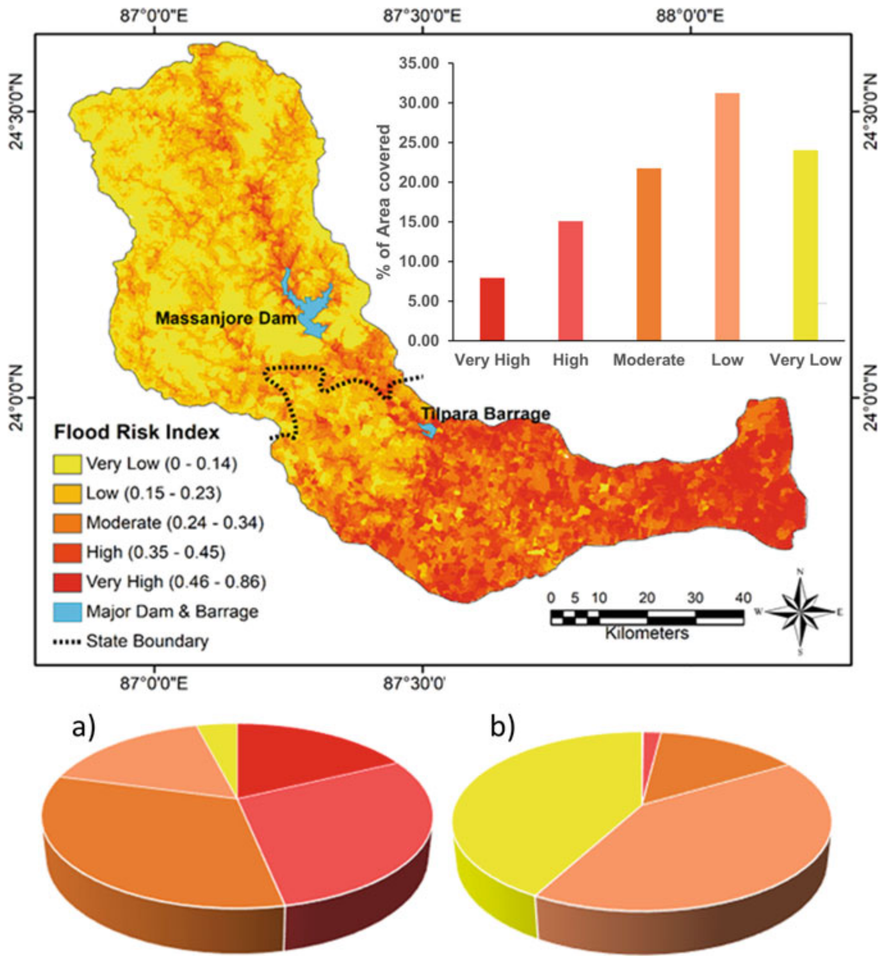

Fig. 14 Spatial distribution of flood risk index (FRI) in the entire MRB region (top) [Inset: Areal (%) distribution of FRI classes in entire MRB]; state-wise areal distribution of different FRI classes in a) West Bengal and b) Jharkhand part of MRB (bottom)

perception of the inhabitants of the lower basin area of MRB reflects more miseries during flood events. The same has been also reflected in our study of FRI.

6 Conclusion

The MRB region located in the eastern part of India has a very old and fascinating history of floods from the pre-independent British period and it is a great concern for all policymakers to introduce a holistic flood risk management (FRM) policy to mitigate the distressing situation. Although several hard meausres had been taken earlier, there has not been much development to the condition. The management regime in which different FRM policies had been undertaken earlier was strictly technocratic and particularly lacks the inculcation of the human aspect which has become one of the pivotal standpoints in the discourse of FRM in contemporary times (White, 1942). This study, therefore, tries to incorporate different socio-economic aspects that control the tenets of flood management in the MRB region and establishes a completely new understanding of socio-economic vulnerability to flooding in the region. Moreover, it also brings out the underlying natural factors and their spatial heterogeneity in the understanding of the spatial distribution of flood susceptibility and finally coalesces all the parameters of flood susceptibility and flood vulnerability in a multi-criteria framework to culminate a complete apprehension of flood risk in the region. This is altogether a new approach in the study of FRM and brings out a holistic comprehension of flood risk, especially in the MRB region.

The study indicates a sharp contrast in flood risk between the two neighbouring states that comprise the entire MRB region and stipulates that the flood risk of the West Bengal part is far higher compared to the Jharkhand part of MRB. This interpretation, therefore, calls for more area-specific policy interventions to ameliorate this situation. The diplomatic relations between these two states should be more strengthened from FRM perspectives and each concerning state should demarcate the most sensitive zones to flooding using the methodological framework described in this study and should take necessary actions at local and micro scales. Finally, as the study incorporates some basic but important parameters responsible for flood risk and the factors are not exclusive for MRB, hence, this framework can also be replicated in other floodplain regions and an integrated discernment of flood risk can be attained which in turn will help to furnish a more sustainable FRM policy in future.

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An Empirical Assessment of the Dynamics of River Morphology of Ajay River, India

Argha Pratim Pal and Arijit Majumder

Abstract Understanding the river dynamics involves analysis of geometry, longitudinal profile, sediment texture of a river etc. The present research focuses on the dynamics of river morphology of the Ajay River of West Bengal, India with an aim of studying the morphological changes of narrowing of river width towards confluence which is still not very well established. The study on the geometrical shape of river on the basis of the relationship within width-depth-velocity is based on the power equations of Leopold and Maddock (1953). The pool-riffle sequence has been observed by taking longitudinal profile of river Ajay using satellite data and field surveying. Sediment samples have been collected from the bed of the river to observe the changes of grain size with changing river velocity. It has also been observed that mean river velocity is the prime factor behind increasing discharge of Ajay River and the frequency of the pool-riffle sequence increases as the river approaches downstream. The grain size results show that the sediments are sorted poorly to moderately and the coarser texture increases as the velocity of river increases. From the analyses, it is also observed that the river Ajay maintains a natural condition of a graded profile.

Keywords Geometry · Longitudinal profile · Width-Depth ratio · Pool-Riffle sequence · Texture analysis

1 Introduction

A river is a dynamic system that is largely controlled by the morphological characteristics in the entire river channel (Tourian et al., 2017; Willett et al., 2014). The morphological dynamics of a river is largely influenced by the processes of river in which erosion is the prime cause for the weathering of the rocks on river bed and banks with the changes of slope that transport the materials (Finnegan et al., 2007; Hassan et al., 2007; Lawler, 1993). These are getting deposited in lower reach of the river due to lesser slope where depositional process maintains supremacy rather than

A. P. Pal · A. Majumder (✉)
Department of Geography, Jadavpur University, Kolkata, India
e-mail: amajumder.geography@jadavpuruniversity.in

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erosion (Ferguson & Ashworth, 1991; Prancevic & Lamb, 2015). These processes mark a significant relationship in the channel geometry as the width, depth, velocity, suspended load each increase with river discharge in a small positive power function (Ashmore & Sauks, 2006; Singh, 2003). In the longitudinal profile of a river, the width and depth start to increase but the slope of the water surface decreases with the increase of water in downstream to maintain channel velocity as slope and discharge are inversely proportionated (Flint, 1974). That leads to lesser slope gradient in large rivers to maintain the water velocity with the increase of width and depth as the river flows towards confluence (Durand et al., 2010). This characteristic is not merely maintained by all river channels in the Bengal basin as there are some eastward flowing tributaries of the Ganges River system in south-western part of Bengal that follow the exact opposite criterion. These rivers are Ajay, Damodar, Dwarakeswar, Kangsabati which are getting narrower in their downstream direction before meeting at their confluences in the Bhagirathi-Hooghly and its tributaries (Bandyopadhyay, 2018; Ghosh & Guchhait, 2014; Roy & Sahu, 2015). All these rivers originate from plateau areas of Chotonagpur region and pass through the alluvial tract of Bengal basin with lesser slope and a significant amount of water discharge (Bandyopadhyay, 2018). These are getting elongated by sinuous and meandering pattern in few areas except Damodar that makes some braided pattern in its middle reach and forms few distributaries which bifurcates the water discharge of main channel maintaining the stream power condition (Ghosh & Guchhait, 2014). The river Ajay marks its unique condition rather than others as it flows through a sustained length in the whole river course with not a single distributary and has some major tributaries that contribute a huge amount of water discharge and sediment load in the main channel (Bandyopadhyay, 2018). Despite all the habitat of a natural river, Ajay maintains it narrow width in the entire reach that makes the character of channel geometry interesting. Previous research works have emphasized on two broad spectra i.e. morphology of a natural river system and geological characteristics of river Ajay. The mean discharge of a river system increased with the changes of width, depth, velocity of that river in downstream direction (Ashmore & Sauks, 2006). The discharge of a river determines the size or cross-sectional area of an alluvial channel but the cross-sectional shape and pattern are identified by grain size and sediment load of the river (Schumm, 1977). There is also a unique relationship between channel morphology and scour-fill in a river. Scour and fill process modify the channel width at a mean reach at a particular cross section and the variability of the channel width is maintained by pool riffle sequence and the lateral migration of the stream (Andrews, 1982; Brew et al., 2015). The sediment transportation dynamics in monsoonal rivers is also important in river morphology as suspended sediment concentration and suspended loads are positively correlated with discharge of rivers (Kale, 2002). There are some rivers which decreased their width-depth ratio at downstream by diminishing discharge of water for maintaining hydraulic efficiency and sediment flux in Deccan trap region (Deodhar and Kale, 1999). It has identified that the channel width decreases when the scour area width increases more than scour depth. They also used the hydraulic geometry of stream channel method of Leopold and Maddock (1953) to derive the amount of discharge of both Silabati and Dwarakeswar rivers that fell upon Rupnarayan river in the south-western part of Bengal basin (Maity & Maiti, 2013). The morphological aspects of other rivers of south-western Bengal basin are not properly studied but the decreasing of channel width of Ajay River towards downstream have identified (Roy, 2012; Roy & Misra, 2019) and it is also studied that the lower portion of Ajay is very much flood prone due to the hydraulic geometry and geological characteristics of the river (Roy, 2012). There are certain geological features that create deformations in Ajay. An eyed drainage pattern is identified in the river Ajay due to NNW-SSE and NNE-SSW fractures near the confluence of Ajay-Hinglo River and Bolpur-Sriniketan block respectively (Jha et al., 2011). This eyed drainage is eye or lens shaped due to two arms of the same river that is the indicator of the ongoing tectonic activity in the area. This type of pattern influences the river to drop the sediment load along its course and prevent the river to wide out and moving of the flow (Ramasamy & Kumanan, 2000). Even the Medinipur-Farakka Fault and Damodar Fault lines indicate the zone of subsidence in the Ajay-Damodar interfluve region due to active tectonics in the quaternary sediments (Roy & Sahu, 2015). From the previous works, the attributes of river morphology and geological conditions of river Ajay are emphasized. The narrowing width of Ajay River towards confluence is also identified but there is not enough study regarding this unique condition of the river. There is also lack of analysis in longitudinal profile of Ajay River and the sediments that have been carried through the river. Hence, the major objectives of this study are-

i. To study the width-depth-velocity relationship of the lower reach of Ajay River.
ii. To analyze the pool-riffle sequence by longitudinal profile of the river.
iii. To analyze the sediment characteristics along the bank and bed of the river.

2 Materials and Methodology

2.1 Study Area

The Ajay is one of the most significant river in Bengal basin and the western tributary of Bhagirathi- Hooghly followed by its principal river system Ganga. It is originated from Saraun village in Jamui district of Bihar at an elevation of 340 m above mean sea level. The length of this river is 291 km with about 6200 sq.km. basin area (Bandyopadhyay, 2018). It flows down over three states i.e., Bihar (Jamui district), Jharkhand (Giridih, Deoghar and Jamtara districts) and West Bengal (Birbhum, Paschim Barddhaman and Purba Barddhaman districts) in India. This basin is bounded by Chotonagpur plateu in west, Ganga–Brahmaputra Delta in east, and in between Mayurakshi and Damodar basin in north and south direction respectively (Roy & Sahu, 2015). After the river emerges, it continues to flow at eastward direction mostly following hilly tracts over Chotonagpur plateau and suddenly it continues to move towards south-eastward direction to Sarwan where it changes movement towards south. Some small rivers join with Ajay like Darhwa River near Sarwan. At about

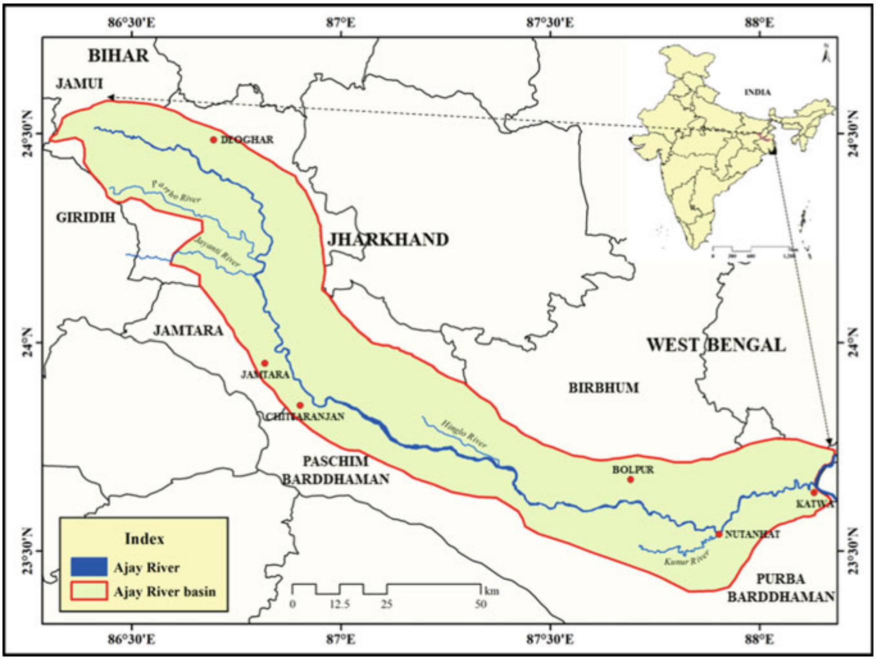

Fig. 1 Location of the study area

25 km distance from Sarwan, Partho river joins with the Ajay River from the west near Sarath gauging site and again Jayanti River joins near Sikatia irrigation barrage in its upstream. After crossing the barrage, the Ajay River flows towards south-east direction and enters in the West Bengal near Chittaranjan following the border between Jharkhand and Paschim Barddhaman district of West Bengal (Bandyopadhyay, 2018). The river starts to follow through alluvium tract in Bengal basin after Pandaveswar where the width of the river is maximum (Jha et al., 2011), and then it is joined with the Hinglo River and flows through Rarh region in Birbhum district in south-east direction. It then joins with the Kunur River and changes its movement towards north-east direction near Mangalkot in Purba Bardhhaman district. The Ajay River changes its course near Kowarpur village towards east and meets with Bhagirathi River near Katwa town with a width of 140 m and 12 m elevation from mean sea level (Bandyopadhyay, 2018) as represented by (Fig. 1).

2.2 Data Collection and Processing

In order to assess the morphology of river Ajay, the channel is minutely analyzed by satellite imageries using Google Earth application and field surveying in a selected stretch over the river bed. From the source to the mouth of the Ajay, a longitudinal profile is taken along the river thalweg that is the deepest section in river channel with the help of Google Earth. The Keyhole Markup Language (KML) data of Google Earth is extracted and converted into a plain text file by GPS Visualizer from which the distances and elevations of the profile is observed. Another longitudinal profile of 860 m is extracted along the river thalweg nearby the mouth of the river by field surveying using Auto level. A total of 42 sediment samples are collected at 20 m interval along three cross-sectional profiles over the river bed. Mean daily discharge of the years of 1986–1993, 2003–2009 and 2012 have been collected from past literatures. This data has been collected for Nutanhat gauging site beside Ajay River bed at a coordinate of 23°32′41.05′′N, 87°54′29.43′′E as it is measured by Central Water Commission (CWC), Government of India (GoI) and is located in the lower reach of river that fulfills the main objective of the study. The data of width and depth of the river in Nutanhat gauging site are computed using imageries of the selected years in Google Earth. The velocity of the river is calculated from daily discharge data as velocity is ratio of discharge and cross-sectional area that is the multiplication of width and depth at that point.

2.3 Hydraulic Geometry Analysis

The geometry of the river is being analyzed by using the power equations of Leopold and Maddock method of 1953. Leopold and Maddock published an analysis regarding the hydraulic geometry of stream channels that is known as at-a-station hydraulic geometry relations. They found that width, depth and velocity each increase as some, small positive power function of increasing discharge over a wide range of conditions. They simplified some equations that are:

$$w = aQ^b \tag{1}$$

$$d = cQ^f \tag{2}$$

$$v = kQ^m \tag{3}$$

where Q, w, d and v denotes mean daily discharge, width, depth and mean velocity of a river respectively. The power values b, f and m are very significant as the changes of width, depth and velocity of a river are largely described by the change in discharge of that river. The values of a, c and k are simple constant value to maintain the dimension of width, depth and velocity with the equal dimension of discharge (Ferguson, 1986). According to Leopold and Maddock, the product of the coefficients a, c and k is equal to 1 and the summation of the power b, f and m is again equal to 1 so as to maintain equilibrium.

$$a \times c \times k = 1 \& b + f + m = 1$$

2.4 Pool-Riffle Analysis

Pools and riffles are characterized as topographical low and high areas of channel bed respectively (Wohl et al., 1993). The longitudinal profiles obtained from both Google Earth and field surveying are analyzed minutely. The depression and ridge sections over the longitudinal profiles are characterized as pools and riffles respectively (Harrison & Keller, 2007). The relative distances between each consecutive pool to pool and riffle to riffle are measured and the mean relative distance of pool to pool and riffle to riffle are computed. The relationship of pool-riffle sequence over these longitudinal profiles is identified from the ratio between mean relative distance of riffles and mean relative distance of pools.

2.5 Grain Size Analysis

During the cross-sectional profile survey, 42 samples have been collected at an interval of 10 m in each profile and dried up in the sunlight and then in the dry oven at 105 °C and 100 g of each sample have been disaggregated into fine materials. The samples have been then mechanically sorted using several mesh sieves of 2.36 mm, 1.18 mm, 600 μ, 300 μ, 150 μ, 75 μ and a pan using a sieve shaker. After sieving for 10 min, mass of sediments from the individual sieves has been measured. The cumulative mass percentage is thus calculated for grain size analysis. The plotted grain size is analyzed using some graphical representations and statistical parameters by Gradistat 8.0 program (Blott & Pye, 2001; Sathasivam et al., 2015). Median, mean, standard deviation, skewness and kurtosis are identified to represent the distribution of grains in a sediment sample.

Equations 4–7 are used to derive the various grain size parameters.

Median is the diameter corresponding to 50% of the cumulative curve (Tables 1, 2, and 3).

Inclusive graphic mean

Table 1 Sorting of grains based on φ value

Φ value	Grain characteristic
<0.35	Very well sorted
0.35–0.50	Well sorted
0.50–0.70	Moderately well sorted
0.70–1.00	Moderately sorted
1.00–2.00	Poorly sorted
2.00–4.00	Very poorly sorted
>4.00	Extremely poorly sorted

Source Folk (1980)

Table 2 Skewness of grains based on φ value

Φ value	Grain characteristic
+ 0.3 to + 1.0	Very fine skewed
+ 0.1 to + 0.3	Fine skewed
+ 0.1 to 0.1	Symmetrical
−0.1 to −0.3	Coarse skewed
−0.3 to −1.0	Very coarse skewed

Source Folk (1980)

Table 3 Kurtosis of grains based on φ value

Φ value	Grain characteristic
<0.67	Very platykurtic
0.67–0.90	Platykurtic
0.90–1.11	Mesokurtic
1.11–1.50	Leptokurtic
1.50–3.00	Very leptokurtic
>3.00	Extremely leptokurtic

Source Folk (1980)

$$M_z = \frac{\varphi(16 + 50 + 84)}{3} \tag{4}$$

Inclusive graphic standard deviation

$$\sigma_1 = \frac{\varphi(84 - 16)}{4} + \frac{\varphi(95 - 5)}{6.6} \tag{5}$$

Inclusive graphic skewness

$$S_K = \frac{\varphi 16 + \varphi 84 - 2\varphi 50}{2(\varphi 84 - \varphi 16)} + \frac{\varphi 5 + \varphi 95 - 2\varphi 50}{2(\varphi 95 - \varphi 5)} \tag{6}$$

Graphic kurtosis

$$K_G = \frac{\varphi 95 - \varphi 5}{2.44(\varphi 75 - \varphi 25)} \tag{7}$$

Here φ5, φ16, φ25, φ50, φ75, φ84 and φ95 are represented by 5, 16, 25, 50, 75, 84 and 95% of sample mass respectively (Folk, 1980). The grain size characteristics are identified by the φ values. As the value decreases, coarser grains are observed (Wentworth, 1922). The characteristics of sediment are shown in Table 4.

Table 4 Sediment characteristic based on φ value

Φ value	Grain characteristic
−10 to −6	Boulder
−5 to −1	Gravel
0 to 4	Sand
5 to 9	Silt
>9	Clay

Source Folk (1980)

3 Results and Discussions

After solving the equation of hydraulic variables, mean channel velocity and mean daily discharge has the greatest exponent that is 0.811(Fig. 2a). It is also observed that the coefficient of determination of all the variables have a positive correlation with mean daily discharge. Although the mean velocity of the river Ajay provides a strong positive correlation ($R^2 = 0.6797$) with mean daily discharge of the river than the other two variables viz. channel width and depth. It can be clearly suggested that the mean channel velocity is the foremost factor behind the increasing river discharge of Ajay. The depth of the river also plays a little pivotal role with mean daily discharge of the river but it is largely controlled due to sedimentation inside the river channel. Ajay River remains in dormant condition in most of the months except monsoon and carries a huge amount of sediment load along its path (Bandyopadhyay, 2018). This excessive amount of sediment restricts depth of the river to be increased that is why the exponent value 0.157 of mean daily discharge and channel depth is lesser nearby 5 times than the mean velocity of the river (Fig. 2b). The exponent of the channel width is 0.032 that is 25 times lesser than mean velocity (Fig. 2c). It seems due to the fact that huge embankments are embedded on both sides just beside the river channel (Roy, 2012), so that the river does not have the potentiality to increase width with the changing characteristics of other variables inside the river. There is considerable variability in all the exponents of these different hydraulic variables whereas the summarized value of exponents and the multiplied values of all the coefficients are almost one unit. Although the hydraulic geometry maintains an equilibrium condition, the pool-riffle condition and sediment characteristics provide significant information regarding the morphology of river Ajay. Along the longitudinal profile of the entire thalweg of the river, a total of 203 pools and 202 riffles have been identified through Google Earth. The mean relative distance among the riffles is 1438.44 m and the mean relative distance among the pools is 1437.01 m. The ratio of these two mean relative distances is 0.99 which is indicated by value of k in Fig. 3. The relative distance of pools and riffles start to increase as the river approaches towards its confluence. The maximum distance between two pools is identified near the confluence of the Ajay River with Bhagirathi River and the minimum distance is observed in its upstream where Partho River joins with the Ajay River. As the tributaries converge with the main stream, the discharge of the main river increases so does the amount of bed materials which leads to sharper erosional activities in the river bed and make consecutive pools nearby, which creates less distance among pools.

The relative distance among the riffles increases as the river moves downstream that is natural criteria of a river. The maximum distance among riffles is observed near the confluence with Bhagirathi River due to high deposition rate of the river than transportation rate while the minimum distance among riffles is found in the extreme upstream of the river near the source as the river discharge is minimal but velocity is in optimum level due to higher slope gradient.

A number of 10 pools and 11 riffles are identified in the selected stretch over Ajay by field surveying. It is found that the mean relative distances among the riffles and pools are 73.18 m and 72.05 m respectively. The ratio between these two distances is 0.99 (Fig. 4). However, the relative distances of pools and riffles increase as the river width gets maximal and start to decrease with the narrowing of width. As the width of the channel increases, the water and sediment flux of the channel diverge at that segment. The depositional rate becomes higher than the transportation rate and the formation of pools and riffles start to decrease. When the channel width starts to decrease, the frequency of pools and riffles start to increase with the convergence of same amount of water and sediment flux.

The sediment characteristics of the samples from the cross-sectional profiles are studied by grain size distributions that signifies the pattern of sediment deposition over the river bed. Median value provides the dominancy of grains in sediment and average grain size of sediment is identified by mean value (Blott & Pye, 2001; Folk, 1980). The observed values of both median and mean fluctuate in between 0 to nearby 2 φ unit which indicate the dominancy of sands in the sediment having fine to very fine grained. It suggests that sandy sediments are deposited under low energy condition. They become finer with the decreasing of energy in the transported medium (Folk, 1980). Very fine grains are observed over the sand bars as the energy of water reduces there.

The values of standard deviation identify the sorting of the grains. It identifies the spread of the grain with respect to mean (Blott & Pye, 2001). The values of standard deviation come in between 0.57 φ unit to 1.96 φ unit. It suggests that the sorting of grains is poor and moderate that depends on the velocity of the current (Folk, 1980). The sorting of grains becomes poor nearby the sand bar in the river due to decreasing velocity of river current. Moderate sorting of grains is identified in the deeper section of the river due to amplifying river current. Skewness reflects the depositional process of a river. It is a measure of symmetry of distribution and identifies fine to coarse tails of size distribution of grains (Table 5).

The fine tail of distribution suggests the presence of single source in the sediments, and coarser tail of distribution shows the presence of multiple sources of sediments be it like pebbles, mud (Blott & Pye, 2001). The value of skewness ranges from −0.02 to 0.57. It identifies that finer to very coarser skewed grains are observed over the river bed. The finer skewed grains are observed in the deeper parts over river bed that suggests the presence of single source of transported materials in the sediments. As the skewness value decreases over certain sectors of the river, coarser to very coarser

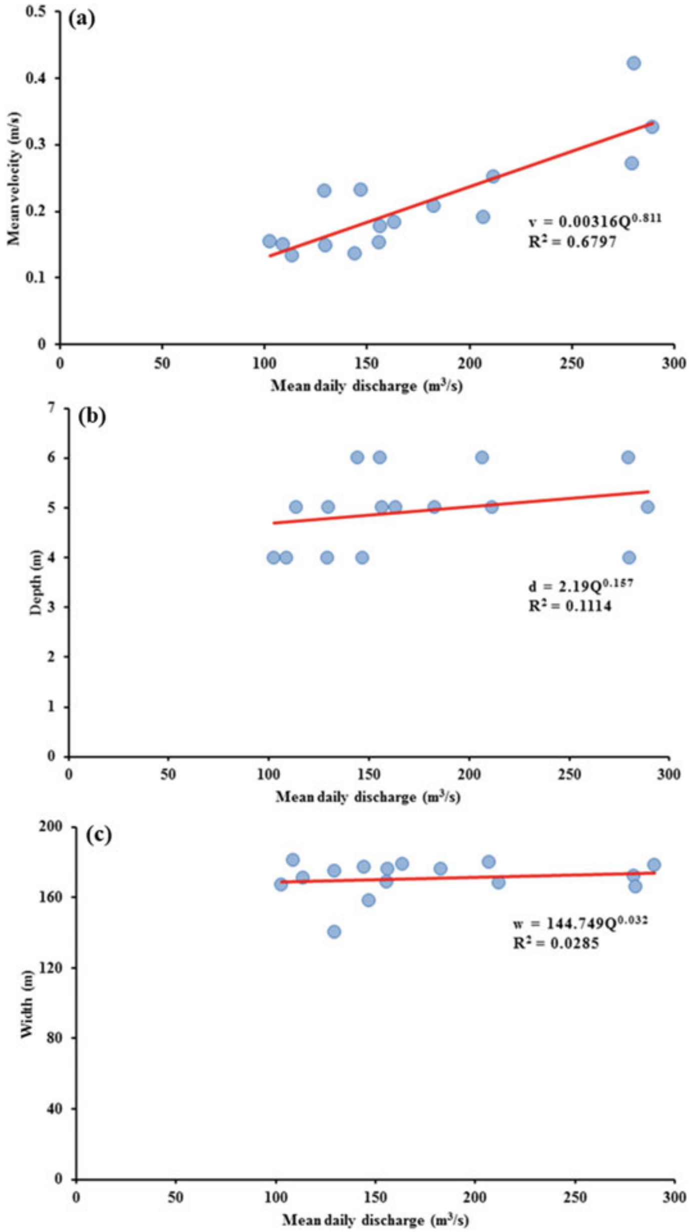

Fig. 2 Relationship of mean daily discharge with (a) mean velocity, (b) depth and (c) width of the river respectively for 1986–1993, 2003–2009 and 2012

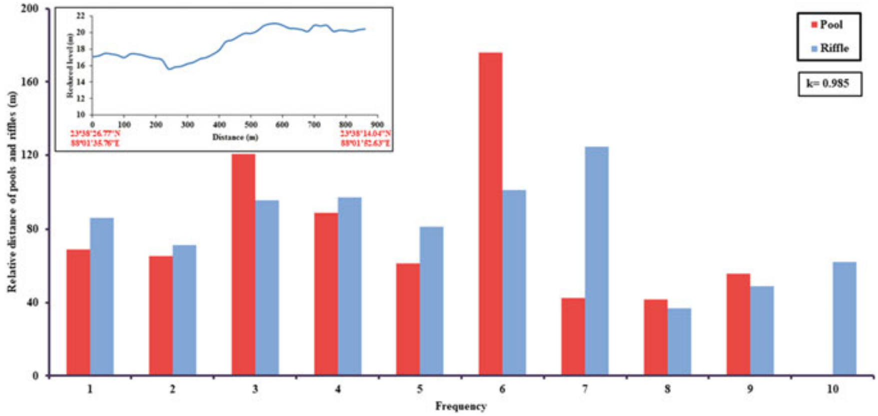

Fig. 3 Sequence of relative distance of pools and riffles from the longitudinal profile selected from Google Earth

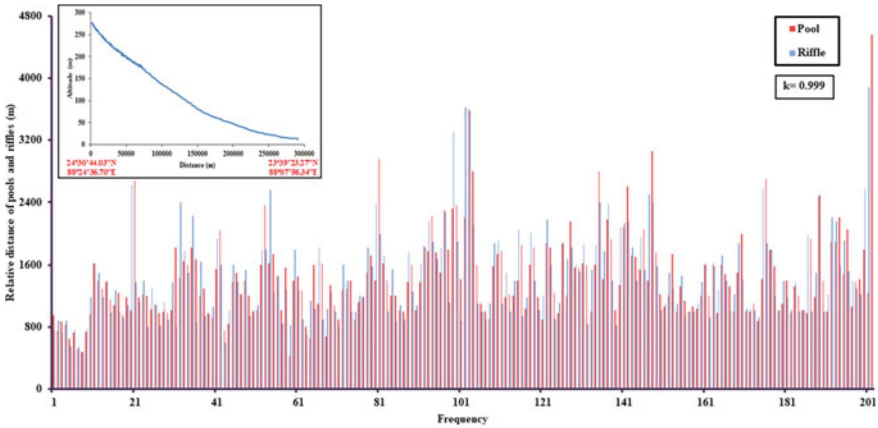

Fig. 4 Sequence of relative distance of pools and riffles from the surveyed longitudinal profile over the river

skewed grains are observed. Kurtosis provides the peakedness of curve towards the coarser grain size (Blott & Pye, 2001). The value of kurtosis comes under 0.53 to 1.40. The samples are mostly leptokurtic while mesokurtic and platykurtic grains are also identified. It clearly suggests that the coarser skewed materials are predominant over the river bed.

Table 5 Summary of obtained results from grain size analysis

Sample	Median (φ)	Mean (φ)	Standard deviation (φ)	Skewness (φ)	Kurtosis (φ)
Cross-sectional Profile 1					
1	1.88	1.82	0.69	−0.08	0.80
2	0.88	0.83	0.76	−0.06	0.92
3	1.23	1.22	0.67	−0.02	1.31
4	1.11	0.99	0.96	−0.21	1.30
5	0.66	1.22	1.96	0.47	0.53
6	0.53	0.68	1.60	0.37	0.67
7	0.32	0.83	1.66	0.57	0.58
8	1.90	1.78	0.79	−0.28	0.92
9	1.60	1.61	0.78	−0.07	0.91
10	2.09	2.00	0.58	−0.27	1.09
11	2.10	2.02	0.57	−0.28	1.14
12	0.37	0.44	0.53	0.28	1.17
13	2.04	1.35	1.36	−0.52	0.90
Cross-sectional Profile 2					
1	1.47	1.56	0.63	0.22	0.83
2	1.24	1.24	0.67	−0.03	1.37
3	1.23	1.21	0.67	−0.04	1.36
4	1.07	0.91	0.87	−0.26	1.21
5	1.15	1.06	0.69	−0.15	1.36
6	1.21	1.21	0.60	−0.03	1.40
7	1.41	1.49	0.65	0.14	1.01
8	1.43	1.51	0.61	0.21	0.89
9	1.64	1.64	0.75	−0.09	0.90
10	1.21	1.10	1.14	−0.14	0.78
11	0.26	0.24	1.03	0.27	0.53
12	1.69	1.48	1.06	−0.35	1.04
13	1.54	1.58	0.80	−0.07	1.02
14	1.69	1.67	0.73	−0.12	0.88
15	1.68	1.64	0.78	−0.15	0.90
Cross-sectional Profile 3					
1	1.58	1.61	0.75	−0.02	0.91
2	2.20	2.20	0.40	−0.14	1.03
3	1.84	1.78	0.64	−0.13	0.75
4	1.41	1.48	0.70	0.08	1.05
5	1.34	1.41	0.75	0.04	1.19

(continued)

Table 5 (continued)

Sample	Median (φ)	Mean (φ)	Standard deviation (φ)	Skewness (φ)	Kurtosis (φ)
6	1.48	1.54	0.75	0.01	0.97
7	1.32	1.25	1.07	−0.20	1.28
8	1.30	1.34	0.78	0.00	1.26
9	1.34	1.33	0.87	−0.06	1.01
10	1.13	1.10	0.93	−0.06	1.02
11	1.29	1.32	0.77	0.01	1.22
12	2.00	1.87	0.73	−0.36	1.06
13	1.75	1.68	0.80	−0.21	0.92
14	−0.37	0.57	1.40	0.10	0.56

4 Conclusions

The hydraulic equillibrium condition is maintained in the lower reach of the Ajay River having a dominant relationship of velocity-discharge. The mean velocity of the river increased heavily with the mean daily discharge as the river gets regenerated in monsoon season. The importance of non-expanding depth and width makes the river more vulnerable. These lead to flooded condition in the lower reach of the river during high intense rainfall in the Ajay River basin. Following the longitudinal profiles, the pool-riffle sequence is controlled from the extreme upstream towards the confluence. The channel width is inversely proportionated with the pool-riffle sequence. Grain size analysis indicates that the sediments are fine to very fine grained having low energetic condition, with poor to moderately sorted and textured matured sedimentation process of a fluvial environment. The natural criteria of a river are being sustained in the whole river course of Ajay. It can be inferred that the fluvial morphology of Ajay River is in equilibrium and graded condition that does not being impacted by the narrowing of the channel width in downstream direction. Although, anthropogenic impact can be a sublime cause for non-widening of river as huge embankments are embedded just beside the river bed. Some tectonic activities and presence of lineaments and faults have made the river bed vulnerable in recent past that might also an intrinsic factor behind this exceptional characteristic of Ajay River.

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Analysis of Fluvial Morphometry and Prioritization of Pagla Jhora Micro Watershed of River Mahananda in Darjeeling District, West Bengal, India

Ayan Das Gupta

Abstract The morphometric analyses are of paramount significances in any type of hydrological study and it is compulsory in holistic management and qualitative improvisation of the target drainage basin. A critical examination and analyses of the morphometric yardsticks (Boulton in Morphometric analysis of river basin characteristics. Water Resource Board, 1968) and prominence of micro-watershed depending upon the water intake capacity of the Pagla Jhora sub-watershed has been taken into consideration in the current research work through the software-based evaluation of linear, relief and aerial aspects (Bull & McFadden in Geomorphology in Arid regions. State University of New York, pp. 115–138, 1977) of the study-area. Remote sensing and Geographic Information system have helped the researcher to focus on the study-area through Google-image and on further quantitative calculations (Chopra et al. in J Indian Soc Remote Sensing 33:531–539, 2005) of the manifold aspects of the drainage basin (Schumm in Geol Soc Am 67:597–646, 1956). In the basin area map, the overall arena of Pagla Jhora watershed in Mahananda basin (Clarke in Morphometry from maps, Essays in geomorphology. Elsevier, pp. 235–274, 1996) has been divided into total twenty eight sub-arenas and here the total basin has been divided under minor segments on the basis of the areal extents only. Thereafter the perimeter, area, absolute relief mean (Costa in J Hydrol 93:313–338, 1987), relative relief mean, elevation mean, hypsometric integral, bifurcation ratio, ruggedness number etc. have been traced out. Drainage density, form-ratio means (Das in Signatures of morpho-tectonic activities in western upland Maharashtra and Konkan region [Unpublished M.Sc. thesis]. Savitribai Phule Pune University, 2017) etc. have also turned up in the forefront through quantitative investigations. This research endeavour will not only focus upon the multiple morphometric analyses (Das & Pardeshi in Spat Inf Resour 26:47–57, 2018) depending upon the various aspects of the micro watershed of Mahananda River basin but also at the same time, the in-depth study will guide the target audience regarding the further explanation of such critical values of the morphometric techniques. From that perspective, the work may be geo-environmentally significant a lot.

A. Das Gupta (✉)
Post-Graduate Department of Geography, Chandernagore Government College, Strand Road, Burrabazar, Hooghly 712136, West Bengal, India
e-mail: dasguptaayan11111@gmail.com

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1 Introduction

Growth and flourishing of a full-fledged drainage system and pattern of its flow over a particular spatial unit (Dornkamp & King, 1971) stand massively influenced by multitude of factors like geo-lithology, geomorphology, Pedology, structure, topography (Horton, 1932) green cover etc. Geo-spatial techniques are used to corroborate as well as assess different terrain features (Horton, 1945) and morphometric parameters of the drainage basin. Micro-watershed (Kale & Rajaguru, 1986) along with drainage basin actually provides a non-rigid platform and powerful geographical environment to study its several geological and geographical nooks (Kale & Shejwalkar, 2007) and corners. Focus can be thrown on constructive manipulations by mapping tools (Valdiya, 2008) and through such cross-profiling, the future trend of various characters of the watershed can get deciphered. Morphometry is basically a fully quantitative measurement (Valdiya & Rajagopalan, 2000) to study the overall configuration or structuring of earth surface in and around the drainage basin. These morphometric analyses can be accomplished through the detailed oriented studies of linear, aerial and relief aspects (Verstappen, 1983) of the entire watershed. The present study has attempted to throw spotlight for critical evaluation of the morphometric indicators of the Pagla Jhora watershed that is an integral part of the Mahananda river (Rao et al., 2010) basin near Kurseong in Darjeeling District. The drainage basin has been cropped at longitude of 88°23′08″ and latitude of 26°49′55″. The study area has been divided into 28 minor areal segments for analyzing thoroughly the miscellaneous geometric parts of the focus of study.

2 Morphometric Analyses

Morphometric study connotes to the mathematical and symbolic explanation and interpretation of landform configuration what is practised under the umbrella of Geomorphological studies (Javed et al., 2009). The morphometric analyses can be done in definite type of landform or drainage basin of large areas and through such study, the spatio-temporal dimensions of the study areas can be understood scientifically. With respect to basin, different quantitative measurements have been developed and further their minute details have been elaborated by the researchers. Geographical information system has come up recently as an effective device for delineation of basin as well as the drainage patterns. In the study of groundwater potential as well, the morphometric studies matter a lot. Supervised and unsupervised image processing techniques in remote sensing may also help to identify the morphological

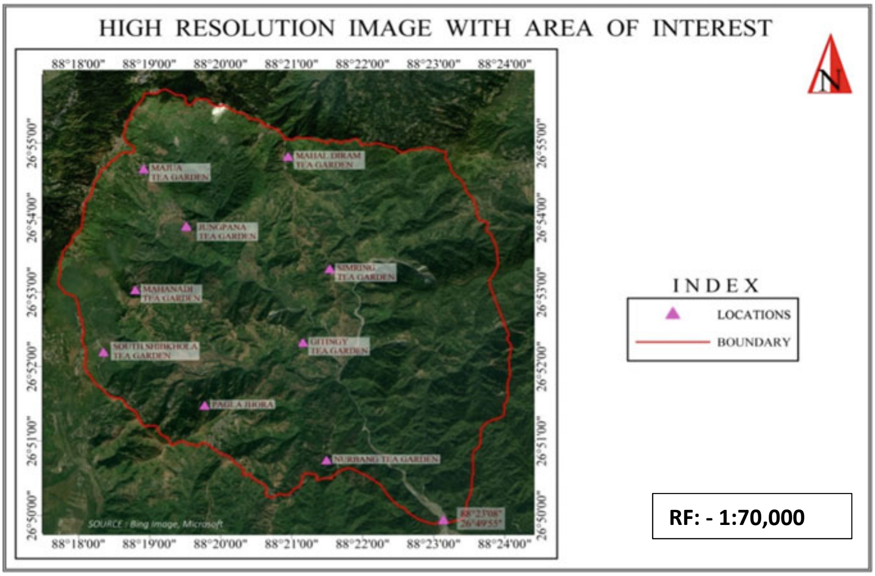

Fig. 1 Study arena at a glance

properties of watersheds as well as basin and their minute details turn up thereafter (Fig. 1).

The quantitative analyses as well as measurements of watershed are conspicuous for the geomorphological discussions (Miller, 1953) and actually here the thrust is put upon the understanding of channel network as well as the hydrological behaviour of the streams in whole drainage area. RS-GIS Techniques are now used in wide scale just because all the numerical databases can be derived afterwards from the software platform and those datasets can be utilized for further statistical discussions and drawing of inferences. Analysis of watershed is carried forward with thorough quantification so that the tasks can contribute in the works of the regional planners as well. For management of water resources also, the work becomes of paramount significance. Three major aspects are there in the analyses of drainage Morphometry and these are: Linear, Areal and Relief aspects. The linear aspect consists of stream ordering, calculation of stream length, finding out of stream length ratio, throwing focus on bifurcation and sinuosity ratio along with calculation of Rho coefficient. Areal aspects cover a large number of assignments like the calculation and mapping of drainage density, drainage frequency, drainage texture, circulatory index, form factor, elongation ratio, length of overland flow and calculation of area and perimeter of the basin segment. Lastly the context of relief aspects turn up and there fall the items like calculation of stream slope, basin relief, ruggedness number, asymmetry ratio, hypsometric integral, valley width to height ration and so on and so forth. River profiling along with the demarcation of Knick point as an indicator of fluvial rejuvenation can also be done.

In fluvial geomorphology, knick point forms as a part of river or channel that denotes a sharp alteration in the fluvial gradient and due to sudden fall of slope, usually the water falls or lake are created over there. Knick points highlights multiple conditions and processes-associated changes within the river, quite often caused by preceding erosion due to variation in lithological components.

3 Study Area

The study area encompasses the Mahananda Basin akin to Kurseong in Darjeeling District of West Bengal. The river comprises of two separate streams one of which is arising out from the orographic belt of Himalayas in Nepal. It traverses through the state of Bihar and it has its confluence with Ganges in the left opposite part of Rajmahal hill of the state of Bihar. The river is locally named as Fulahar. The rest of the stream named as Mahananda originates in foothill at Darjeeling in West Bengal and crosses a distance of 400 Kms through Darjeeling District. After serving the districts like West Dinajpur and Malda, the river enters into the territory of Bangladesh and ultimately meets the mighty Ganges close to Godabari Ghat in the neighboring state of Bangladesh just at the opposite side of Lalgola in Murshidabad of West Bengal. The right channel of the river passes through the state of Bihar with the local name of Fulahar. The left channel enters and serves the Districts of West Dinajpur as well as Maldah and then takes entry into Bangladesh with the name of Mahananda. Mahananda has been originated from Pagla Jhora Watershed and here the unit of discussion is also the Pagla Jhora Micro watershed. Mahananda has its mention in the ancient Indian scriptures as well as local literatures. Multiple archaeological evidences also plead in favour of river Mahananda. Mahabharata, Acharansutra, Kalpasutra etc. corroborates the importance of river Mahananda and therefore it is one of the conspicuous fluvial segments of India (Fig. 2).

Being a notable tributary of the holy Ganges, Mahananda originates from the springs in Dow Hills forest and there it is named as Mahanadi near Darjeeling District. Mahanadi part is getting its full course from the Mahaldiram hill close to Chimli at the eastern part of Kurseong in Darjeeling district at a height of 2100 m that is equal to 6900 ft. According to some fluvial geomorphologists, the Mahananda stands actually as a flow of two separate rivers one of which is Mahanadi and the rest one is Balason. They are found in their full forms in the plain of Siliguri Subdivision. Mahananda may also be regarded as a trans-boundary river of the greater Himalayan range. Mechi the right bank tributary of Mahananda forms the portion of Nepal's eastern boundary with west Bengal while another similar stream named Kanki flows down out of Nepal. The full length of river Mahananda is of 360 Kms from which the 324 Kms passes through India whereas the rest 36 Kms gets envisaged in Bangladesh. Mahananda's point of origination and its catchment found in the Himalayan region are not established over the calcareous minerals but acidic substances are predominant over there. Due to preponderance of the acid-based minerals in the pedological substances, the entire zone stands as non-calcareous by

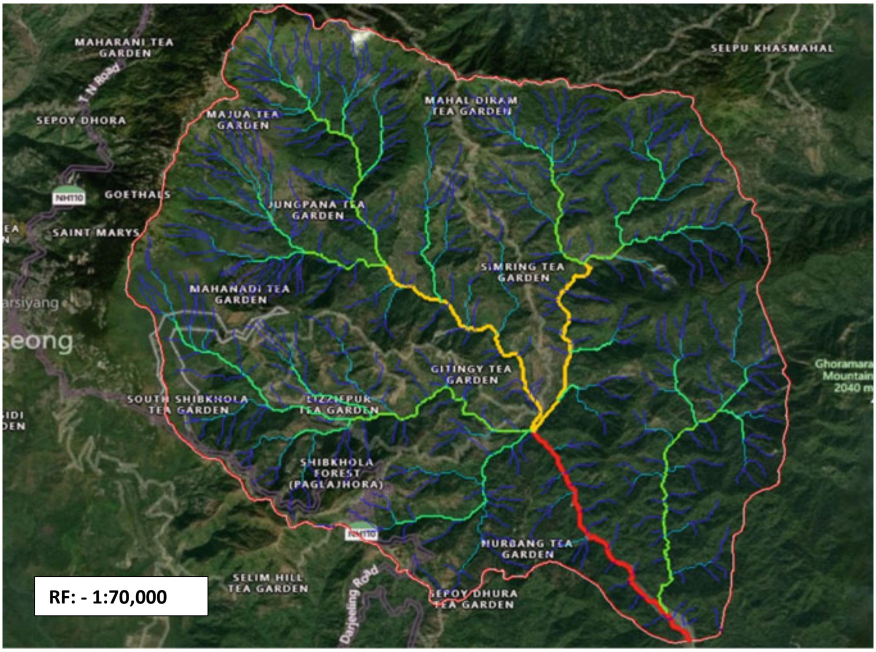

Fig. 2 Drainage basin delineated from the Google Earth

nature. The geological configuration of the River system of Mahananda at the hilly area of Darjeeling District comprises of the unmodified sedimentary rocks captivated to the hills at the north comprising of manifold grades of petrological metamorphism over the area. The outcrop of different rocks gives rise to a series of bonds akin to the general lineament of Himalayas and it's having the angular inclination towards the hills. Mahananda fluvial system has a commanding role in governing the entire economy of the catchment belt of Darjeeling, North Dinajpur and Maldah District of West Bengal and Kalihar, Purnia and Kishangunj districts of Bihar, in multiple ways. Surprisingly the upper course of river Mahananda shapes the linguistic border between the Bengalis and the communities where the major vernacular is Hindi.

From the map of the study area, it is pretty clear that different tea gardens serve as prime locations in the entire drainage basin of Mahananda. Majua, Jungpana, Simring, Gitingi Nurbung, South Shibkhola, Mahanadi, Mahaldiram tea gardens are sufficiently prominent in the map accompanying with. From the picture of the Google-earth, it is clearly envisaged that the topography of the study area is mainly wavy and undulating by nature. The 5th order drainage of Mahananda has been developed over the study area. Pagla Jhora micro watershed being a prominent part of the Mahananda basin because of one point of origination of river is situated between South Shibkhola Tea garden and Gitingi tea garden.

4 Objectives Behind the Study

After delineation of the drainage basin of river Mahananda in Darjeeling District, the main focus has been thrown on the detailed oriented study of the stream ordering and stream Morphometry. So the focal objectives are as follows.

- To prepare a layout of the stream ordering and calculation of the bifurcation ratio.
- To make a clear contour map and studying the absolute relief, relative relief and hypsometric integral on the same.
- To highlight upon the elongation ratio, form ratio, drainage density, dissection Index and ruggedness number from the study area.
- Calculation of the sectoral micro segments of the overall drainage basin area and calculation of the various types of ratio along with establishing regression-based relationship between different sets of parameters.

5 Methodology

All the morphometric analyses are done in the platform of TNT Mips software and the overall Watershed process in TNT Mips uses the Deterministic-8 (D8) algorithm for flow path identification of all cells. The D8 algorithm computes actually the terrain gradient between the central cell and each of its eight neighboring cells. Flow direction is then established as the direction to the nearest neighbor, either perfectly adjacent or diagonally placed, with steepest downward slope (Fig. 3).

A sequential processing option (in non-parametric approach) is also available in the platform of TNT Mips for filling the depressions in the elevation model prior to determine the route of flowage. This procedure may be helpful in evaluating the impact of any natural depressions in the overall landscape configuration. This is chronologically processed to eliminate the smaller watersheds using elimination of smaller sizes of polygons.

6 Result and Discussions

6.1 Digital Elevation Model with Drainage Network

The accompanying layout shows the clean ordering of streams in the Mahananda basin near Kurseong of Darjeeling District. The fingertip channels or the initial overland flows are generated near Majua tea garden, South Shibkhola Tea garden and Mahal Diram tea garden. Impressions of fingertip channels are also found in western and northern part of the spatial overlay. Two first order streams have met with each other in order to give rise to the second order stream as per Strahler's technique and near Jungpana Tea garden and Simring tea gardens, the third and fourth order streams

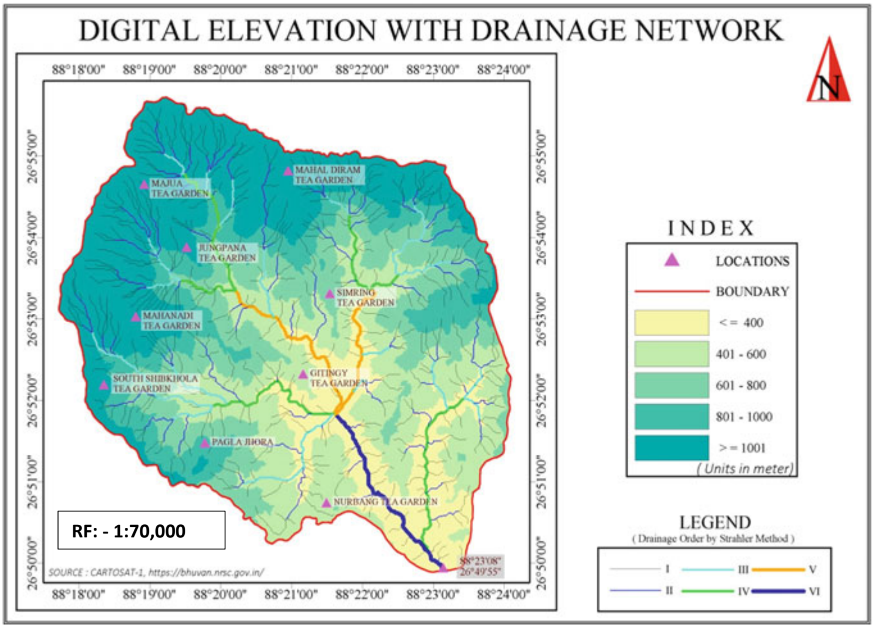

Fig. 3 Digital elevation model of the study-area

have been originated. Near Pagla Jhora watershed akin to Nurbung Tea garden, the fourth order streams are assembled with each other to end up in highest fifth order drainage. The digital elevation model has also been prepared on the basis of the entire delineated drainage basin and so far the chromatic variations are concerned, the highest elevation or topographic rise is envisaged near Majua Tea garden and South Shibkhola tea garden. Due to extensive development of fluvial channels, the whole topography is dissected intensively. Gradually the gradient falls from the wavy and undulating northern and north eastern portion of the Mahananda Basin and the elevation becomes of less than 400 m near Gitingi Tea garden and Nurbung tea garden. In the western part of the Pagla Jhora watershed also, the elevation comes closer to 44 m.

6.2 Contour Map and the Map on Absolute Relief

From the contour map it is evident clearly that two major contours are spread over the total study area and the slopes fall from the elevation of 500 mt contour towards the 100 m contour. From the graded shading, it becomes predominant that the high elevation is seen at the Northern, northern eastern and south eastern portion of the drainage basin. Near the Pagla Jhora watershed, the elevation has also risen up. The absolute relief denotes the exact contour heights and on the basis of different heights

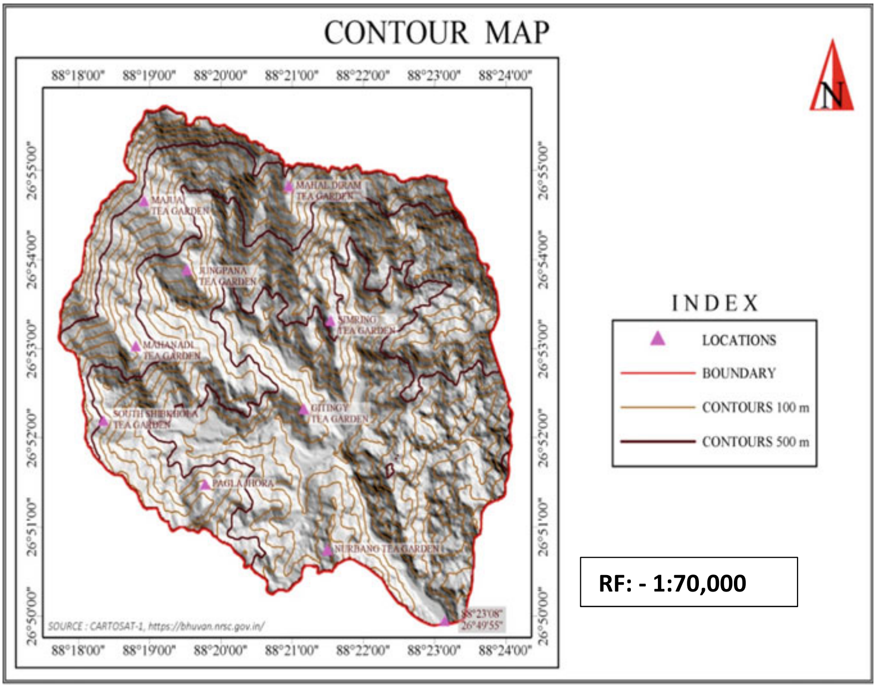

Fig. 4 Contour alignments in the study-unit

of the locational points, the graded shading has been made and from the absolute relief map, it is worthy to mention that the highest relief is concentrated in the western, northern and north eastern part of the basin area (Figs. 4 and 5).

6.3 Relative Relief Map and Hypsometric Integral Map

The theory or the formula of Relative relief was propounded by David Smith and after subtraction of the minimum value of contour heights from that of maximum contour value, the relative relief can be deciphered. Here from the relative relief map above, it can be stated distinctly that in the western part near the Pagla Jhora watershed, Mahanadi tea garden and Shibkhola Tea garden, highest value of relative relief is accentuated whereas gradually the relief fades out near Nurbung Tea Garden and Gitingi tea garden. It is the exact change or variation of height within a unit of study in relation to the local base level and in other terms, the difference or gap in height between the highest and lowest point is plotted in the grid framework and contour lines are drawn accordingly (Fig. 6).

A hypsometric integral is generally counted or calculated through plotting of the cumulative or additive height and the sum total of area under that altitude for

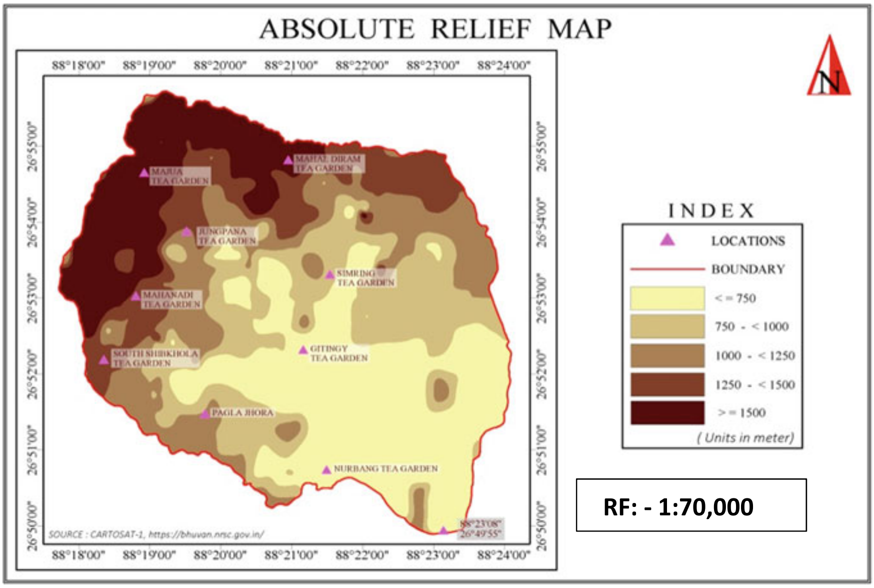

Fig. 5 Absolute relief map

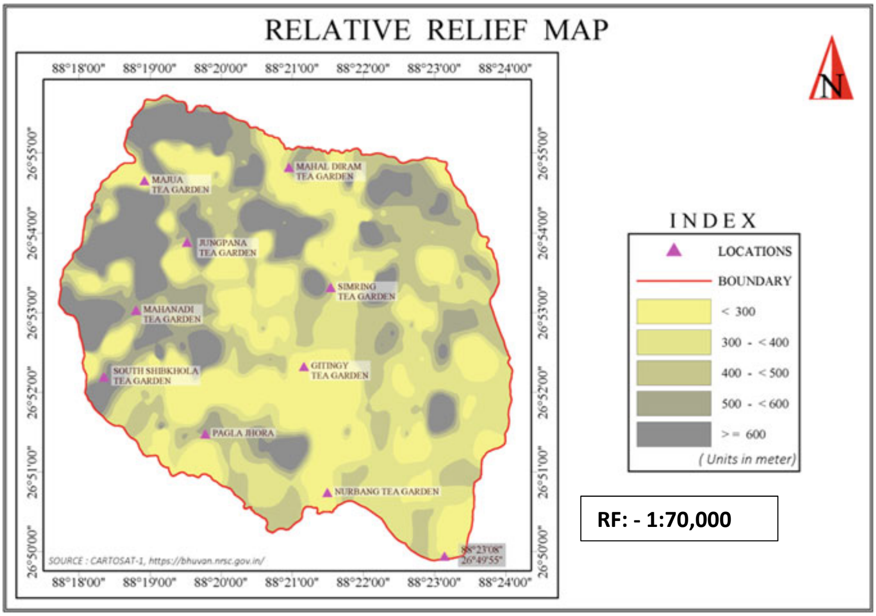

Fig. 6 Relative relief map of the study area

separate watersheds and then taking into consideration the total area falling under that curve to obtain the value of hypsometric integral. The curve was initially expounded by De Apparent in the year of 1883 and Murray in the year of 1888. Walter Penck, in the year of 1894, said that the surface of the earth is divided into two statistically unique steps or levels, one of which is the continental platforms of about 100 m above sea level and the deep-sea floor made up of the plates of silica and magnesium. This hypsometric curve is typically used to elaborate that the Earth has two different types of crusts namely continental and oceanic. The curve actually says about the percentage of the Earth's surface above any definite or particular elevation. A hypsometric integral denoted a HI is a macroscopic index that is usually used to study the numerical relationship between the area of a regional horizontal section and its successive elevation that can plead in favour of watershed development. A low value of Hypsometric integral corroborates older and much more eroded segments and more or less evenly dissected drainage basin. On the other side, the high values of HI denote the high level of occurrence of the most of the topography above the level of mean height. In this map, the northern portion, eastern and north western parts are having higher HI values explaining their heights to be greater than the average of mean height of the rest of the areas (Fig. 7).

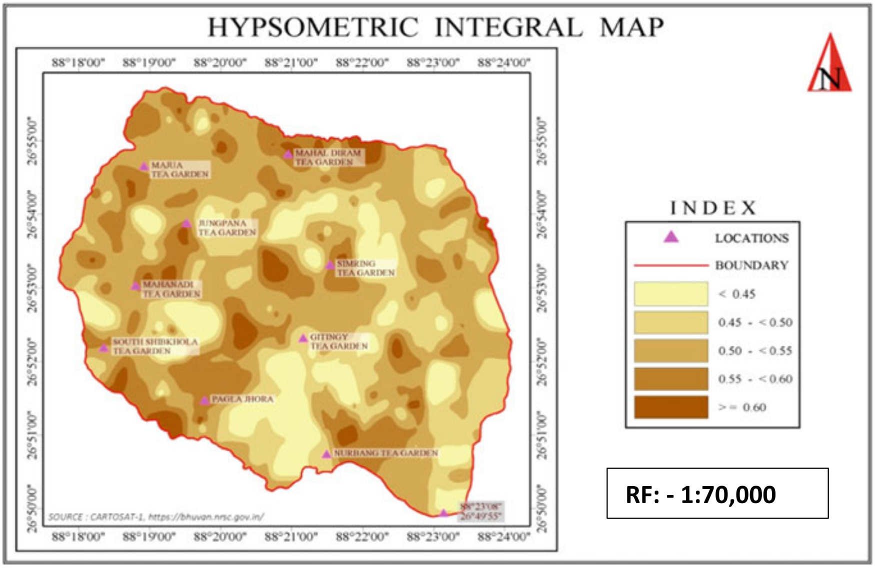

Fig. 7 Hypsometric integral map

6.4 Drainage Density Map

Drainage density actually is regarded as an important index and it's a measure regarding the texture of the fluvial network and corroborates the perfect balance between the potentiality of erosion of the surface run-off or the overland flow and the obstruction or resistance put forth by the surface soil layer and the underlying rock substances. In a drainage density map, it is defined as the close coherence regarding spacing of the stream channels. It is a quantitative measure of the total length of the stream of all orders in a given unit of area. High drainage densities can also indicate inundation after rainfall or downpour. This is just because the drainage basin encompasses lots of tributaries which ultimately join the main river. Hence after the torrential rainfall, the entire water-load gets released in to the higher order stream leading to the occurrence of inundation. In the accompanying diagram, the highest drainage lengths in Km per square kilometres are found in the western and both-central part of the Mahananda river basin. So it can be assumed that the regions near to Majua, Jungpana and Mahanadi tea garden, the intensity of flooding is high in comparison with the rest of the areas of the basin (Fig. 8).

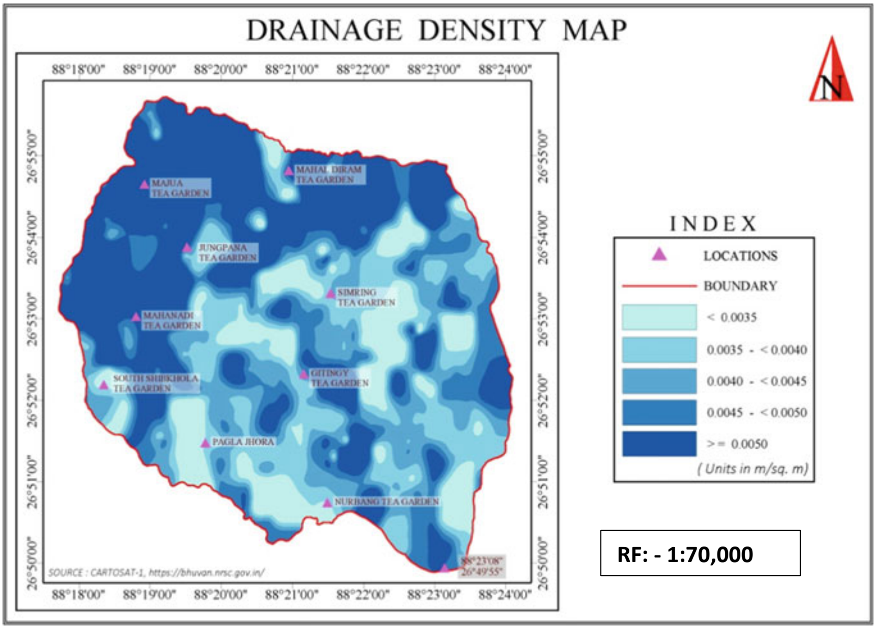

Fig. 8 Drainage density map

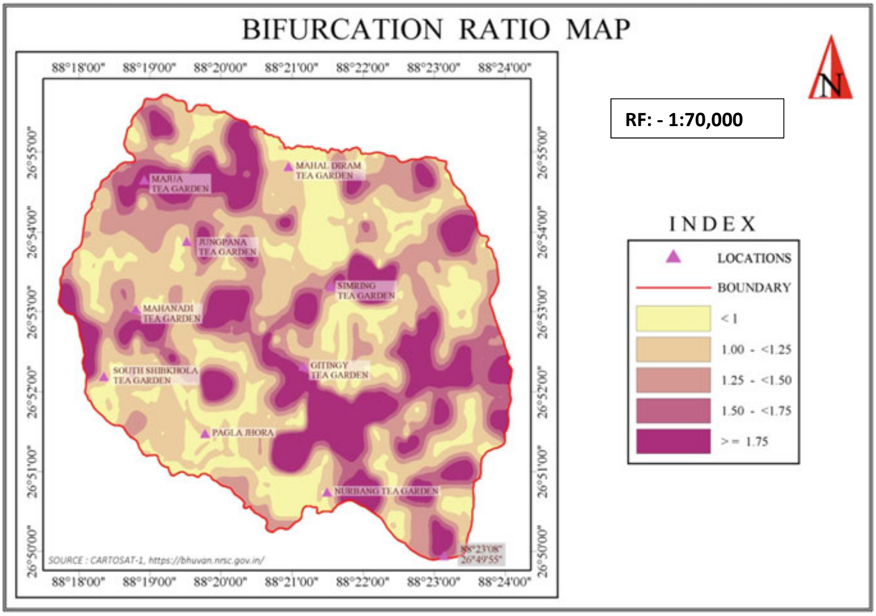

Fig. 9 Bifurcation ratio map

6.5 Bifurcation Ratio

(Rb) or Bifurcation ratio is the ratio of a particular number of the stream domains or segments of specified ordering and a number of streams lying in the next or successive higher order. From the first order stream uptil the fifth or sixth order streams, this bifurcation ratio can be calculated in the similar way. Being the dimensionless number, bifurcation ratio denotes the ratio between the number of streams of one order and those of the next-higher order in a definite drainage network.

It may be a very significant measure of probability in occurrence of flooding. The higher the bifurcation ratio, the greater will be the probability of occurrence of flood. Here the maximum bifurcation ratio has been concentrated near the Pagla Jhora micro watershed and apart from the same; the maximum concentration of the bifurcation ratio is found close to Gitingi tea garden and Mahal Diram tea garden (Fig. 9).

6.6 Dissection Index and Elongation Ratio

Dissection index connotes to the roughness of the surface created by good number of valleys, ravines and rivulets. Dissection index is a conspicuous parameter of the Drainage Morphometry. It is sometimes used by the fluvial geomorphologists for

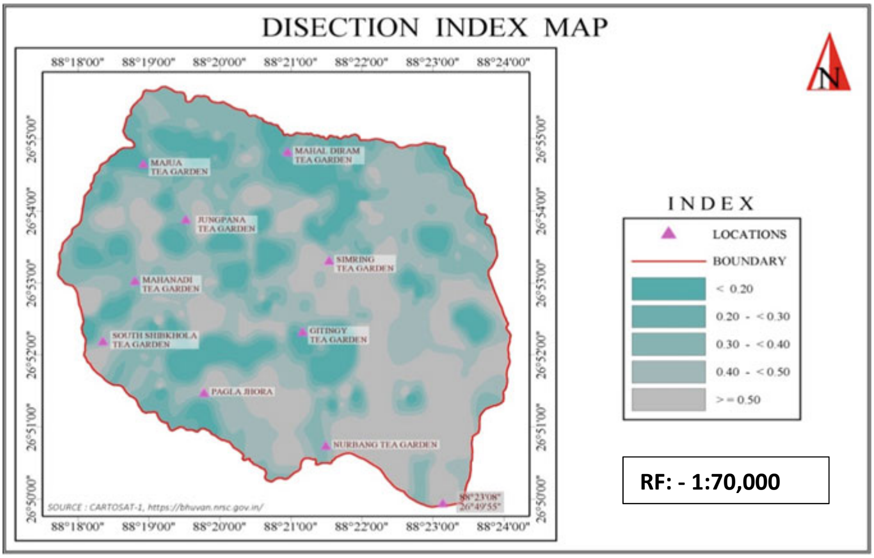

Fig. 10 Dissection index map

terrain analysis. The dissection index may corroborate of stage of the streams in the drainage basin in the cycle of fluvial evolution. In the map aside, the high dissection index has been obtained in the eastern and south eastern part of the Mahananda drainage basin. On the other side, the elongation ratio connotes to the ratio between the diameter of a circle of the same area of the basin and the highest basin length. It is a dimensionless figure as well (Figs. 10 and 11).

6.7 *Form Ratio and the Ruggedness Number Map*

If the ratio is calculated between the width of the streams and that of its depth then the result is called as the form ratio. If width of a channel is divided by its mean depth then also the form ratio will ultimately be calculated. In the map aside, the higher value of form ratio is concentrated near the eastern portion of the whole basin area and if seen minutely then it will be noticed that in the eastern part of Nurbung tea garden and Gitingi tea garden, the higher form ratios have been obtained whereas in the northern, north western and north eastern part, the low values are concentrating. The expression of topographic ruggedness index that is commonly known as TRI was coined by Riley and others in the year of 2009 in order to enunciate the magnitude of height difference between adjacent cells of a Digital elevation model. It calculates as well the difference in elevation values from a pivotal cell and the eight other cells immediately surrounding it. In the map of the study area, the high roughness or ruggedness is found in northern, eastern and north western parts whereas the low

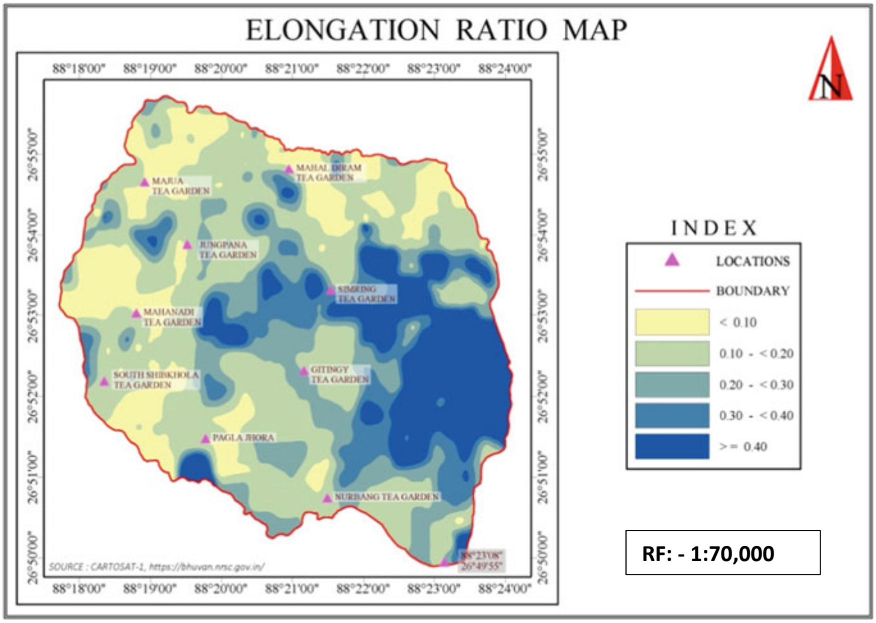

Fig. 11 Elongation ratio map

values are concentrated in the southern and the south central segments (Figs. 12 and 13).

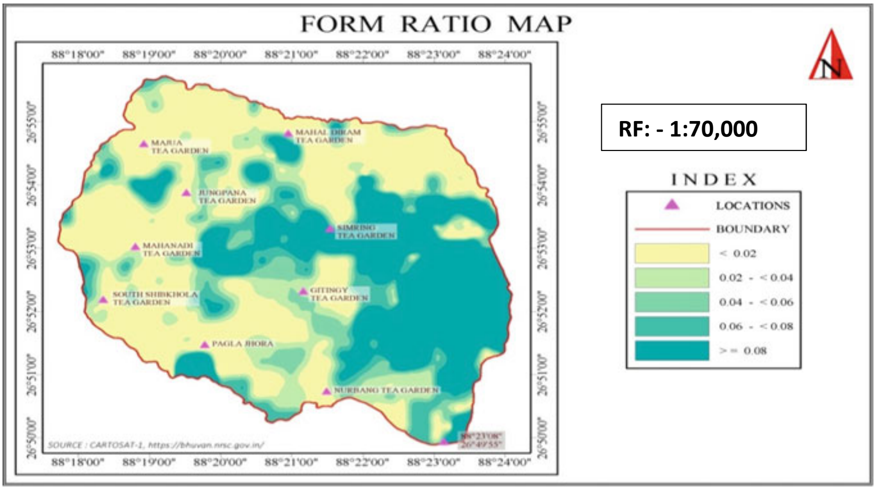

Fig. 12 Form ratio map

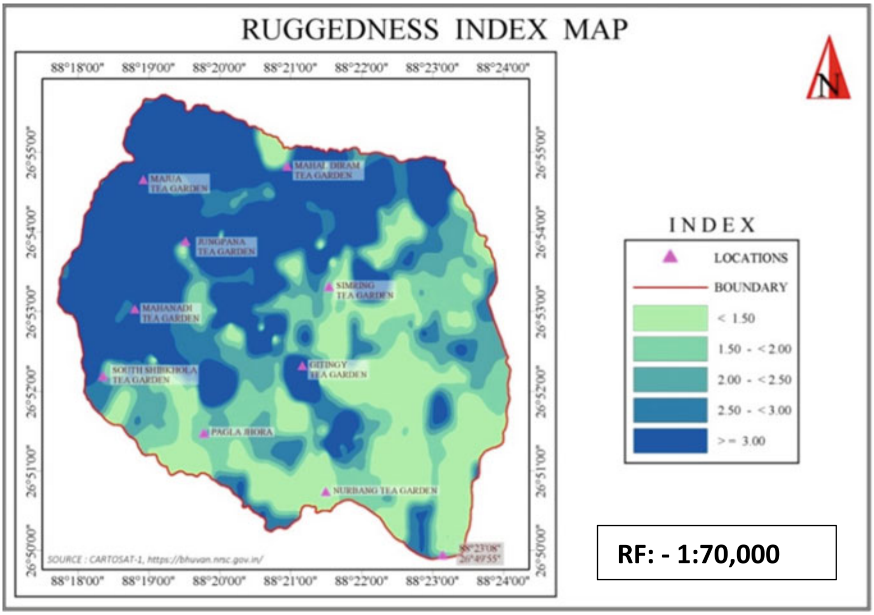

Fig. 13 Ruggedness index

6.8 Drainage Basin Area Map and Regression Analyses

After the completion of specific morphometric analyses (Table 1), the entire Mahananda Basin area was divided into total twenty eight areal segments (Fig. 14) and mean values with respect to different morphometric indices have been written in the tabular format (Table 2) in order to accomplish the relationship-assessment through regression analyses.

First of all, in a tabular format the central latitude and longitude values are plotted with reference to different basin areal segments. In a composite linear diagram, (Fig. 15) the dissection index mean and the elongation ratio mean are plotted and from the composite curve, it is clearly evident that the values of dissection index mean is on an average higher than that of the elongation ratio mean. Through the regression analysis, a relationship in positive has been obtained between the area of the microwatersheds in square kilometres and the perimeter in metres (Fig. 16).

There is a perfectly negative relationship (Fig. 17) between the ruggedness ratio mean and the form ratio mean. On the other side, the strong positive relation (Fig. 18) gets established between absolute relief mean and the relative relief mean.

From the value of Pearson's product moment correlation coefficient regarding the relation between elevation mean and hypsometric integral mean, it can be inferred that there stands a weak positive relation (Fig. 19) between the two aforementioned variables. Lastly also a weak negative relationship (Fig. 20) has been established between drainage density mean and the bifurcation ratio mean.

Table 1 Mathematical formulae for basin Morphometry

	Morphomctric parameters	Methods	References
Linear aspects	Stream order (Nu)	Hierarchical ordering	
	Stream length (Lu)	Length of the stream	Horton (1945)
	Mean stream length (Lm)	Lm = Lu/Nu	Horton (1945)
	Stream length ratio (Rl)	$Rl = Lu/L(u-1)$, where Lu is stream length order u and $L(u-1)$ is stream segment length of the next lower order	Horton (1945)
	Bifurcation ratio (Rb)	$Rb = Nu/N(u-1)$, where Nu is number of streams of any given order and $N(u-1)$ is number in the next higher order	Horton (1945)
	Rho coefficient (p)	$p = Rl/Rb$	Horton (1945)
Areal aspects	Drainage density (Dd)	$Dd = L/A$, where L is total stream length, A is area of watershed	Horton (1945)
	Stream frequency (Fs)	$Fs = N/A$, where N is total number of streams and A is area of watershed	Horton (1945)
	Drainage texture (Dt)	$T = Dd \times Fs$	
	Length of overland flow (Lg)	Lg = ½Dd	Horton (1945)
	Constant of channel maintenance (C)	$C = 1/Dd$	Schumm (1956)
	Form factor (Ff)	$Ff = A/Lb^2$	Horton (1945)
	Circularity ratio (Rc)	$Rc = 4\pi A/P^2$	Miller (1953)
	Elongation ratio (Re)	$Re = 2\sqrt{(A/\pi)}/Lb$, where A is area of watershed, π is 3.14 and Lb is basin length	Schumm (1956)
	Shape index (Sw)	Sw = I/Ff	Horton (1932)
Relief aspects	Basin relief (R)	$Re = H - h$, where H is maximum elevation and h is minimum elevation within the basin	Schumm (1956)
	Relief ratio (Rr)	$Rr = R/Lb$	Schumm (1956)
	Ruggedness number (Rn)	$Rn = R \times Dd$	
	Dissection index (Di)	$Di = R/Ra$, where Ra is absolute relief	
	Gradient ratio (Rg)	$Rg = Es - Em/Lb$, where Es is the elevation at the source, Em is the elevation at the mouth	
	Melton ruggedness number (MRn)	$MRn = H - h/A^{0.5}$	

Actually by mean-based analyses of different parameters regarding morphometric indices have put in forefront to us the minute intricacies of the nature and characteristic features of different minor geometric segments of the watershed in the gigantic river basin of Mahananda in Darjeeling district.

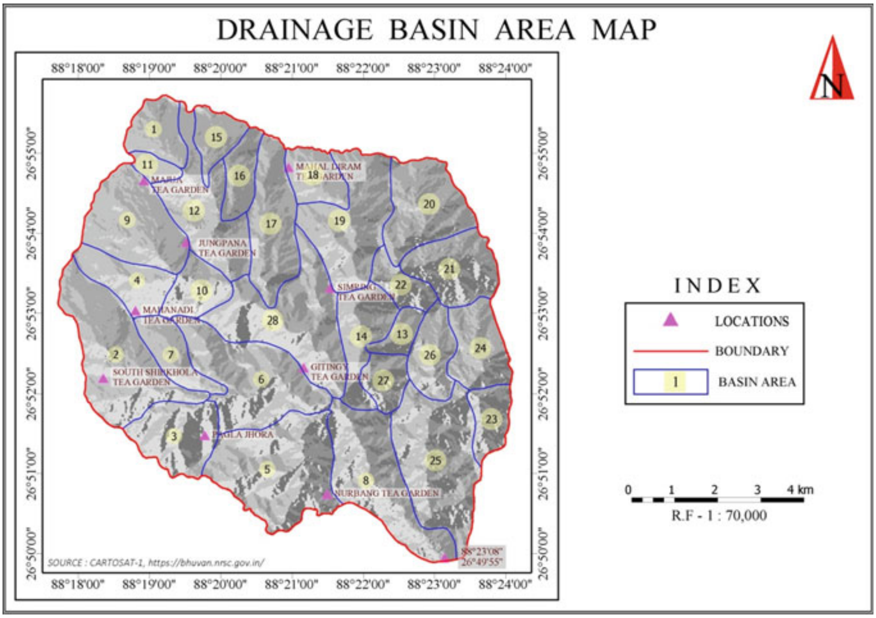

Fig. 14 Basin area map

7 Conclusion

In the aforementioned discussion, the morphometric analyses have been presented on manifold parameters with reference to the big drainage basin of Mahananda near Kurseong in Darjeeling District and actually the results of high and low degree of concentration of the values of multiple morphometric indices have been corroborated so that the reader can understand clearly the exact present situation of the target watershed. Lastly the bivariate regression analyses are also accomplished to decipher the positive and negative relationship between the variables. Through the value of Pearsonian r_{xy}, the strength and weakness of the positive and negative relationship has been manifested clearly.

Table 2 Latitude and longitude of the sub-basins of the Mahananda Basin

Sl. No.	Longitude in Easting (center-X)	Latitude in Northing (center-Y)
Area 1	88.3106	26.9135
Area 2	88.2953	26.8593
Area 3	88.3103	26.8488
Area 4	88.2986	26.8822
Area 5	88.3287	26.8373
Area 6	88.3213	26.858
Area 7	88.3127	26.8664
Area 8	88.3581	26.8315
Area 9	88.3007	26.8914
Area 10	88.3187	26.8821
Area 11	88.3116	26.9103
Area 12	88.3168	26.8898
Area 13	88.3276	26.8655
Area 14	88.3671	26.8745
Area 15	88.3605	26.8632
Area 16	88.3268	26.9096
Area 17	88.3333	26.9025
Area 18	88.3393	26.8843
Area 19	88.3482	26.9049
Area 20	88.3506	26.8875
Area 21	88.3711	26.8929
Area 22	88.3751	26.8846
Area 23	88.3681	26.8834
Area 24	88.3909	26.8512
Area 25	88.3862	26.8673
Area 26	88.373	26.8321
Area 27	88.3768	26.8652
Area 28	88.3656	26.8624

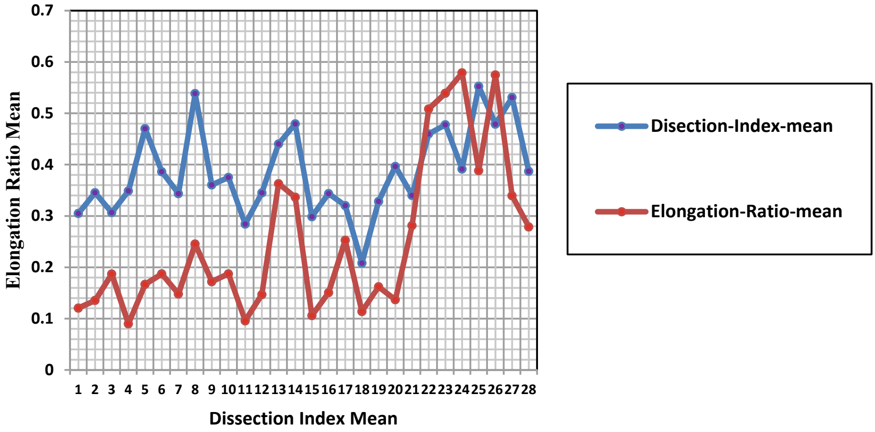

Fig. 15 Dissection index mean and elongation ratio mean

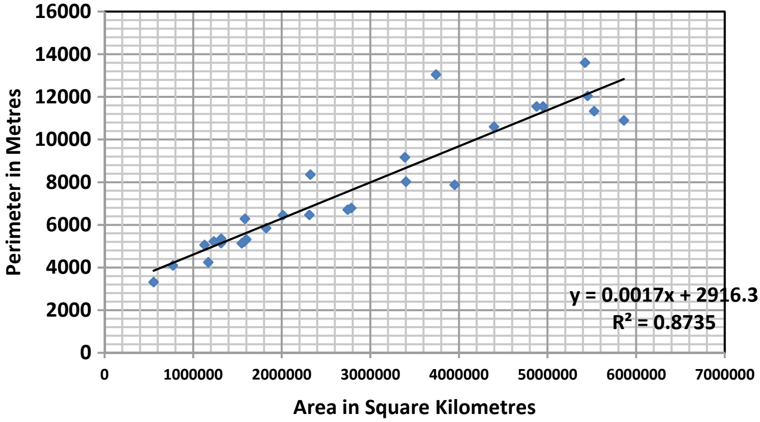

Fig. 16 Relationship between area in square kilometres and perimeter in metres

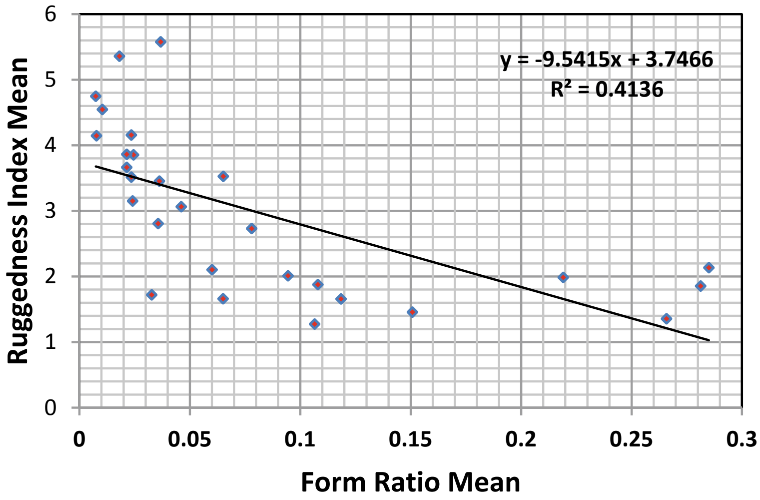

Fig. 17 Relationship between form-ratio mean and ruggedness-index-mean

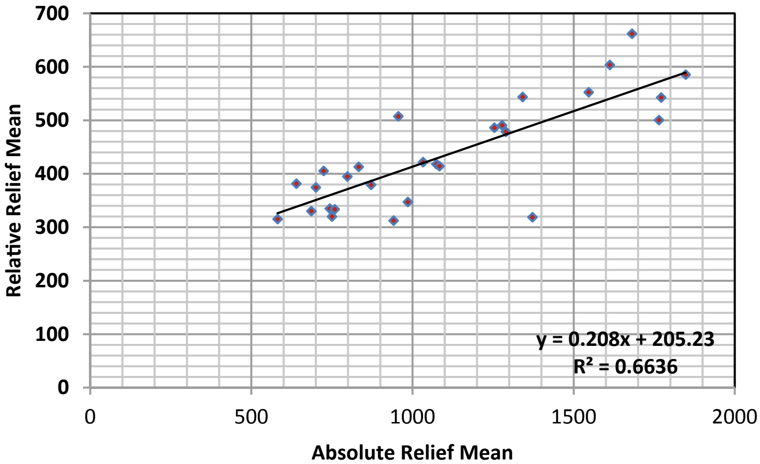

Fig. 18 Relationship between absolute relief mean and relative-relief-mean

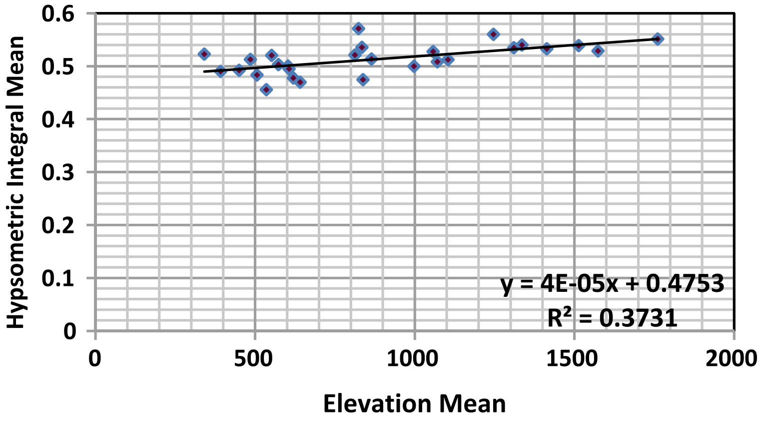

Fig. 19 Relationship between elevation mean and hypsometric-integral-mean

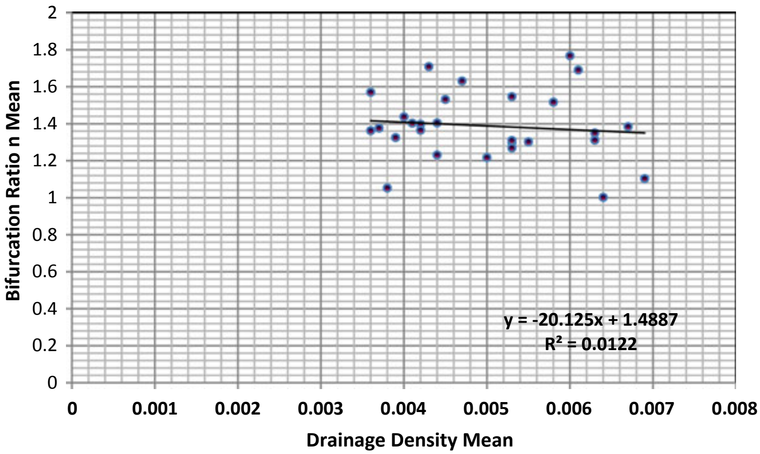

Fig. 20 Relationship between drainage density mean and bifurcation-ratio-mean

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Watershed Prioritization Based on Morphometric Analysis Using Geospatial Technique in the Upper Kasai Sub-Watershed of Purulia District, West Bengal (India)

Biraj Kanti Mondal, Rajib Das, and Rima Das

Abstract The current study intended to assess the watershed prioritization of upper Kasai sub-watershed of Purulia District of West Bengal, India, using geospatial technology. The study district is a drought prone and facing the problems of water scarcity and soil erosion, to prevent the degradation of these natural resources, watershed prioritization can significantly used. Thus, to delineate micro-watersheds of Kasai river basin area, watershed prioritization through morphometric technique has been attempted through the integration of RS and GIS. The study deals with the quantitative investigation of the various morphometry taking SRTM DEM, IRS P6, LISS-III and LISS-IV remotely sensed data. The application of the geospatial method was carried out for such geospatial and morphometric analysis in the Kasai sub-watershed to portray various physical setting and scientific information, like geology, geomorphology, slope, lineament, drainage, soil, land use land cover, etc. Moreover, the present estimation includes rectification of DEM, extraction of various derived layers, like slope, flow direction, drainage network, drainage density, soil erosion etc. The morphometric attributes covering linear, areal aspects and assorted parameters, like stream length, stream frequency, drainage density, drainage texture etc. was also carried out for the delineation of mini watershed area and thus, it is divided into 12 sub-watersheds. According to RUSLE model the area is characterized by potential average annual soil loss, which is especially high and severe (>1 to 15 t ha^{-1} $year^{-1}$) in the north-eastern and south-eastern parts of the watershed. Furthermore, the problem of water scarcity enduring in this area can be minimized through its prioritization and accordingly watershed management has been suggested. The outcomes facilitate the planner to formulate location specific plans and implement these effectively and therefore, it is useful for social benefits of the stakeholders at different levels for resilient management.

B. K. Mondal (✉)
Department of Geography, Netaji Subhas Open University, Kolkata, West Bengal, India
e-mail: birajmondal@wbnsou.ac.in

R. Das
Agarpara Mahajati Vidyapith, Kolkata, North 24 Parganas, India

R. Das
Department of Geography, Bhangar Mahavidyalaya, Bhangar, West Bengal, India

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Keywords Watershed prioritization · Kasai sub-watershed · Morphometric techniques · Geospatial technology · RS · GIS · Water management

1 Introduction

Watershed based development has been accepted as a successful method of sustainable development (Gajbhiye, Mishra, et al., 2014; Gajbhiye, Sharma, et al., 2014; Patel et al., 2012; Uniyal & Gupta, 2013). The watershed development projects have been undertaken in India since last few decades. Although there are some successful instances, but the majority of these projects are major failure. Moreover, watershed development project even where successful in terms of physical and financial aspect, there also lack of integrated approach towards sustainable development is found negligible. In most of the places, scientific inputs are lacking, detail reliable survey is missing and integrated scientific approach is absent (Singh et al., 2010; Smyle et al., 2014). As a result, not only huge amount of money is wasted at the same time the opportunity of restoration and regeneration of degraded natural resources is lost. Here, geoinformatics can play a very crucial role for making this integrated with purely scientific and accurate way. Using geoinformatics ensures various physiographic inputs like geology, geomorphology, runoff, oil, digital elevation model etc. and thus, scientifically valid development plan can be prepared at the time of execution (Magesh & Chandrasekar, 2014; Mesa, 2006). Furthermore, geoinformatics may help in forming deciding design parameters, even after execution of plan; impact assessment can also be done using various spatial and non spatial data.

This hydro-geologic technical term 'watershed' was initially used by the british to demarcate a common drainage area. It is considered as the catchment area that separating drainage basin from its neighbouring basin or catchment. There are a number of studies completed on the watershed priotization, especially for management (Balasubramanian et al., 2017; Bharath et al., 2021; Das et al., 2012; Dubey, 2020; Pande & Moharir, 2017; Shrivatra et al., 2021). The morphometric analysis of watershed was also studied by diverse aspects by many researchers as it gives valuable information necessitates for its conservation and management. The watershed characteristics, geometry, geologic character, drainage features etc. are very significant for groundwater and soil erosion studies at that level. The application of geospatial techniques is very significantly used in some earlier studies (Iqbal, 2012; Manjunath & Suresh, 2014; Panhalkar et al., 2012; Patel et al., 2012; Vandana, 2013).

The present study area belongs to the western upland of Purulia district of West Bengal. This is a part of eastern periphery chhotonagpur plateau consisting of hard crystalline rock of Archaean age. Geomorphologically the area is characterized by an upland area with rolling topography which gradually lies out toward east. The area often suffers from severe drought and acute shortage of water specifically for domestic and drinking purpose. Apart from that soil erosion is a major problem of the area. The objective of the present study is exploration of possibility of using geoinformatics in soil conservation and surface and ground water management. In spite of sufficient rainfall, proper ground water recharging cannot take place due to comparatively lower time of concentration as a result of undulating topography. Moreover, the ground water level is stored in the zone of secondary porosity with low permeability unsustainable yield. Ground water mostly found in the weathered mantle zone (maximum depth of 25 m below ground level), where the weathered mantle is in the top and fresh rock is in the bottom and therefore, it is located in between saprolitic zone and fracture zone. Moreover, the surface water bodies having insufficient catchment area do not get recharge even during the monsoon season. Therefore, the tanks get dried up due to seepage and evaporation loss in most of the time of the year and consequences water insufficiency and crisis is observed in the area. Besides, all kinds of soil erosions such as sheet, rill, and gullies are occurred, which enhances due to lack of sufficient vegetation cover, deforestation, over utilization less capable land resource, lack of conservative measures.

Globally, it is observed that human always trying to adapt in difficult or challenging environment mostly by changing the landforms and its operational process. Thus, human plays a significant role in changing landscape and thus, they often execute associated problems and difficulties knowingly and or unknowingly. The current study area is facing high soil erosion and water scarcity related problems mostly due to the geologic, lithologic, physiographic, hydrologic and climatic setting and the continuous land use land cove changes carried out by the stakeholders aggravated the situation. The cleaning of forest cover, changing cropping pattern etc. by the anthropogenic agent accelerated the rate of soil erosion and due to the lack of knowledge about the features of the watershed, the problems enduring extensively in the area since very long. Moreover, the area strictly adheres to the conventional agricultural practices, which is low yielding in nature. Besides, crop failure due to erratic rainfall even during monsoon season as most of the area does not received assured irrigation. This enhances the economic stress and there is a lack of alternative income opportunity since the backwardness persists and most of the inhabited people is belongs to BPL category. These, interconnected consequences like a chain with other major social problems like illiteracy, migration, insurgences are making them more vulnerable to any hazardous circumstances and that are increasing day by day. In spite of getting sufficient attention, since the area's long considerable progress has not been achieved due to improper planning especially for faulty implementation mechanism, the area is getting worsen gradually. It is imperative that geoinformatics can play very crucial role in execution of proper planning in such a area as this technique may reduce the necessity of extensive survey work. It can easily integrate various scientific inputs, like geology (lithology, fractures, folds, faults) hydrogeology (aquifer characteristics, thickness), geomorphological features (landforms, relief, slope, ruggedness, surface driange), hydrology (runoff characteristics, peak discharge, drainage network), soil (thickness, texture), DEM etc. and thus be created a scientific framework. These inputs are scientifically valid and therefore, sustainable and resilient development plan can be prepared, implemented and monitored. At this juncture, the execution of geoinformatics in the current study may help in the formation of plan, decision making, designing parameters etc., even after execution, impact assessment can be done.

The morphometric analysis of watershed and its developemnt related researches have been conducted in other parts of India (Mantry & Vyas, 2013; Panhalkar et al., 2012; Patel et al., 2012; Patel, Gajjar et al, 2012; Patil & Mali, 2013; Sangita & Nagarjun, 2010; Sarma & Saikia, 2012; Singh et al., 2014) using RS and GIS as a technique and by employing diverse methods, but very limited researches have been found related to the present study area. Some studies have been conducted in the Purulia district, especially in its western part about drainage morphometry (Das et al., 2012; Nag, 1998), morphometric parameters and hydrological processes (Dolui et al, 2022), watershed and soil erosion (Saha et al., 2018), geo-hydrological condition of sub basin of Kangsabati river (Modak et al., 2018), land degradation (Chakrabarty & Chatterjee, 2008; Saini et al., 1999), ground water (Mondal, 2012), water scarcity (Halder & Saha, 2015); forest degradation (Manna & Mondal, 2017) etc., but this kind of watershed priotization is attempted newly. Therefore, to execute the research gap of addressing the issue of soil erosion and water scarcity accelerated by anthopogenic agents, this attempt has been made. The rationale of the study lies in the fact that the study employed the geospatial techniques to estimate and mapped the study area, potrayed the nature and status of the problems enduring in the area by using recent remotely sensed data morphometriclly and scientifically. The geospatial techniques is the best suitable method to analyze the drainage basin and watershed morphometry, prioritization of sub-watershed and to assess the rate of soil erosion and related water management. It also reveals that the delineation of mini sub-watershed using diverse methods employing the satellite data and its prioritization have been attempted to suggest location specific plans for soil conservation and surface and ground water management.

Objectives:

The prime objective of the present study is to assess the watershed prioritization of Kasai sub-watershed of Purulia district of West Bengal, using geospatial technology. Specifically the objectives can be explored in a splitting way like:

1. To prepare various thematic maps, like geomorphology, slope map drainage map, weathering profile map, specific yield map, land use land cover etc. by integrating the scientific information of geology, physiography, hydrology, soil including the thematic maps using GIS platform.
2. To delineation of mini watershed and catchment areas by using DEM for the prioritization of watershed by physically based methods, like delivery ratio and morphometric techniques using GIS.
3. To design the water resource management, soil conservation, land resource management plans through integration of various thematic layers in GIS environment.

2 Materials and Methods

2.1 Study Area

The present study is concentrated on the Kasai sub-watershed, which is a part of Kongsaboti watershed and covers an area of about 276.20 sq. km. The area extended from 23°13′26″N to 23°28′33″N latitude and 85°17′18″E to 86°11′56″E longitude (Fig. 1). The prime river of the study area is Kognsaboti, also known as Kasai, which comes from the Chhotonugpur plateau and entered in the Purulia district near Jhalda, then it passes by Khatra and Ranibandh in the Bankura district and finally entered in the Paschim Medinipur district near the Banipur area. At Keshpur the river split into two branches; the northern branch flows through the Daspur area (named as Palarpai) and joins the Rupnarayan river; while the other branch flows in south-eastern direction and joined with the Kaliyaghai river and Mukutmonipur, Midnapur and Kharagpur are the known towns found near the bank of the river. The study region is characterized by granite-gneiss geological features which denotes its undulating plateau upland with periodic hilly terrain. Moreover, the sub-humid climate with high temperature and more surface runoff than seasonal rainfall accounts soil erosion and water scarcity related problems. The soils with less organic matter generates immature and weak soil horizons and thus, less vegetation cover is observed in the area. Furthermore, due to undulating nature and moderate to steep slope, the residual material very often undergoes deep weathering in certain places.

2.2 Methodology

The methodology of the entire work is presented by the figure (Fig. 2).

Delineation of Watershed Boundary from DEM:
In the current study, the rectification, flow direction, flow accumulation, drainage extraction, delineation of watershed boundary using SRTM DEM were employed. With the help of SRTM DEM and other remotely sensed data, some significant morphometric parameters were considered, the methodology of which are mentioned below:

Drainage Features: Drainage Density, Bifurcation Ratio, Stream Frequency, Texture Ratio were considered.
Watershed Features: In it, the Form Factor, Circularity Ratio, Elongation Ratio, Compactness Constant were employed.

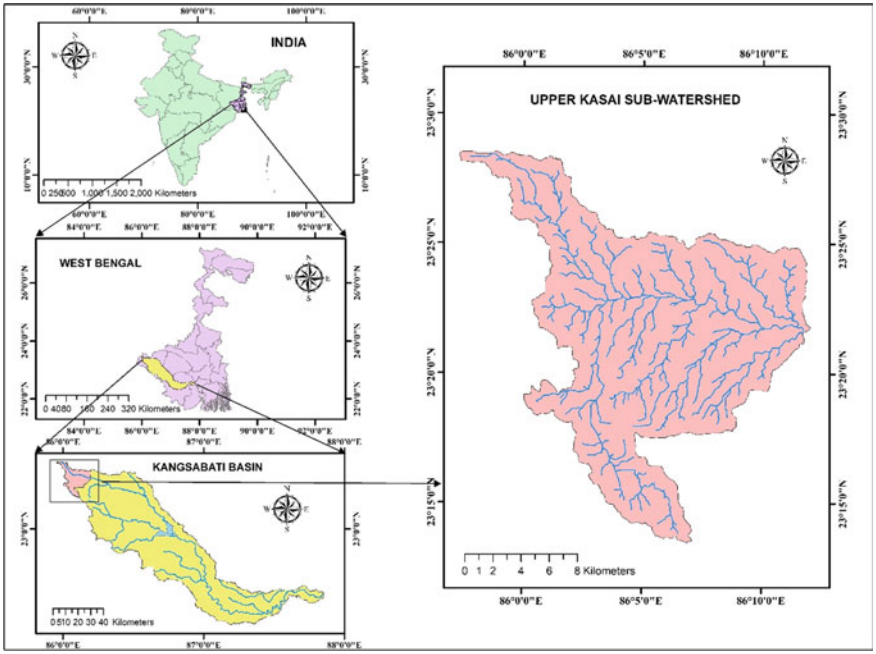


Fig. 1 Location of the study area

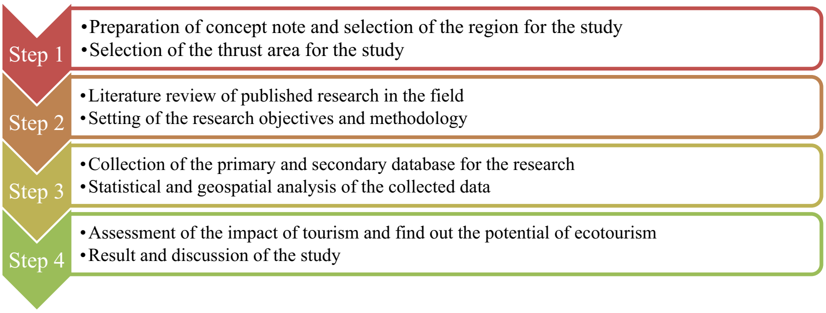


Fig. 2 Structural framework of the study

Delivery Ratio: The ratio of transportation of eroded soil to outlet point was also taken into consideration.

Methodology of using Morphometric Techniques:

- The delineation of mini watershed from DEM.
- The drainage map was prepared using remotely sensed satellite image data.
- The stream order was determined using Horton’s Law.

- The significant morphometric parameters, value of each parameters, namely stream length, bifurcation ratio, drainage density, stream frequency, form factor, texture ratio, elongated ratio, circularity ratio and compactness constant were calculated.

The prioritization rating of all the 12 mini watersheds was carried out by calculating the compound parameter values. In it, the mini watershed with the lowest compound parameter value was given the utmost priority.

Methodology for using RUSLE model:

To determined the Revised Universal Soil Loss Equation (RUSLE), the universally accepted standard empirical erosion model, the study have considered five parameters for the equations, like—Rainfall runoff factor (R), Soil erodibility factor (K), Support practice factor (P), Crop/Vegetation and Management factor (C), Slope length factor (LS) (Markose & Jayappa, 2016; Naqvi et al., 2012; Renard et al., 1997; Saha et al., 2018).

After the determination of the Rainfall runoff factor (R), the Soil erodibility factor (K) factor values were calculated and added these values in the soil attribute table. Then masteries the soil layer with K value. Thereafter, the crope /vegetation and management factor (C) values were considered and added in the land use attribute table. Then, the rasterising the land use layer was matched with the identified support practice factor's (P) value. Then, reclassify the prepared map. Finally, the potential soil loss has been determined using given formula in raster calculator:

$$A = P\,x\,K\,x\,C\,x\,R\,x\,LS \tag{1}$$

Rainfall run-off modeling

The hydrological features of the study area have been considered to understand the nature of runoff occurring which helps for locating and designing various water harvesting structures.

Methodology for estimation Peak Rate of Run off

- The determination of the catchment of check dam from the DEM in the GIS environment.
- Then union these thematic layer like hydrological soil group, land use and catchment of the check dam
- Determined the curve number for each catchment of the check dam from the SCS curve. The higher the curve number signifies the greater runoff.
- Estimate the weighted curve number value of the entire watershed.
- Adjust the value of CN depending on the antecedent moisture condition, where generally CN is given for AMC-II. Therefore, the adjustment for AMC-I & III is done.

- Determined the Tc of the each catchment using Tc = 0.0195 Kc ^ 0.77, and determined the Tp using equation:

$$Tp = 0.6Tc + (Tc)^\wedge 0.5 \tag{2}$$

- Then determine the S = Maximum Potential Storage (in mm) using this formula:

$$S = (25400/(CN - II) - 254) \tag{3}$$

- Then computed the Runoff Qd by using the formula:

$$Qd = (P - 0.2S)^\wedge 2/(P + 0.8S)(Qd = \text{Run off depth cm}) \tag{4}$$

- Determined the area from each catchment area of check dam
- Maximum elevation of height was determined from the DEM.
- Maximum flow length was determined from each catchment by using measuring tool of GIS.
- Finally peak rate of runoff was calculated by using the formula:

$$Qpeak = (0.0208X\ A\ X\ Qd)/Tp\ \text{(Qpeak = peak rate of runoff Cumec)} \tag{5}$$

Methodology for watershed prioritization using the delivery ratio
The watershed prioritization using the delivery ratio is calculated by the following equation:

$$DR = 1.366\, x\, 10^{-11} x \left(DA^{-0.0998}\right) x \left(ZL^{0.3629}\right) x \left(CN^{5.444}\right) \tag{6}$$

(Where, DR—Delivery Ratio; DA - Drainage Area [in Sq. km]; ZL—Relief Length Ratio [in m/km]; and CN- Long-term average of SCS Curve number).

2.3 Data used

The present study concentrated on the secondary data along with the execution of advanced remotely sensed data using geospatial technique. In the current study, several datasets have been used integratedly according to the need, like Topographical sheets ((73 I/3, 73 I/4, 73I/7, 73 I/8; R.F. 1:50,000) of Survey of India; Shuttle Radar Topography Mission (SRTM) data of 30 m resoulution; IRS P6, LISS III, LISS IV remotely sensed data; soil data of NBSS & LUP (National Bureau of Soil Survey and Land Use Planning; rainfall data of India Meteorological Department five years (2014–2018). All the data used, its structural methodology, and analysed maps of the entire work is presented by the figure (Fig. 3).

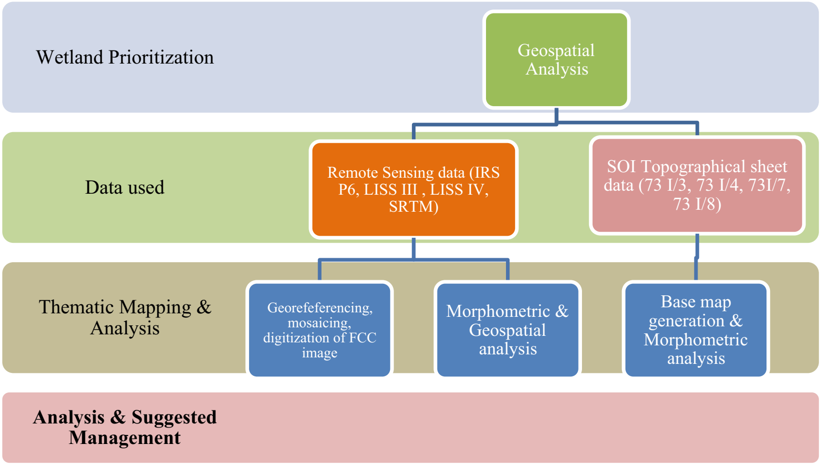


Fig. 3 Data used and its structural methodology

2.4 Data Analysis

The remotely sensed data and topographical data was analysed using the geospatial environment by using ArcGIS (10.3) and Edras Imagine software (2014). The SRTM DEM was created apart from the preparation of base map from the SOI topographical sheets for the morphometric analysis. Several thematic layers were prepared in the GIS environment considering the multi-criteria, like geomorphology, geology, slope, lineament, drainage, soil, LULC, specific yield, water tabe fluctuation, weather profile. All these criteria were analysed, ranked, weighted and produced watershed priotitization maps both using morphometric analysis and delivery ratio. After completing such, the soil erosion map and suggested soil conservation map were also prepared. Thereafter, suggested check dam, water harvesting structure map, proposed LULC maps were prepared for land resource management were also carried out.

Morphometric Analysis:
In the study, the delineation of micro-watersheds of Kasai river basin area and the prioritization of these sub-watershed through morphometric technique has been attempted through the integration of various morphometric parameters (Table 1) by employing the geospatial technique. Here, the parameters are related to areal, linear and relief aspects; the estimation of each parameters are computed using standard numerical formula and their descriptions are mentioned accordingly.

Table 1 Morphometric parameters and methodological formula

Parameters	Caculation Formula	Description	References
Areal aspect			
Drainage density (Dd)	Dd = L/A	L = Length of a stream; A = Sum of the area of pixels through which the stream flows	Horton, 1945
Drainage texture ratio (Td)	T d = N1/P	N1 = Total number of 1st order stream; P = Basin perimeter	Horton, 1945
Stream frequency (Sf)	Sf = N/A	N = Total number of streams in particular stream order	Horton, 1945
Circulatory ratio (Rc)	Rc = 4π × basin area/square of basin perimeter		Miller, 1953
Elongation ratio (Re)	Re = $2\sqrt{(A/ð)}/Lb$	A = Diameter of a circle having area as same as basin; Lb = Maximum basin length, ð = 3.14	Schumm, 1956
Form factor (Rf)	Rf = A/ Lb^2	A = Basin area; Lb^2 = Square of maximum basin length	Horton, 1932
Compactness coefficient (Cc)	Cc = $0.2821P/A^{0.5}$		Horton, 1945
Shape basin (Bs)	Bs = $Lb^{2/\,A}$	Lb^2 = Square of maximum basin length, A = Basin area	Ratnam et al., 2005
Linear aspect			
Stream order (U)		Hierarchical rank	Horton, 1945
Stream length (Lu)		Lu = Total length of streams in particular stream order (km)	Horton, 1945
Bifurcation ratio (Rb)	Rb = Nu/Nu + 1	N = Number of streams of one order, Nu + 1 = Number of streams of next higher order	Schumm, 1956
Stream length ratio (Rl)	Rl = Lu/Lu-1	Lu = Total length of streams, Lu-1 = Total stream length of next lower order	Horton, 1945

(continued)

Table 1 (continued)

Parameters	Caculation Formula	Description	References
Relief aspect			
Evevation (E)		Generated from SRTM DEM	
Basin relief (Bh)		Bh = Vertical distance between higher and lower points	Horton, 1945
Relief ratio (Rh)	Rh = Bh/Lb	Bh = Basin relief, Lb = Basin length	Schumn, 1956
Ruggedness number (Rn)	Rn = Bh x Dd	Bh = Basin relief, Dd = Drainage density	Moore et al., 1991
Actual slope (Sa)		Slope of a particular pixel area generated from DEM	
Lineament (L)		Lineament of the area generated from DEM	

3 Result and Discussion

3.1 Watershed Prioritization Using Morphometric Technique

The current study considered some significant parameters to prepare the thematic maps, like geomorphology, geology, slope, lineament, drainage, soil, land use land cover, specific yield, water table fluctuation, weathering profile. The illustration of the each criteria was tabulated in a table, which is self descriptive (Table 2). The thematic maps of the multi-criteria for morphometric and geospatial analysis for watershed prioritization were nested below (Fig. 4 to 7) and it reveals from the description and illustion that it is very much imperative in the study. Each thematic layers of the multi-criteria were used to prepared the watershed prioritizatio maps; some selected criteria were used to prepare the soil erosion map; and most of the criteria were combinedly used to prepare the conservation and management maps of soil, water and land resources and the methodology of each was described in the concerned section. These scientific information of geology, physiography, soil, drainage, LULC etc. are usefull to delineate the mini watershed and the suggested measures, like check dam location, water management are suggested accordingly.

All these morphometric criteria were analysed, ranked, weighted to produced the watershed priotitization maps using morphometric technique (Fig. 8). The entire study region was divided into 12 sub-watershed based on the watershed priority rank.

Table 2 Description of the multi-criteria

Criteria	Illustrative description
DEM (Fig. 4a)	The Digital Eevation Map (DEM) of the study area is prepared using the SRTM (Shuttle Radar Topography Mission) data to observe the elevation of the study area. It revels that the area is mostly ranges from 233 to 652 m. The higher elevation i.e. about more than 300 m is positioned in the north-western and lower middle to south and south-western parts of the study area. The drainage basin has the comparatively lower elevation
Geomorphology (Fig. 4b)	The area is covered by the six geomorphological units, among which the buried pediment shallow and medium, hill wash deposition covered the most of the area. The hills are located in the north-west and southern part; pediments are sparsely distributed and valley fill are observed in the area of tributaries and sub-tributaries. A water reservoir is found in the south-western parts
Geology (Fig. 4c)	The area is geologically very significant. The chotonagpur granite gneiss complex and quartz texture granite gneiss; chotonagpur granite gneiss complex geo-hydrostatic granite gneiss and unclassified sedimentary and igneous are the major rock coverage of the area. Apart from that the alluvium deposits are also noticed in the southern part
Slope (Fig. 4d)	The area has a slope ranges from 1° to > 35°. Most of the segments besides the streams have the slope up to 10° and those are located in the east to west part (approximately 75%). The slopes 15° to 35° and above are mostly observed in the southern parts
Lineament (Fig. 4e)	The lineament of the area is almost same in the middle to uppert parts, while they area very haphazardly found in the southern parts of the area
Drainage (Fig. 4f)	The micro watershed of the region is covered by first order to fifth order streams. The main river is belongs to fifth order. There are a noticeable number of pond are observed mostly in the middle to northern parts
Drainage Density (Fig. 4g)	The study area is covered with upto 823 km/km^2 drainage density. The densities are grouped into five zones; and the prime Kasai river with its tributaries, mostly located in the central part of the study area, have the higher (>500 km/km^2) density value
Soil (Fig. 4h)	The entire region is mostly covered by three main soil types. Fine loamy and loamy skeletal covers the maximum coverage, whereas, coarse loamy soil is mostly located in the middle and southern parts
Specific yield (Fig. 4i)	The proportion of specific yield of the region is ranges from 3 to 20%. Most of the area is covered by 5%, followed by 8% and 3%

(continued)

Table 2 (continued)

Criteria	Illustrative description
Land use land cover (Fig. 5)	Forest, agricultural land, waterbody, wasteland and settlement are the major land use and land cover of the region. Forest area is prewhile the west land are observed in the eastern parts. dominant in the southern part while settlement is good enough in the upper parts connected by the required transport. The agricultural lands are is mostly observed in the middle part,
Water table fluctuation (Fig. 6)	The water level fluctuations of the entire region is 2 to 4 m and mostly observed in the western to eastern parts. A patch of 4 to 5 m was found in the northern and north-western parts
Weathering profile (Fig. 7)	The depth of saprofile is varied from 7 to 14 m, by which we can imagined the weather profile. Most of the area is covered by 9–12 m (approximately > 75%). Comparatively lower values are located in the north-western parts, whereas a small patch of 12 to 14 m is located in the northern part like a ring like pattern

3.2 *Watershed Prioritisation Using Delivery Ratio*

The sediment yield of the drainage basin is the total amount of sediment moved by sheet erosion and channel erosion (Chowdary et al., 2013; Sharada et al., 1993; Walling, 1983), which was calculated by using the delivery ratio (Table 3).

The watershed prioritization map was prepared besed on the calculated delivery ratio (Fig. 9). The Kasai river basin area was divided into 12 sub-watershed through this method.

3.3 *The Necessity of Watershed Prioritization*

The watershed priorization was utmostly felt due in the current study and therefore, the divisions of sub-watershed was completed and thereafter from an diverse angle the cause and concern's of the watershed priotization was tabulated (Table 4). This helps to understand the areas scenario and accordingly the managements procedure is prescribed for the area.

3.4 *Estimation of Soil Erosion*

The estimation of soil erosion is very essential in the watershed area as here the rate of soil erosion is affected by four main factors, i.e. climate, soil, topography/slope and vegetation. In the current study region, climate determines how much rain will occur in an area; soil characteristics determine erodibility and infiltration rates; topography or slope determines the velocity of runoff and the energy water may cause erosion;

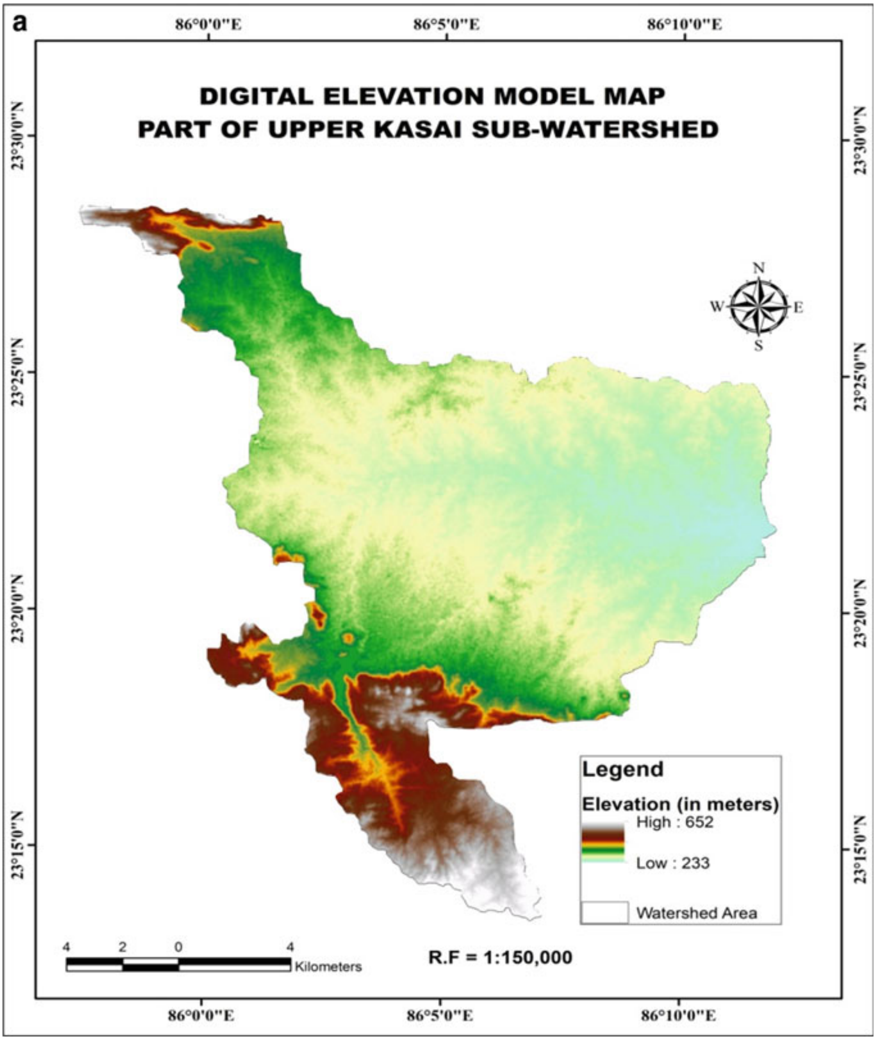


Fig. 4 (**a**) DEM map of the study area; (**b**) Geomorphology map; (**c**) Geology map; (**d**) Slope map; (**e**) Lineament map; (**f**) Drainage map; (**g**) Drainage density map; (**h**) Soil map; (**i**) Specific yield map

and vegetation controls the runoff and prevents erosion by holding soils in place. The RUSLE model is used to estimate the soil erosion and the outcomes was plotted in a map (Fig. 10). The morerate to high erosion were mostly observed throughout the region, while severe erosion was noticed in the eastern and south-eastern parts of the region. The potential soil loss of the watershed ranges from < 0.014 to 15 t ha^{-1} $year^{-1}$. The soil erosion isgrouped into four zones and most of the watershed

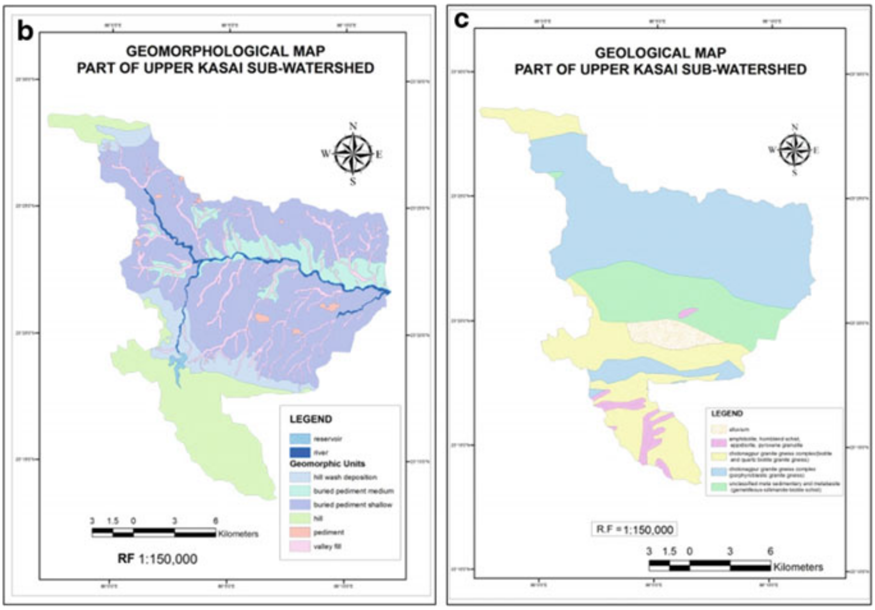


Fig. 4 (continued)

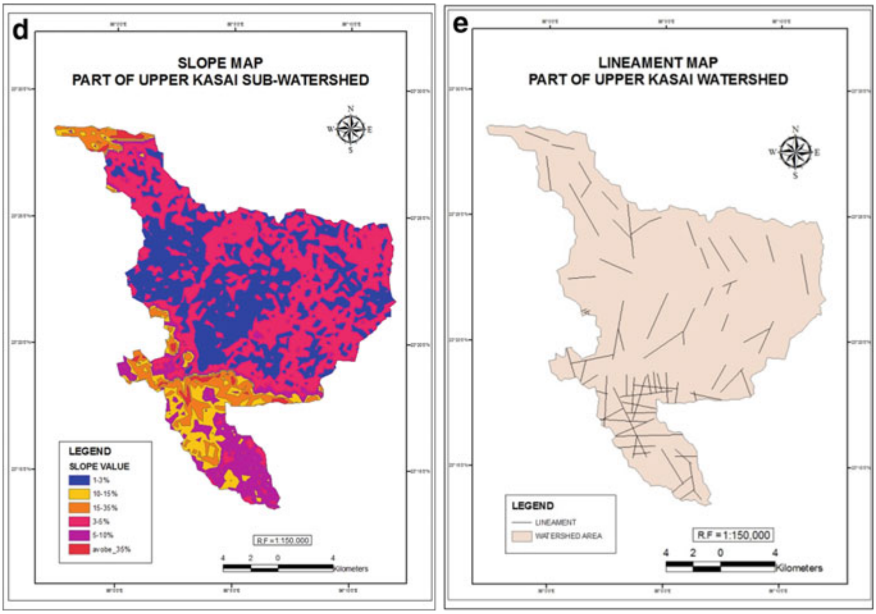
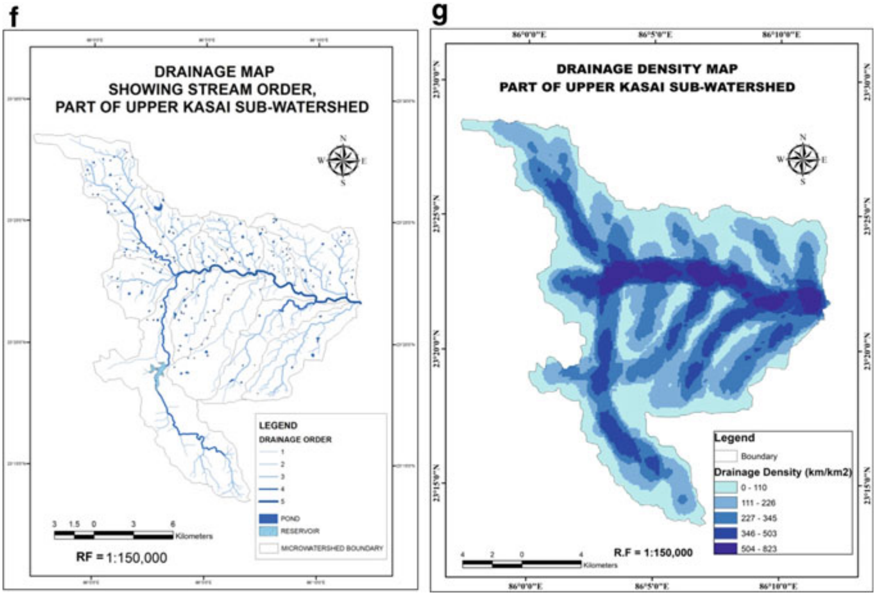


Fig. 4 (continued)



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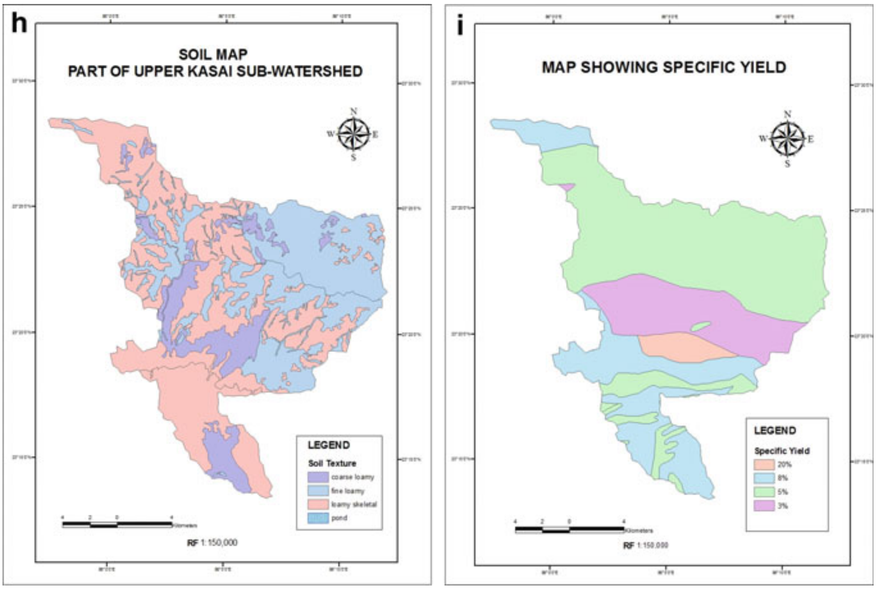

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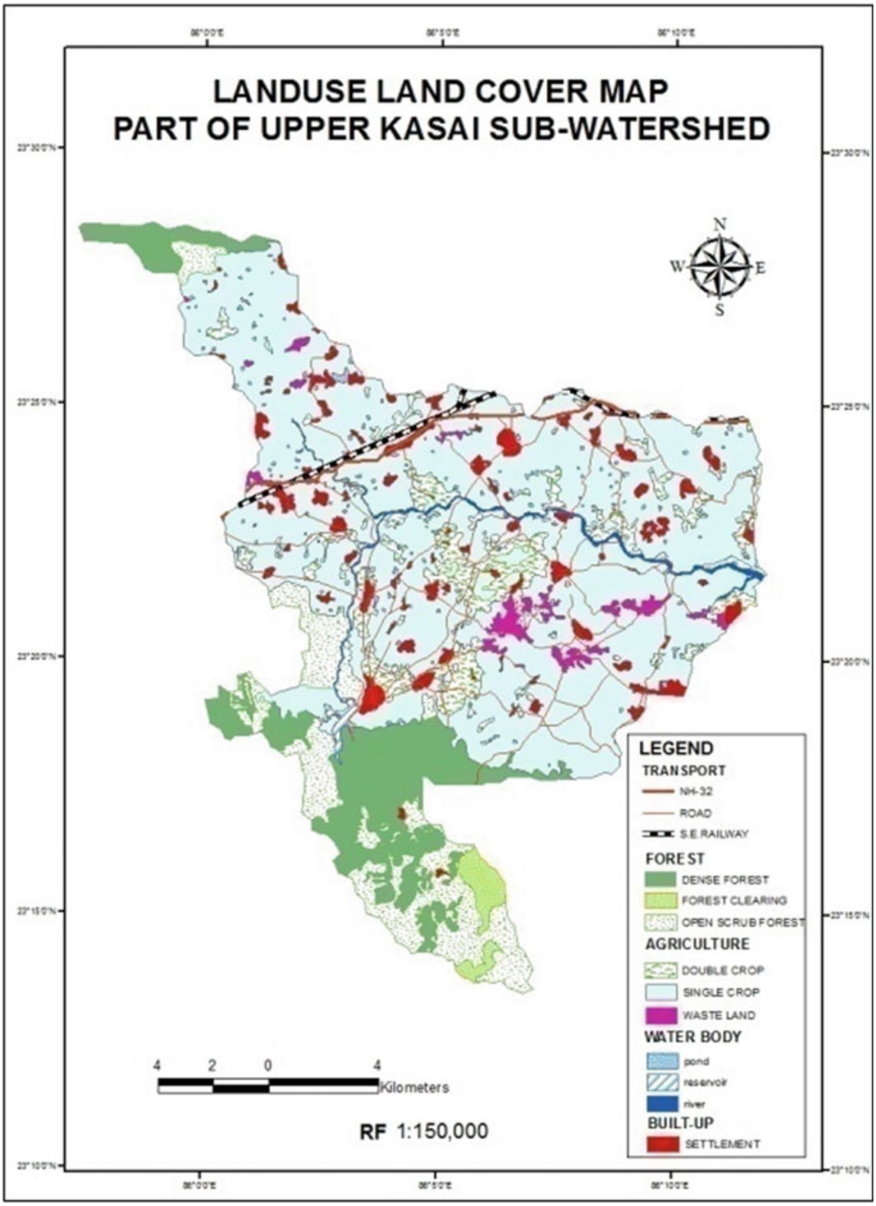

Fig. 5 Land use Land cover map

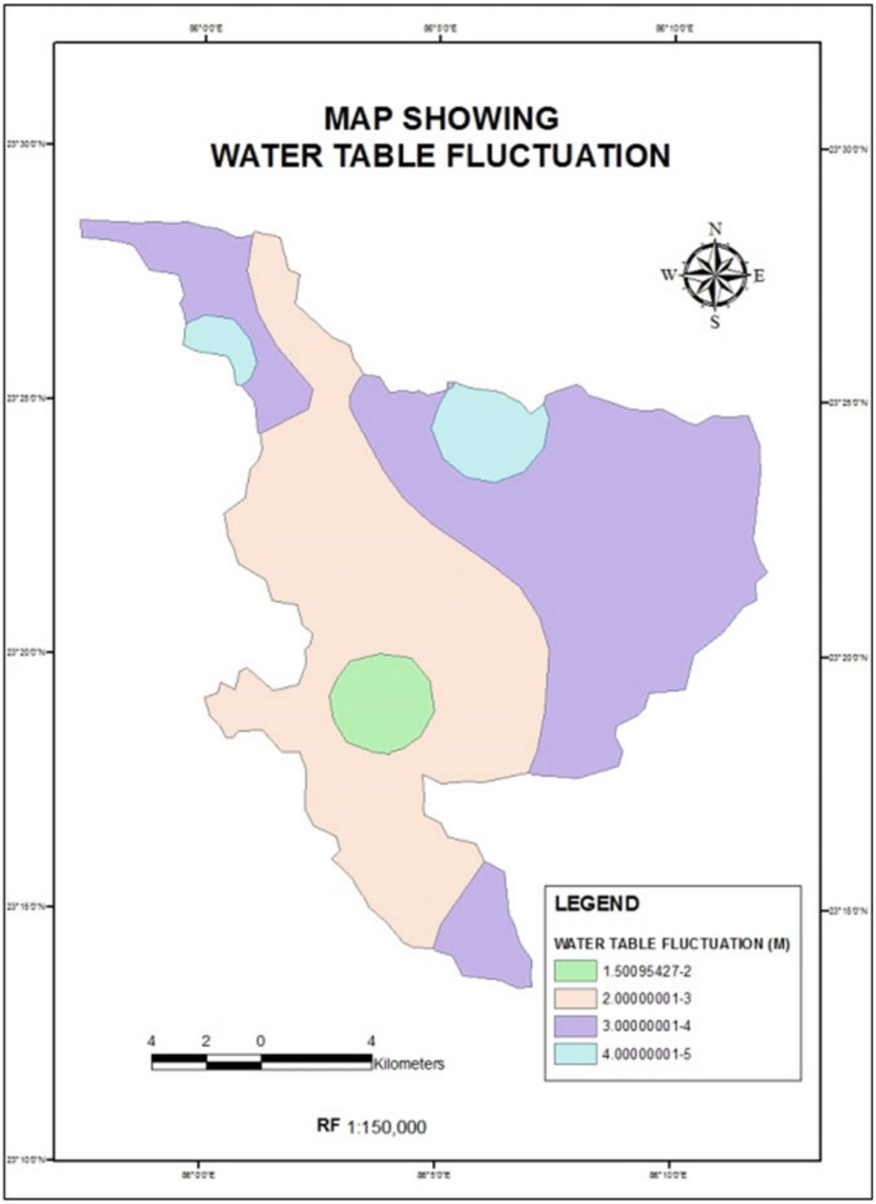

Fig. 6 Water table fluctuation map

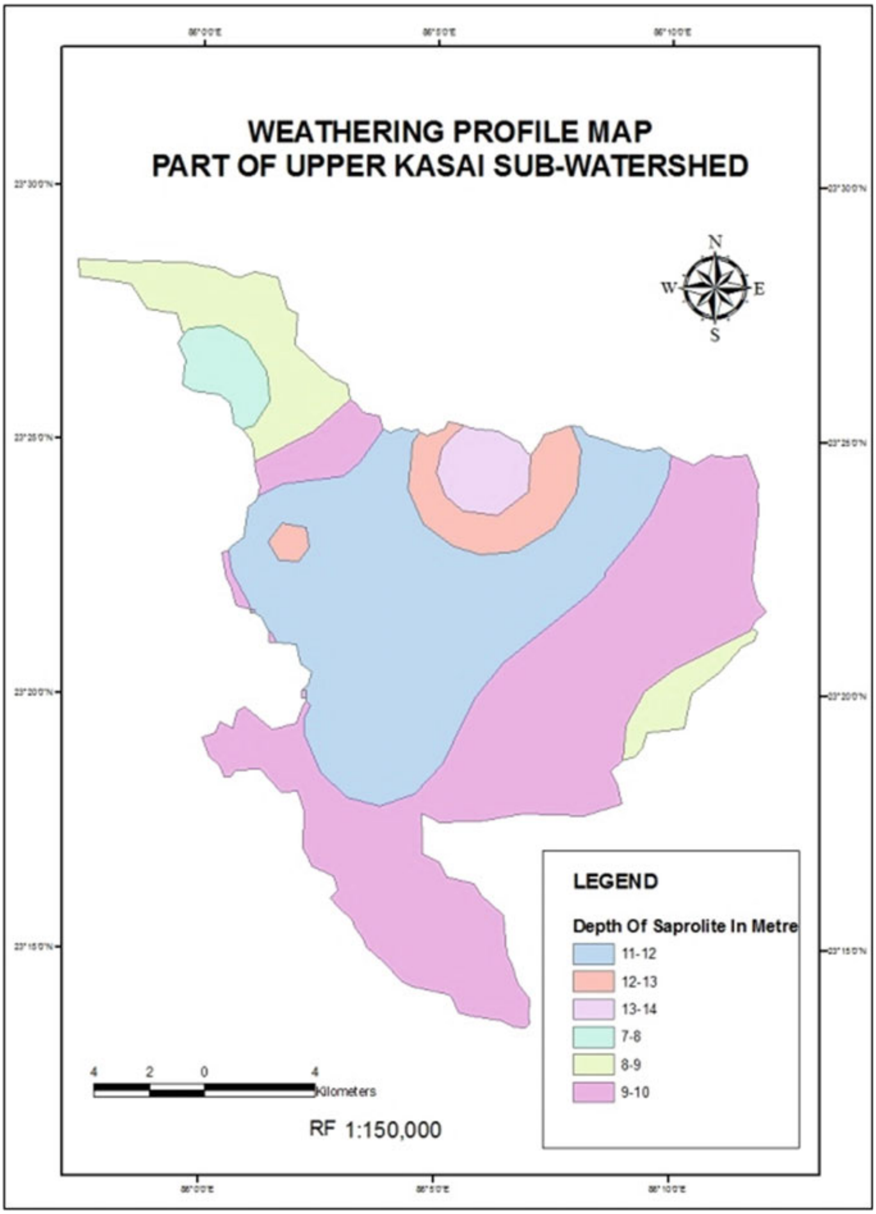

Fig. 7 Weathering profile map

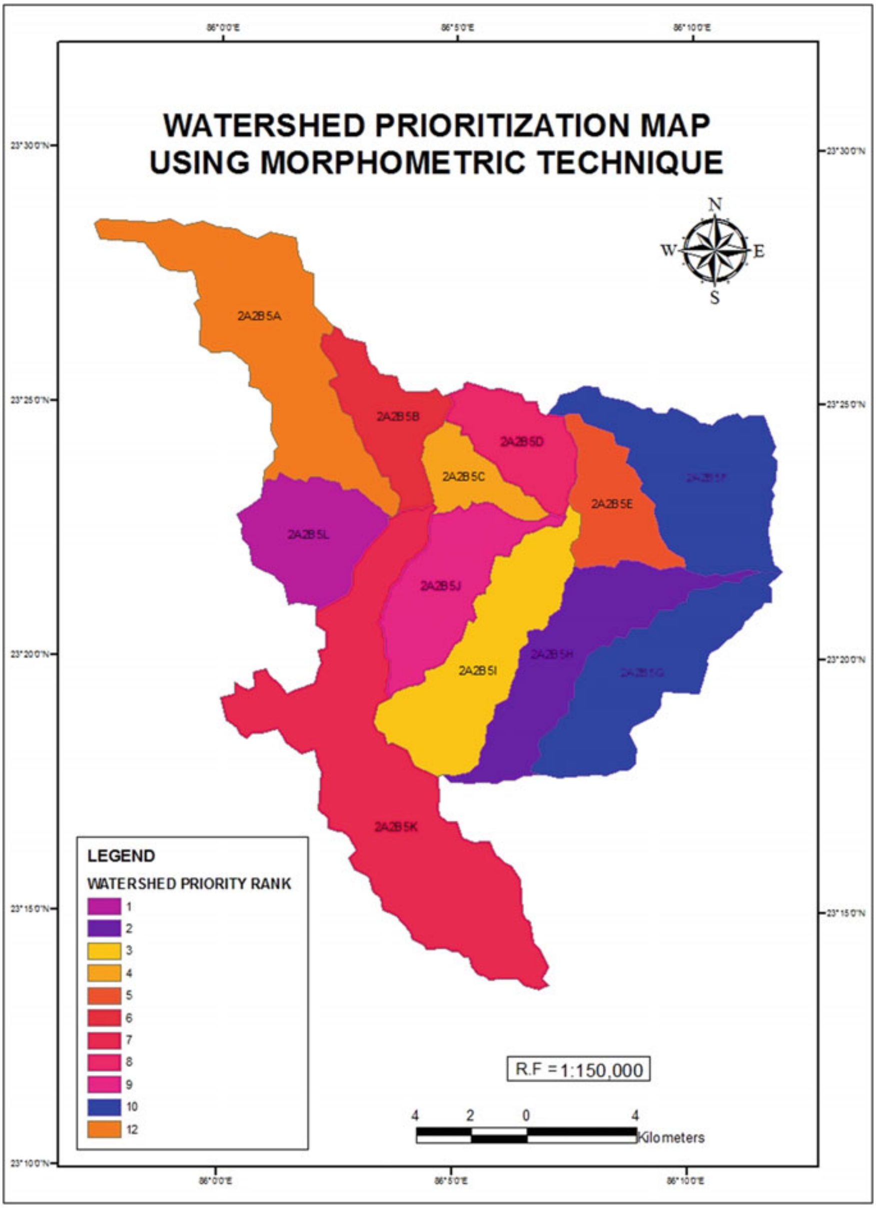

Fig. 8 Watershed prioritization map using morphometric technique

Table 3 Calculation of watershed prioritisation using delivery ratio

Mini Watershed	Max. basin length(KM)	Elevation (Mt.)	Relief length ratio (Mt./Sq. KM)	Weighted CN (long term average)	Area in Sq. KM (DA)	Delivery Ratio	Rank
2A2B5A	15.186	352	23.18	70.44	38.3630	0.34	10
2A2B5B	7.339	49	6.68	70.07	13.7994	0.23	12
2A2B5C	3.274	30	9.16	78.27	7.95581	0.50	4
2A2B5D	5.74	44	7.67	78.38	12.9775	0.45	7
2A2B5E	6.785	46	6.78	79.21	13.2698	0.46	6
2A2B5F	9.992	61	6.10	79.44	29.0271	0.41	9
2A2B5G	9.882	171	17.30	77.35	25.2923	0.53	3
2A2B5H	9.648	302	31.30	77.59	24.2692	0.67	1
2A2B5I	10.595	290	27.37	74.11	26.9194	0.49	5
2A2B5J	7.805	61	7.81	77.92	19.2308	0.43	8
2A2B5K	20.745	311	14.99	68.62	61.7108	0.24	11
2A2B5L	5.204	139	26.71	77.18	17.1063	0.64	2

area is characterized by low to moderate erosion. The high to severe zones are mostly observed along the rivers.

3.5 Soil Conservation and Management Plan

Soil is the basic and essential resource and in the study it is found very much vulnerable due to various erosion processes, like sheet, rill, gully erosion. This soil erosion creates some critical problem like, crop production, siltation of tanks, flood etc. Thus, a soil conservation map was prepared (Fig. 11) and the entire region is categorized into four zones accordingly. In the southern area where gully erosion is higher, gully plugging and bench terracing (southern and north-western parts) are suggested. The countour building or trenching was also suggested in the area of the middle, eastern and western parts of the region. While, the entire region needs mostly the strengthening of existing soil conservation measures. All these practices should be undertaken to control the soil erosion and to increase the vegetation cover, especially in the non-agricultural fields, which definitely helps in reducing the major problems regarding soil and water.

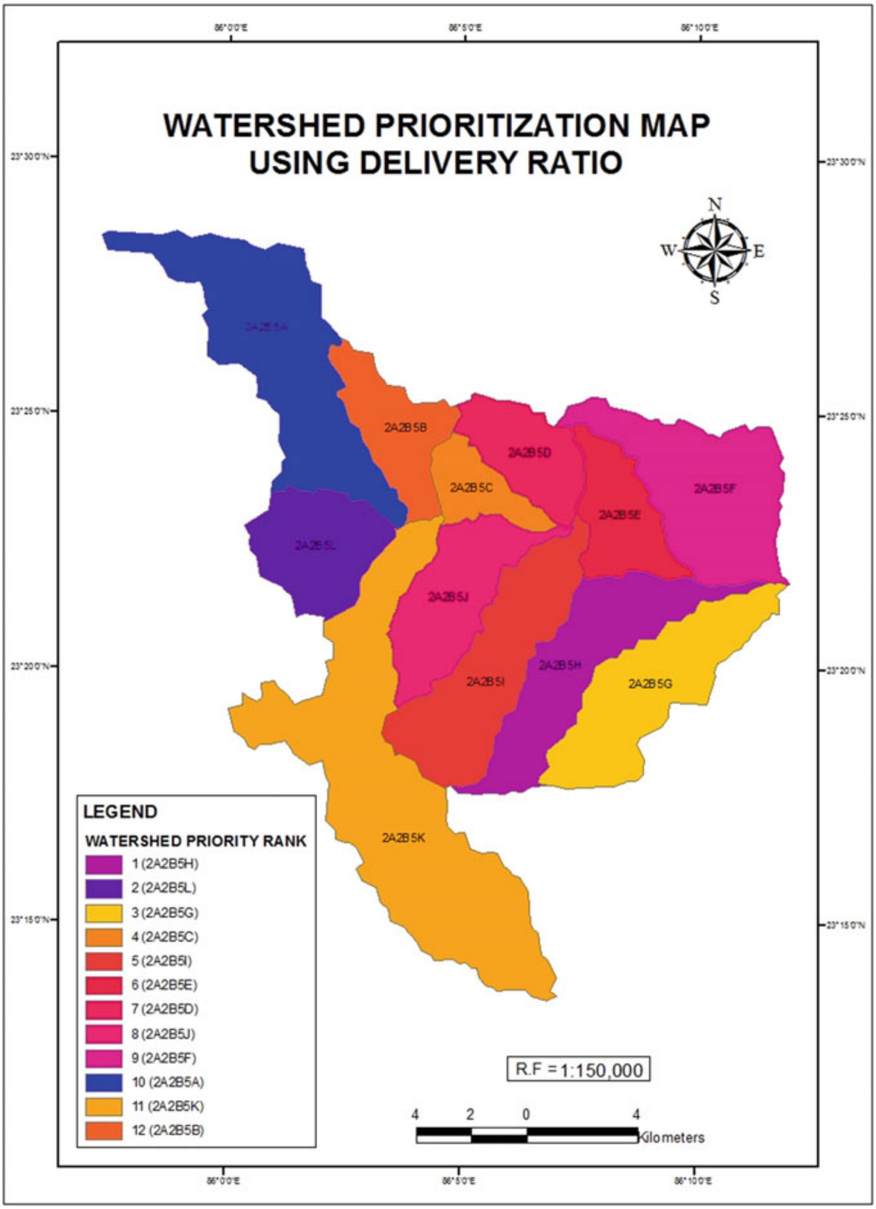

Fig. 9 Watershed prioritisation map using delivery ratio

Table 4 Causes and concern's of watershed prioritization

Causes	Concern's
Deterioration of watershed	• Manage to utilize runoff • Control damaging runoff • Control soil erosion • Flood control • Enhance groundwater recharge • Land resource management • Water resource management • Soil conservation plan • Periodic assessment of watershed condition • Evaluation through geospatial and morphometric techniques • Scientific planning with community participation
Unscientific, unplanned land use	
Uncontrolled cultivation, over cropping	
Cultivation without agronomic measures	
Shifting cultivation	
Destruction of forest cover	
Uncontrolled grazing	
Damages of soil and soil erosion	
NTFP collection from forest	
Unscientific mining	
Unplanned and uncontrolled construction	
Breaking natural drainage lines	
Damaging and reducing ecosystem services	
Non-cooperation from inhabiting community	

3.6 Water Resource Management

The water resource management (WRM) depends a largely upon the structure and physical set up and it was found that the granite and gneiss are the main rock types in the present study area which signifies less ground water recharge possibility. Thus, the ground water is found mainly in weathered mantle, between the saprolitic zone and fracture zone. In spite of having high rainfall, there is scarcity of water is observed mostly due to high slope and run-off. On the other hand, the recharge potential is much less due to its lithological characteristics, which concurred that the radical solution is not possible but local level water conservation is the only solution to resolve the issue and reducing the possibility of reduce water scarcity. The various structure of WRM and their methodology are scrutinized below:

Strategy for Minor Irrigation Tank

- Extraction of zone of over land flow above first order stream from the DEM.
- Creation of specific yield map and weathering profile map from field data by doing interpolation of the data.

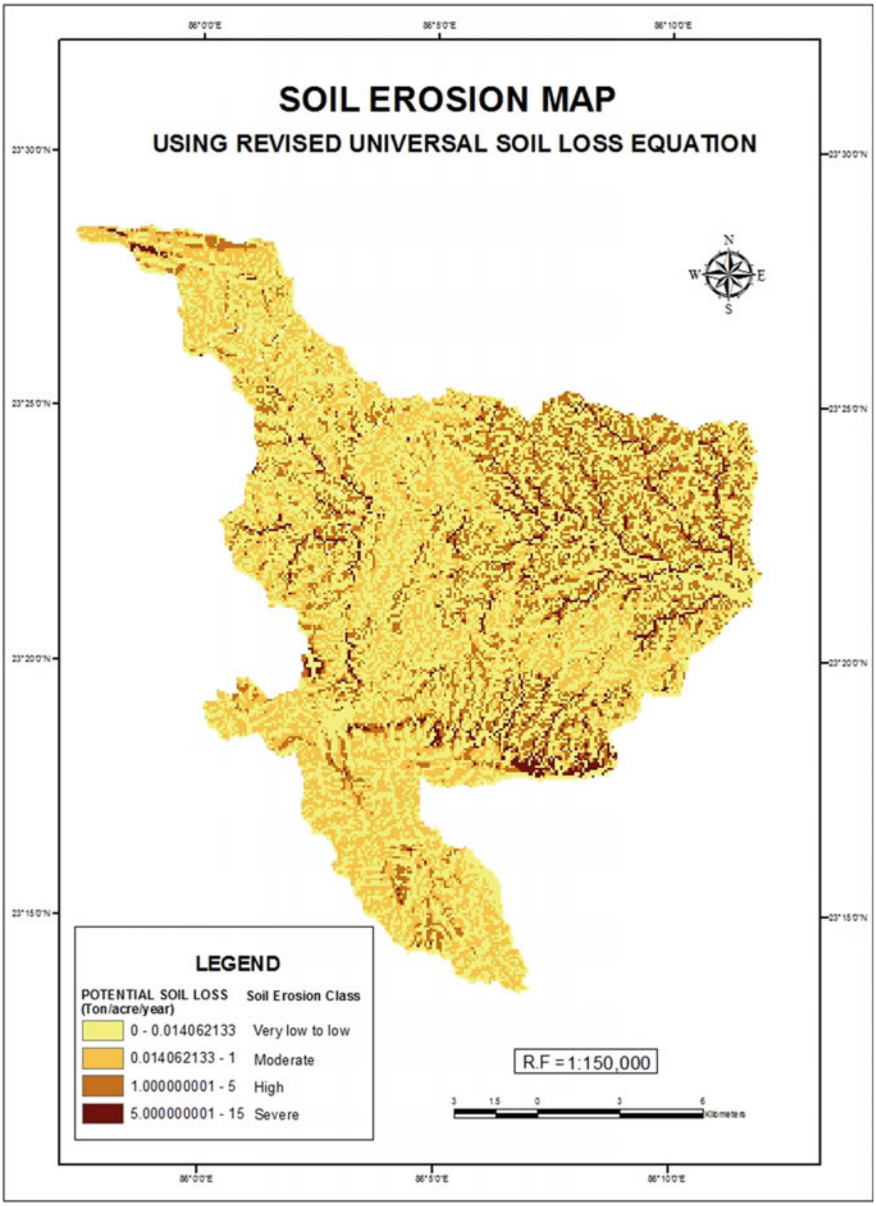

Fig. 10 Soil erosion map

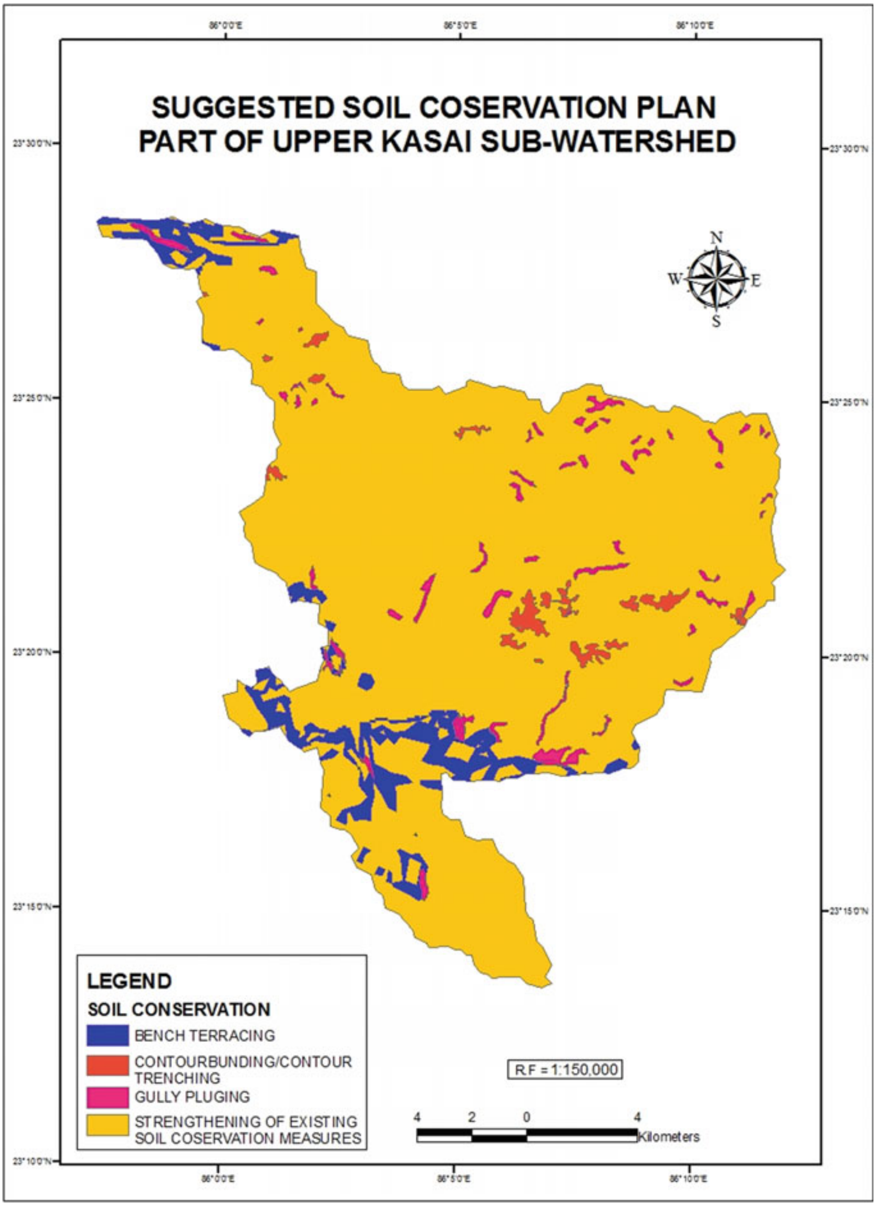

Fig. 11 Soil conservation plan map

- Consideration of the specific parameters viz. stream order, specific yield and weathering profile is done for suitable location of minor irrigation tank.

Strategy for Percolation Tank

- Consideration of specific parameters viz. stream order, specific yield, weathering profile and lineament.
- Creation of buffer area for the lineaments
- Intersection of stream order, specific yield, weathering profile and lineament is done.
- Attribute query is done for suitable location of percolation tank.

Strategy for Check Dams locations

- First of all we have considered six parameters, like specific yield, weathering profile, slope, land use, stream order, and soil.
- To determined specific location of the check dam in the study area, queries has been made in GIS environment (Stream order = 2; Specific Yield = 5% – 20%; weathering profile = 9 – 14 m; slope = 1% - 5%).
- Thereafter, we go for the buffering (500 m) of the settlement area.
- After that, we prioritised the check dam location according to the soil and land use –(Where, Soil = Well Depth and Land use = Single crop and Settlement buffer are consider).

Based on the above analysis, the the suggested minor irrigation tanks, percolation tanks, check dams and harvesting structure for the land resource development were mapped (Fig. 12). The check dams are found mostly in the upper parts of the prime river and they are located in the small catchment area suitable to control the soil erosion. The check dams are not only helpful in controlling the soil erosion, but is is also planned to be use successfully for the irrigational prupose. Accordingly the suggested water harvesting map (Fig. 13) has been prepared, where the series of tanks, percolation tank and minor irrigation tanks are plotted and this could be definitely helpful for successful land management with the intensive agricultural development.

3.7 Land Resource Development Plan

Land is the important resource and therefore, the optimum utilization of land of the current study region can help in sustainable use of such resource. The morphometric and geospatial analysis of this is playing an imperative role in optimum utilization and improvement of the productivity of land. It is also to be noted in this regard that this development process completes when participation of community is ensures. Here, on the basis of various scientific inputs like slope, land use/ land cover, soil, geomorphology etc. land resource management plan has been prepared (Table 5), which could be executed in the planning and development of the region.

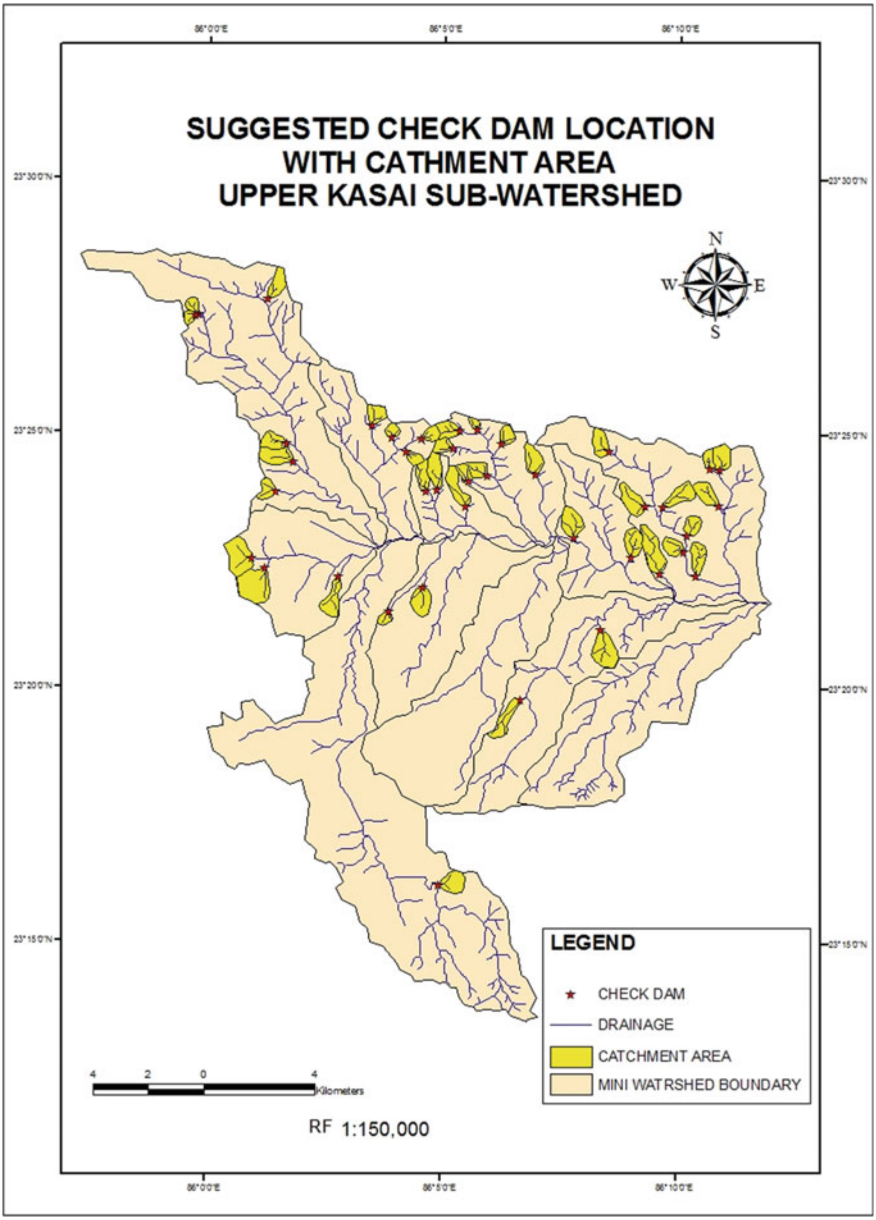

Fig. 12 Suggested Check Dam Location

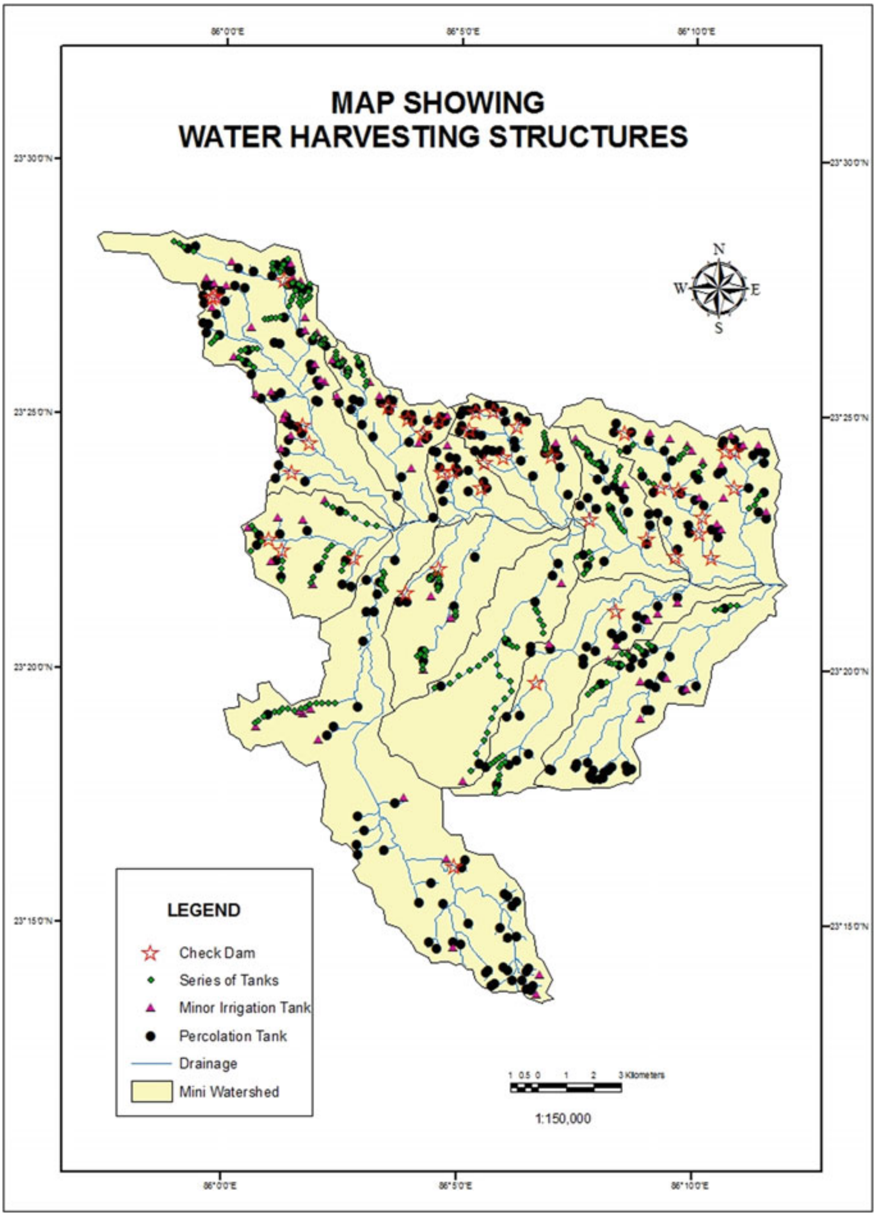

Fig. 13 Water Harvesting Structures

Table 5 Suggested Land use for Land Resource Development

Sl	Present land use	Geomorphology	Soil texture	Soil series	Suggested land use
1	Single crop	Valley fill	Loamy skeletal	Kotshila	Dry agriculture / agro-horticulture/ crop intensification
2	Single crop	Valley fill	Fine Loamy	Parsidh	Agricultural development / crop intensification
3	Single crop	Valley fill	Fine loamy	Parsidh	Agricultural development/ crop intensification
4	Single crop	Valley fill	Fine loamy	Hathinada	Agricultural development/ crop intensification
5	Single crop	Valley fill	Coarse loamy	Belabahal	Dry land agriculture/ crop intensification
6	Single crop	valley	Loamy skeletal	Jabar	Afforestation/agro-horticulture
7	Single crop	Valley fill	Coarse loamy	Kotshila	Crop intensification
8	Double crop	–	Coarse loamy	–	No action
9	Waste land	–	Coarse loamy	Belabahal	Dry agriculture/agro-horticulture
10	Waste land	–	Loamy skeletal	Kotshila	Pasture/silvipasture
11	Pond & reservoir	–	–	–	Desiltation
12	Clear forest/ open scrub forest	–	–	–	Refoestration

Strategy of Land Resource Development

- First we consider the present land use, soil and geomorphological condition.
- Then union these parameters are need to carried out.
- After that attribute query has been done.
- Then suggest the proper land use where it is applicable.

The suggested land use map of the region was intended with a suitability of land of the region (Fig. 14). There are 15 categories in the entire region which is need to be supervised for the land resource development and management. Mostly the afforestation,agro-horticulture, dry land agriculture, crop intensification, pasture,silvipasture are the suggested main land use types for the agricultural land, whereas desiltation and reforesentation are the suggested measures for the pond/reservoir and open forest area. The supervison of the agricultural development especially in the single and double crop area is suggested in a way that will help for community development as they are the stakeholders.

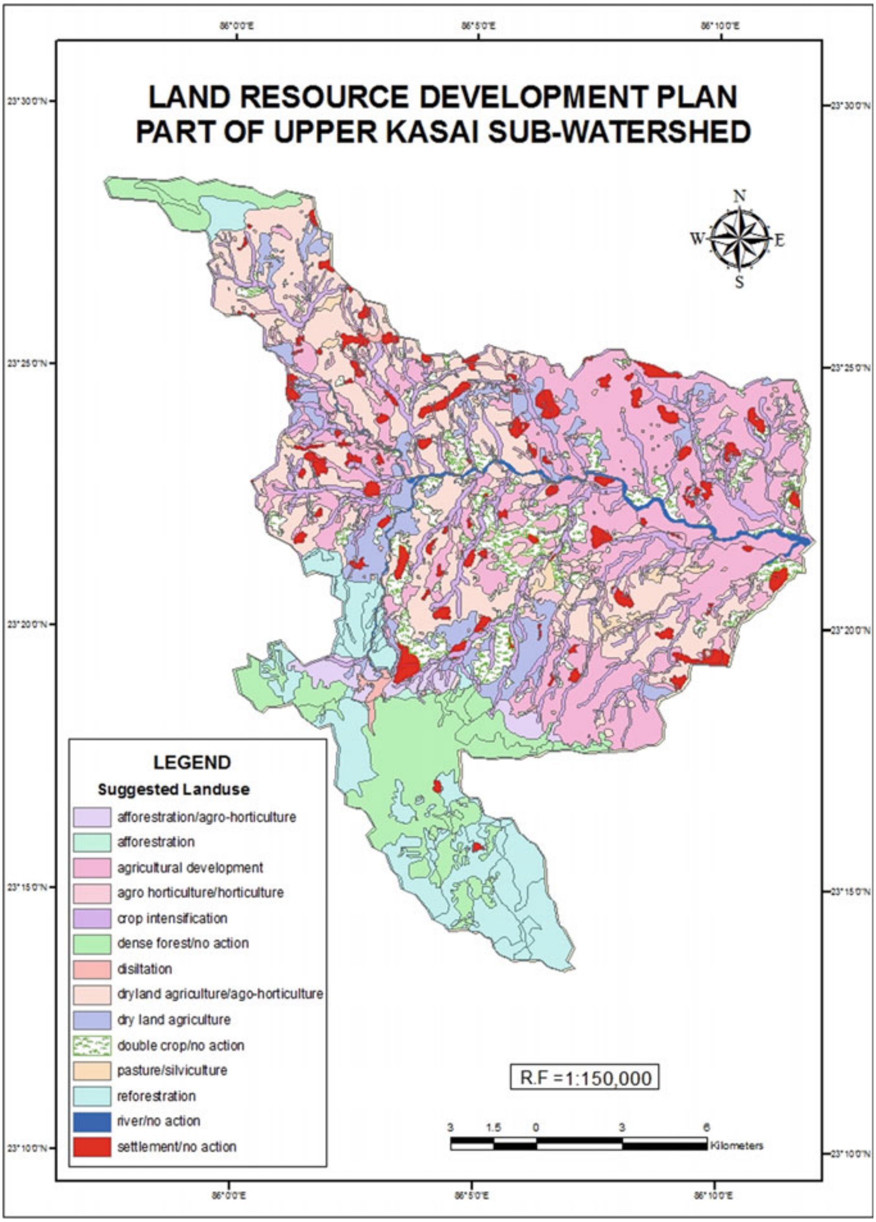

Fig. 14 Land Resource Development Plan

4 Conclusion

The land and water resource planning is largely depends on the watershed prioritization especially for the drainage dominat area and the current study area is not an exception. The present study depicts the appliance of morphometric technique with the help of recent remotety sensed database using the GIS platform. The geospatial analysis critically depicted the real scenario which helps to suggest suitable management methods for the study area. The current study watershed is more vulnerable to soil erosion and therefore, the suggested management need to be followed with more attention towards the conservation of water resource also. Moreover, to avoid any land hazard, the suggested land management steps need to be followed with its time to time modification. Thus, it reveals that the current study successfully demonstrate the priotitization of upper Kasai sub-watershed based on the morphometric techniques carried out and this is indeed very much helpful in the formation and execution of planning and managemenet at this micro-level.

The study classified the study area into 12 sub-watersheds on the basis of morphometric technique and delivery ratio and these may be grouped into three categories, i.e. low, medium and high priority. About four sub watersheds are belong to each category and according to this it may be noted that high priority signified higher the rate of soil erosion, that means it needs more supervision. Whereas the low priority signifies the low risk of soil erosion and land degradation and the moderate region belongs to in between situation. Through the geospatial technique, the use of high resolution satellite data, high resolution DEM, cadastral level mapping, soil survey, more reliable outcomes of soil erosion mapping and modelling are completed; and if the detail hydrogeological and socio-economic survey were conducted in the study region that will be excellent for such kind of assessment, which will be very much imperative especially for drinking water, irrigation land and water resource management. Therefore, it may be concluded that these sub-watersheds of the current study region need supervision and must be taken as the suitable control heads for soil erosion, land degradation and the recurrent assessment of the region is suggested to be carried out using the morphometric and geospatial techniques.

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Morphometric Attributes and Land Cover–Land Use: A Correlation and Association for an Interactive Analysis on Integrated Watershed Development in the Upper Kasai Basin, West Bengal, India

Amrita Kar and Sandipan Chakraborty

Abstract Watershed or catchment area is the part of a drainage basin on the earth's surface and offers a significant geo-hydrological unit which drains into a small or medium or large river. Watershed management is a significant constituent for sustainable management and development of natural resources and is the process of formulation carrying out a course of action that involves modification in the natural system of watershed to achieve specific objectives. The study area involves five small watersheds of Kasai upper catchment area and comprises a micro level study of the morphometric and geometric characteristics of the watersheds and subsequent correlation and association with land use and land cover categories to show the spatial arrangement of drainage network and distribution of land use and land cover categories. The major characteristics and identity of morphometric and geometric attributes of the studied part of the basin have been derived by using SOI Topographical maps and RS Images which have been processed and represented by GIS platform. It has been enlighten that Morphometric and shape parameters (Variables) of the Physical components are directly influencing the parameters of the land use components, that is, human and development activities are smoothly activated in the physically favourable areas, whereas, due to rugged and non-favourable environmental condition human activities are not well established in the respective areas of studied watersheds. Separate management practices are needed where rugged physical environment is the major constraints of development and needs special priority for sustainable management.

Keywords Micro-catchment · Topometry · Dissected topography · Multi-level image · Correlation and association · CGA

A. Kar (✉)
Earth Science Department, JIS University, Kolkata, India
e-mail: karamrita16@gmail.com

S. Chakraborty
Department of Geography, Chandernagore (Govt.) College, Kolkata, India

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1 Introduction

The analysis and exploration of drainage basin provides valuable information about its geology, morphology, structure and tectonics, geometry, topometry and evolutionary history of the surrounding areas. Measures of morphometric attributes provide clues regarding spatial variation of network development, Velocity and discharge, runoff efficiency, channel stability, boundary resistance etc. and economic, social and cultural efficiency and capability as well. Morphometry and topometry are the distinct expression of integrated structure, process and morphological shape and orientation of the basin. Its pattern expresses the underlying structure, rock resistance, exogenic processes, morphological process-form and its spatial distribution, hydrological actions and processes etc. Each parameter of all measures has credit to express the topographical and hydro geomorphic features of the basin.

Watershed or catchment area is the part of a drainage basin of a river, is a significant geo-hydrological unit which drains into a small or medium or large rivers. These are the areas of inter connected drainage network, thus revealing a distinguishing characteristics of different physical, morphological, biological and environmental (interlinked parameters) aspects of the area concerned. Watershed management is a significant constituent for sustainable management and development of natural resources and is the process of formulation carrying out a course of action that involves modification in the natural system of watershed to achieve specific objectives. It further implies appropriate use of land and water resources of a watershed for optimum production with minimum hazard to natural resources.

Individual river basin has several distinct physical, biological and socio-economic identity, which affect its functioning and format of management processes. All activities within the river basin have again an impact on its natural resources. Land cover is distinguished by different natural coverage like, different magnitude and orientation of land, flora, fauna and land use is the utilization of the parcel of land and also the description of how people utilize the land for their particular uses and activities may be rural or urban. All anthropogenic involvement and activities like agriculture, Settlements, roads, infrastructure and industrial development (called land uses) modify the river basin and affect its natural resources. Land use is essentially under the control of land users (human beings) and *hence its judicious management is of vital importance to river basin management and functioning.*

Integrated management of a river basin requires a thorough understanding of the physical, chemical, geological, natural, and environmental resources of the basin, as well as the social, political, and financial constraints pertaining to the basin parameters. Management alternatives developed should be based on these and other related factors. The major objective of the river basin management is to make beneficiaries within the basin, enhance their quality of life, and reinforce their interactions with the environment.

2 Aims and Objectives of the Study

The major aims of the watershed development and management are—(a) to control of floods and droughts; (b) to enhance the reduced flows during the dry season for promoting irrigation facility and to supply the drinking water within the basin; (c) Water quality protection, avoidance of point source and non-point source pollution; (d) availability of regular water supply for human consumption and industry; (e) to prevent the accelerated erosion and degradation and thereby sustainable conservation of soil and water within the basin; (e) to check the sedimentation hazards; (f) biodiversity preservation, protection of wetlands and lastly the holistic well being of the people in general. The present work is primarily enabled —(i) *To find out the geomorphic status of the watersheds; (ii) To find out their inter relationship; (iii) To find out the areal coverage of various land cover; (iv) Finally to draw association between the various physical parameters with the land cover land use.*

3 Methodology and Data Base

A number of qualitative and quantitative methods are employed for the present form of work. The phases of work are conducted by a systematic approach comprising of various methods of data acquisition, tabulation and processing, statistical analysis, various types of mapping and interpretation and finally inference has drawn for final conclusion and suggestions. So to maintain the whole process a number of steps are taken into consideration for sustainable management and development of the studied basin. Data are generated from SOI Topographical Map and Multi-level (Spatio-Temporal) Image. Phases of ground level survey have been done to review the ground truth observation. Morphometric data have been generated both from Topographical map and RS Image through multi-level processing through RS and GIS environment.

4 Study Area

The study area involves five small watersheds of Kasai upper catchment area and comprises a micro level study of the morphometric and geometric characteristics of the watersheds and subsequent correlation and association with land use and land cover categories to show the spatial arrangement of drainage network and distribution of land use and land cover categories. The selected five sub-watersheds are: Upper Kasai basin, Shahar jhor basin, Chunmatia (Nala/ Nadi) basin, Bundu basin, Kasai basin (Fig. 1).

The area under study constitutes the upper part of the Kasai River watershed within the small part of the Purulia District, West Bengal. The area under study

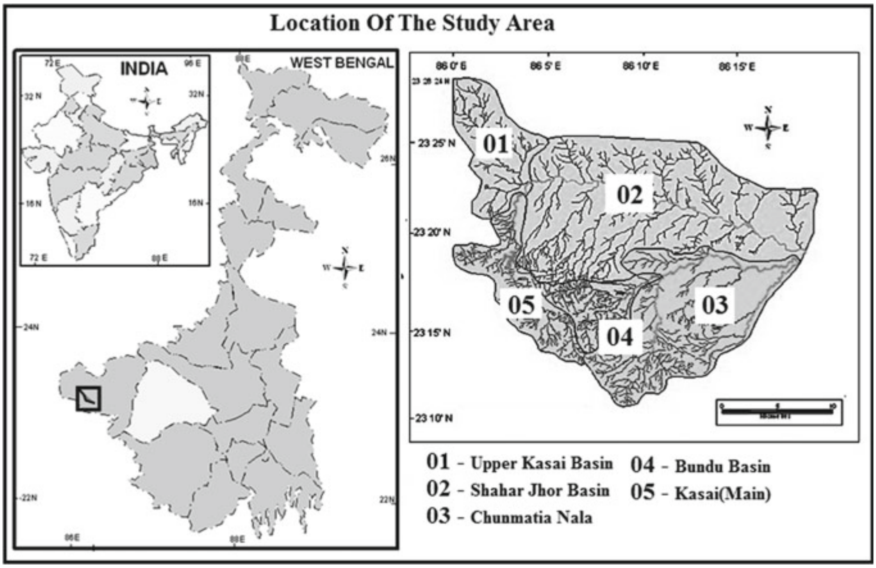

Fig. 1 Location of the study area

is most significant in relation to the variegated structure, Topography and litho-stratigraphic characteristics. The area forms the eastern transition of the hills of central India and Chotanagpur plateau and gradually descends from the rough and undulating topography to the Damodar plains of Rarh Bengal. As a shield-rimland, the area displays typical age-old characteristics of a moderate absolute altitude and moderately low relative relief. Absolute relief increases towards the south and west and the south marked by a line of sharply rising flat topped arches. The rest of the area has gently undulating plains with occasional hillocks or residual form. The general slope of the area is towards the east and south-east and the absolute relief ranges from 220 m. to 660 m. The area has been divided into a number of micro water sheds which are marking the catchment area of the Kasai River Watershed.

These micro watersheds are characterized by a number of stream networks having more or less Dendritic to sub-Dendritic pattern. *The five micro watersheds are namely*, *Bundu Watershed* (04) consisting of Bundu river and its tributaries, *Chunmatia watershed* (03) having Chunmatia Nadi / Nala river as a main stream which connect Bundu from North West. Similarly *Kasai watershed* (05) is the main course of the kasai Nadi having numerous defined and undefined streams and numbers of small channel bar. Another watershed is Shahar *jhor* (02) which joins middle kasai course from north west direction having a name of Girgiri nadi in the southern part of a natural reservoir, which lies almost at the middle of the basin area. And the last watershed is *Upper (Stretch) Kasai* (01) which evolves from the southern hilly region and joins Kasai and Shahor jhor.

5 Results and Discussion

The major characteristics and identity of morphometric and geometric attributes of the studied part of the basin have been derived by using SOI Topographical maps and RS Images which have been processed and represented by GIS platform. Following table (Table 1) representing and explaining the nature and characteristics of major morphometric parameters of the study area. Comparative analyses among those parameters are depicted in Table 1. The relative relief of the sub watersheds ranges from 32 to 151 m Shahar Jhor and Chunmatia Nala representing high relative relief, moderate to high average slope, moderate to high drainage density and ruggedness of relief; whereas upper kasai and Kasai have moderate to moderately low status relief and drainage parameters.

Similarly a comparative analysis among shape parameters of those five sub watersheds are represented in Table 2 *where we got the explanatory analysis of the shape of the watersheds whether they are elongated, ellipsoid or semi-circular in shape.* Shape indices of different sub watersheds revels the fact that circularity ratio of all watersheds ranges about 0.4 to 0.5, form factor ranges 0.2 to 0.3, elongation ratio is also ranges from 0.7 to 0.9 and lamniscates ratio ranges from 2 to 3. Thus it can be concluded that almost all the sub watersheds are conformal in nature i.e., partially elongated to semi circular in nature; so they are representing the same hydro-geomorphic behaviour in terms of runoff, flow and discharge of water, but the physical attributes are varying in nature resulting varying land use and land cover.

Table 1 Indices of major morphometric parameters

Watershed (S)	Relative relief (m)	Dissection index	Ruggedness no	Drainage density (Km/Sq.Km)	Average slope (in degree)
Upper Kasai	43.46	0.0718	0.1105	3.85	$1^{o}\ 55'6''$
Shahar jhor	108.9	0.2238	1.2238	5.92	$8^{o}1'22''$
Chunmatia Nala	151.33	0.3027	2.301	5.16	$9^{o}16'46''$
Kasai	32.13	0.0848	0.2769	5.94	$2^{o}4'54''$
Bundu	86.58	0.1810	0.8463	7.08	$5^{o}29'51''$

Table 2 Indices of major (basin) shape parameters

Watershed(S)	Form factor	Circularity ratio	Elongation ratio	Laminiscate ratio
Bundu	0.3475	0.4995	0.9411	2.259
Chunmatia Nala	0.3664	0.4818	0.9561	2.27
Kasai	0.3250	0.4583	0.9502	2.41
Shahar jhor	0.212	0.320	0.9173	3.703
Upper Kasai	0.3894	0.546	0.7048	2.01

In Table 3 we get the correlative and analytical features of land cover and land use parameters of the studied five sub watersheds. In this respect I also extracted the bi-variate analysis among the parameters where different physical and cultural attributes of different sub watersheds reveal the fact that the physical parameters are very much significantly related which leads as a controlling factor for the cultural fallow or residential area etc., the study depicts that the regions having high relief ensures high drainage density, high dissection index, moderate to high average slope and all those are positively related, whereas the socio-economic and cultural parameters are negatively responding to all aforesaid physical parameters having higher degree of identity.

6 Degree of Correlation

Bi-variate correlation matrix has been prepared considering the available data on different physical and land use parameters of five sub watersheds. *Based on this relationship correlation matrix has been prepared and based on this matrix cluster components and correlated variables (positive or negative) are extracted.* Two major components are distinguished—physical and socio-economic or land use components. We are getting one inter-component relationship and another intra-component relationship within this system. It has been enlighten that Morphometric and shape parameters (Variables) of the Physical components are directly influencing the parameters of the land use components, that is, human and development activities are smoothly activated in the physically favourable areas, whereas, due to rugged and non-favourable environmental condition human activities are not well established in the respective areas of studied watersheds. Moreover, spatial variations of intra variable aspects are also observed both in physical and land use components. *Following observations are sorted from the extracted correlation matrix* (Table 4*).*

(a) X_1, X_2, X_3, X_4 and X_5 variables have very high or high mutual correlation with each other and all are positively correlated from one to other. Actually, the areas which have high relief, steep slope and high ruggedness have also highly rugged and dissected topography, high drainage density with considerable length of overland flow.

(b) *X_7, X_8 and X_{10} have also high mutual positive correlation.* Moreover, it can be visualise that cultivated areas, area sown more than once and residential areas have mutual response.

(c) *X_1 to X_6 are presenting moderate to moderately high negative correlation with X_{10}*, because residential areas have distinct negative response to high relative relief, steep slope, high dissection, high drainage density with dense forest. Those areas are not socio-economically and culturally suitable and men are not preferring those areas for their residence and development work.

Table 3 Comparative analysis and characteristics of land cover and land use parameters

Watershed	Relative relief	Dissection index	Drainage density	Ruggedness number	Average slope	Forest area	Cultivated area	Waste land	Residential area
Upper Kasai Basin	Highest altitude is 661 m. and relative relief is low	Very low	Very low	Very low	Low	Low	Moderate	Low	Moderate
Shahar jhor basin	Relative relief is quite high	Moderate	High	High	High	High	Low	Low	Low
Chunmatia Nala	Relative relief is very high	High	Very high	High	High	Moderate	Low	Moderate	Low
Kasai basin	Comparatively low 32 m	Very low	Low	Low	Low	Low	Very high	Moderate	High
Bundu basin	Moderate in nature, 87 m	Low	moderate	moderate	moderate	high	Moderate	High	Moderate

Table 4 Correlation matrix among land cover and land use parameters

Variables	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
X_1	1	.99*	.95@	.98*	.98*	-.16	-.62	-.61	-.10	-.75
X_2		1	.96*	.98*	.99*	-.24	-.53	-.52	-.03	-.67
X_3			1	.98*	.94@	-.47	-.35	-.35	-.18	-.54
X_4				1	.94@	-.37	-.45	-.44	-.08	-.61
X_5					1	-.17	-.56	-.56	-.11	-.71
X_6						1	-.61	-.62	.18	-.41
X_7							1	.99*	.19	.97*
X_8								1	.19	.97*
X_9									1	.33
X_{10}										1

*Correlation is significant at the 0.01 level (2-tailed); @Correlation is significant at the 0.05 Level (2-tailed)

X_1 – Relative relief, X_2 – Dissection index, X_3– Drainage density, X_4– Ruggedness number

X_5– Average slope, X_6– Forest area, X_7– Cultivated areas, X_8– Area sown more than once

X_9 – Waste land, X_{10} – Residential areas

(d) *X_1 to X_6 have moderate to moderately high negative correlation with X_7, X_8*, that is cultivated areas and area sown more than once offering negative response to physically challenged variables.

7 Conclusion and Suggestions

Degree of association among the land cover and land use parameters has also *extracted using the principles of Coefficient of Geographical Association Index (CGA).* CGA is the principle to explain the degree of association among the geographical variables and inter-space association as well. It has been extracted using the following principles.

$$\text{CGA} = 1 - \frac{\sum_{i=1}^{n} |\text{d}|}{200}$$

where, *CGA stands for Coefficient of Geographical Association; n* is the number of observation; stands for absolute deviation from surface to surface or watershed to watershed or intra-variable deviation. 200 is the absolute value (k) of summation of deviation that is, no value will cross this constant value (200).

Following this principles I have extracted the deviation matrix and also the CGA matrix and based on these two matrix degree of association among the watersheds have been found out. Based on the CGA matrix map with degree of association among the watersheds have been prepared. There are Two different types of association—(i) directly associated and (ii) indirectly associated. In this regard the following map can be referring to explain the relative degree of association among the sub watersheds. *From the following map it has been highlighted that W-I, W-II and W-IV form Region -1 (R-1) and W-III and W-V form Region -2 (R-2) also form system –I and System – II in relation to the organisational behaviour of the considered variables* (Fig. 2*).*

It has been ascertained from the foregoing discussion that in some systematic and procedural treatments are needed for the integrated watershed development and management in the present area of study. Considering two major clusters in terms of land cover and land use intra and inter sub-watersheds treatment is needed as we got correlation status from the correlation matrix. Two distinct categories of sub-watersheds are also extracted need separate attention for two different system of development practice. Separate management practices are needed where rugged physical environment is the major constraints of development and needs

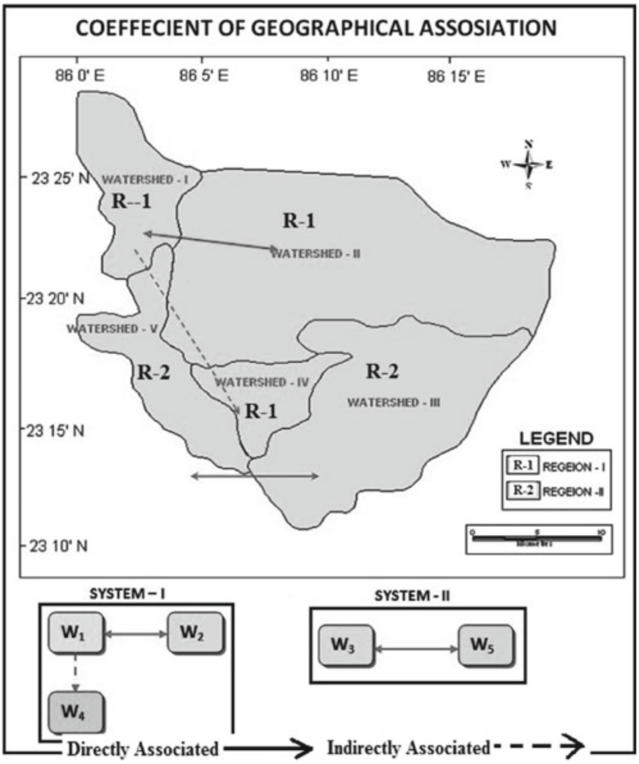

Fig. 2 CGA among watersheds—A system component

special priority for sustainable management. W-III and W-V have somewhat better environment for taking the formal procedure of development practices.

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Morphometric Analysis to Prioritize for Flood Risk of Sub-Watersheds of Teesta (Sikkim and West Bengal) Through Hazard Degree (HD) and Principal Component Analysis with Weighted Sum Approach (PCAWSA)

Prasanya Sarkar, Madhumita Mondal, Koyel Roy, Utpal Seal Sarma, and Shasanka Kumar Gayen

Abstract Risk assessment is an effective tool for flood monitoring and mitigation since it identifies flood-prone areas. In terms of flood dynamics and watershed prioritisation, morphometric parameters play an essential role. Morphometric analysis can be used to prioritise sub-watersheds for flood potential mapping by examining the linear, aerial and shape aspects of the watershed. Fifteen parameters such as Stream order, number of Streams, Stream length, Bifurcation Ratio, Basin Length, Basin Area, Basin perimeter, Elongation ratio, Shape factor, Drainage density, Drainage texture, Stream frequency are selected for the evaluation of flood risk assessment. The Digital Elevation Model (DEM) was used to delineate the watershed and drainage network using Arc GIS. On the basis of Morphometric Hazard Degree (MHD) and Principal Component Analysis (PCA) with Weight Sum Approach (WSA), 14 sub-watersheds are prioritized. The values that have a high effect on floods are rated according to their priorities in the assessment of the results obtained. The findings were evaluated in terms of flood priorities using hazard score and compound factor. Watershed flood priorities are graded as high, medium, or low based on the results of two different methods. The number of common watersheds 01 with "high" priority, 04 with "medium" priority, and 05 with "low" priority, as calculated by two separate methods. Hazard index-based findings showed that Rangit (SW-5) is under a

P. Sarkar (✉)
Department of Geography, Cooch Behar College, West Bengal, Cooch Behar, India
e-mail: sarkarprasanya@gmail.com

M. Mondal
Department of Geography, Bhairab Ganguly College, Belghoria, West Bengal, India

K. Roy · U. S. Sarma · S. K. Gayen
Department of Geography, Cooch Behar Panchanan Barma University, Cooch Behar, West Bengal, India

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highly susceptible zone. While sub-watersheds SW-1, SW-3, SW-4, SW-9 and SW-14 are moderately susceptible to flood risk. PSAWSA based approach suggests that sub-watersheds SW-1, SW3, SW-5, SW-13have high flood susceptibility.

Keywords Flash Flood · Hazard Degree · Principal Component Analysis · Weighted Sum Approach

1 Introduction

Flood is one of the most devastating natural hazards. It has led in significant social and economic casualties, as well as property damages and countless injuries and deaths. (Mahmood & Rahoman, 2019). Floods in the Himalayan rivers of Sikkim and Darjeeling, particularly flash floods, have wreaked havoc on the region (Starkel, 1972; Starkel & Basu, 2000). It is quite common during the monsoon season and occurs on a regular basis. Floods and flash floods frequently strike the Jalpaiguri and Darjeeling districts, which are located in the piedmont region of the Sikkim-Darjeeling and Bhutan Himalayas, causing severe loss of life and property each year (Sarkar, 2008; Karmokar & De, 2020). Floods that occur within a few hours of rainfall are referred to as flash floods. A small amount of rain can cause flash flooding in rocky terrain (Nasir et al., 2020). The amount and magnitude of rainfall are important factors in determining whether or not a flash flood will occur. Thunderstorms are responsible for the majority of flash flooding triggered by rainfall. (Gad et al., 2016; Nasir et al., 2020). Other factors that cause flash floods include evaporation, soil permeability, lithology and stream network, as well as anthropogenic factors and watershed features (Costa, 1987; Elsadek et al., 2018).

A watershed is an ideal unit for natural resource conservation and dealing with natural calamities such as flash floods. Watershed morphometric analysis is an important to understand watershed dynamics. For accurate representation of varied watershed demarcation and morphometric analysis, Remote Sensing and GIS are used (Altın & Altın, 2011; Pramanik, 2016). GIS aids in the development of a watershed data base, which is extremely important for performing spatial analysis and assisting policy makers in designing suitable responses. (Thakkar & Dhiman, 2007). Pramanik (2016) carried out the evaluation of morphometric parameters from SRTM for water resource management of the Teesta River.

Watershed prioritization for flood mapping and management is crucial (Malik et al., 2019). Watershed prioritization through grading the morphometric parameters has become critical in ungauged basins where no data is available. In past work, different methods are used for prioritization of watershed among which morphometric parameter is the best approach (Sukristiyanti, 2018). The morphometric assessment helps in the development of a fundamental hydrological diagnosis for predicting watershed behaviour. (Setta et al., 2019). It is useful to the decision maker as it can easily rank watersheds for prioritization and determining the flood potential. Flood risk assessment is an important flood mitigation technique because it has a wide range of practical applications in flood management and can helppeople become more aware of flood risks (Yang et al., 2018). The mapping and delineation of flash flood-prone areas is a key step in the risk management process (Abdalla et al., 2014). Several researchers have used morphometric parameters for flood modelling in recent years, including the analytical hierarchy process (AHP) approach (Ghosh & Kar, 2018), Morphometric Hazard index (Bajaba et al., 2014; Elmoustafa & Mohamed, 2013; Abuzied & Mansour, 2019; Nasir et al., 2020), Abdalla et al., 2014), and Principal component analysis and weighted sum approach (Meshram & Sharma, 2018; Sharma et al., 2015; Farhan & Al-Shaik, 2017; Malik et al., 2019). In flash flood susceptibility modelling, the Morphometric Ranking Approach (MRA) and El-Approach Shamy's are becoming more popular (Farhan & Anaba, 2016; Nasir et al., 2020; Syed et al., 2017). The study aims to assess the risk mapping of flash floods among sub-watersheds of the Teesta River. In this study, we intend to focus on Flash flood potential prioritization of 14 Watersheds of the Teesta Basin, using two approaches: (1) Hazard degree and (2) PCAWA.

2 Study Area

The study area is one of the watersheds of the Teesta River basin lies between 28° 7′42.83″N, 26°14′27.21″Nlatitude and89° 1′26.83″E, 87°59′16.15″E longitude. For analysis of Flash flood Teesta River has been undertaken which had a history of catastrophic flood events. It is overbearing to discuss the Basin as a whole in the Indian part (Sikkim and West Bengal). Teesta is an international river. Several flash floods affected Darjeeling and Jalpaiguri districts in the Himalayan foreland. In 1968, the district suffered the worst flash flood in its history, with 1200 mm of rain falling on the Himalayan margin and all rivers merged to form a single flood sheet (Sarkar, 2008). The earlier catastrophic floods happened in 1950, 1968, 1973, 1975, 1976, 1978, 1993, 1996, 2000, 2003 and 2015 (Pal et al., 2016; Mandal & Chakrabarty, 2016). The Teesta exhibits large variability in geography. The glacial, periglacial deposition, dissected valley, flood plain and landslide slope are all examples of the diversity of the Teesta basin (Mukhopadhyay, 1982; Rudra, 2008). The slope is the most significant attribute that has a direct impact on the quantity of infiltration and runoff in any terrain condition, as well as controlling aquifer growth (Pramanik et al., 2016). The slope map of the basin has been grouped into six categories. The upper middle part of the watershed is found to be steep, very steep and very high, indicating that the area has a mountainous topography. The lower section of the basin has a gentle slope intended for flat topography. The southern part of the Teesta River Basin has 4° slope. The central part has a slope of 23° to 51°, the northern part has a slope of 25° and the extreme northern part has a steep slope (Fig. 1).

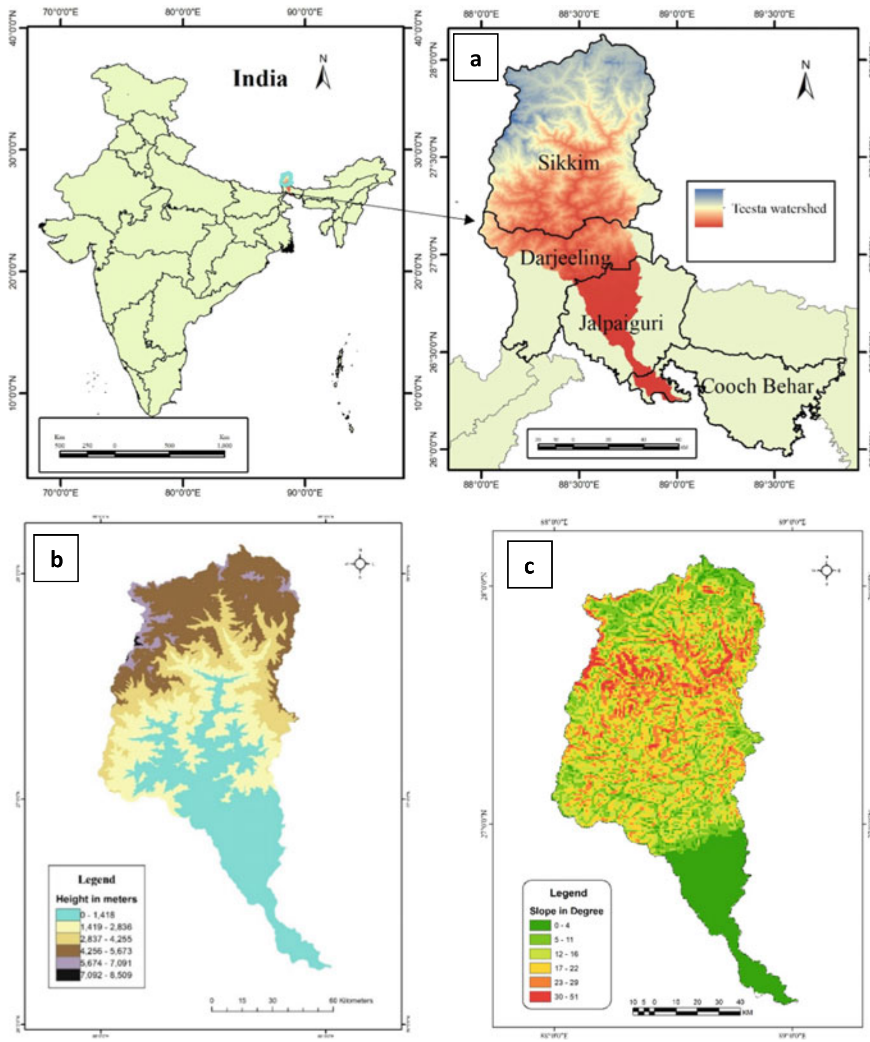

Fig. 1 (**a**) Location map of the study area in Sikkim and West Bengal (**b**) Elevation map of study area (**c**) Slope map of the study area

3 Methodology

Drainage and watershed boundaries were delineated using Aster DEM data (ASTGTMV003_N26E088, ASTGTMV003_N27E087) and Google Earth. The graphic map shows the methodological flow chart for morphometric analysis. A threshold value of 500 was used for the extraction of the stream network. (Lin et al., 2006) Arc GIS tools were used to derive and calculate morphometric parameters of the watersheds. Using spatial analyst tools, different maps such as Slope, and Elevation were developed. Morphometric parameters were calculated based on the mathematical equation illustrated in Table 1. The morphometric parameters were categorized into two categories. Category 1 comprises all parameters that are directly proportional to the level of risk. (Youssef et al., 2011; Nasir et al., 2020). Stream order, Number of Streams, Stream length, Bifurcation Ratio, Basin Length, Basin Area, Basin perimeter, Drainage density, Drainage texture, and Stream frequency are all included in the parameter. Only the Elongation ratio and Shape factor, which are inversely proportional to the risk, are included in category 2. To assess the flood hazard of the Teesta sub-basin, Morphometric Hazard Degree has been carried out as follows- all the parameters were assigned a hazard scale number ranging from 1 to 5. The minimum and maximum values of each morphometric parameter of all sub-basin have been determined. Equation 1 is used to determine parameters with a directly proportional relationship, while Eq. 2 is used to calculate parameters with an inverse proportional relationship (Youssef et al., 2011; Bajabaa et al., 2014; Nasir et al., 2020).

$$\text{Hazard Degree} = \frac{4(X - Xmin)}{Xmax - Xmin} + 1 \quad (1)$$

$$\text{Hazard Degree} = \frac{4(X - Xmax)}{Xmin - Xmax} + 1 \quad (2)$$

Where, Xmin and Xmax are the minimum and maximum values of the morphometric parameters for all basins, respectively, and X is the value of morphometric parameters to be measured for the hazard degree for each basin.

Hazard degree for all sub-basins is calculated by Equations. The sum of hazard degrees for each sub-basin represents the final flood hazard of that sub-basin (Table 3). This value ranges between 27.5 to 58.19. The ranking score is grouped into three classes i.e., low flooding susceptibility, moderate susceptibility and high susceptibility. The ranking score ranges between 1 and 5. For category 1, rank 5high risk and rank 1 low risk. For category 2, rank 5 low risk and rank 1 high risk.

This research employs a hybrid approach that combines PCA and a weighted sum approach (Malik et al., 2019). The most potent morphometric parameters for prioritising watersheds based on factors that are strongly related to important components were investigated using Principle Component Analysis. Important morphometric parameters that were identified using PCA were applied to a weighted-sum analysis. The following equation was used to obtain the compound factor value (Aher et al., 2014; Farhan et al., 2016; Fenta et al., 2017; Rai et al., 2018; Malik et al., 2020).

$$\text{CF} = \text{PPR}_{\text{SMP}} \times \text{WS}_{\text{MP}}$$

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Table 1 Formulas adopted for computation of Morphometric Parameter

	Morphometric parameters	Formula	References
Linear variables	Stream Order ($_U$)	Hierarchical order	Strahler (1957)
	Number of Stream (Nu)	$N = N_1 + N_2 + \cdots N_n$	Horton (1945)
	Stream Length (Lu)	$L = L_1 + L_2 + \cdots Ln$	Strahler (1957)
	Bifurcation Ratio (R_b)	$R_b = N_u/N_u + 1$ Where, N_u = Number of stream segments present in the given order, $N_u + 1$ = Number of segments of the next higher order	Schumm (1956)
	Basin Length(L)	Length of Basin in km	Horton (1945)
	Basin Width in Km(W)	Width of the basin in km	Horton (1945)
	Length Width ratio	L/W	Horton (1945)
Areal variables	Basin area in sq. km (A_u)	Area of watershed in sq. km	Horton (1945)
	Basin Perimeter in km(P)	Perimeter of the watershed in km	Horton (1945)
	Drainage Density (Dd)	$Dd = Lu/Au$ Where, Lu = Length of the Stream, Au = Area	Horton (1945)
	Drainage texture (Dt)	$Dt = Nu/P$ Where, Nu = Number of Stream P = Perimeter	Horton (1945)
	Stream frequency (Fs)	$Fs = Nu/Au$ Where, Nu = Number of Stream Au = Area	Horton (1945)
Shape Variables	Elongation Ratio (R_e)	$R_e = D_c/L_b$ Where, Dc = Diameter of basin, Lb = Basin length	Schumm (1956)
	Circulatory Ratio (R_c)	$R_c = 4\pi A/P2$ Where A = Area of basin, P = Perimeter of basin	Miller (1953)
	Shape Factor (Bs)	$Bs = Pu/Pc$ Where P_u = perimeter of circle of watershed P_c = perimeter of watershed	Sameena et al. (2009)

Where CF denotes compound factor; $PPRs_{MP}$ denotes preliminary priority rank of the significant morphometric parameter identified using PCA; and WS_{MP} signifies the weight of significant morphometric parameter obtained using cross-correlation analysis and computed as:

$$WS_{MP} = \frac{\text{Sum of correlation coefficient}}{\text{Grand total of correlations}}$$

Based on the CF values 14 watersheds were applied for priority category in terms of flood potential mapping.

4 Result and Discussion

The Morphometric analysis was carried out using RS and GIS for 14 sub-watersheds to assess risk zonation for soil and water conservation. The morphometric parameters such as stream order (u), number of stream (Nu) stream length (Lu), bifurcation ratio (Rb), drainage density (Dd), stream frequency (Fs), texture ratio (T), elongation ratio (Re), circulatory ratio (Rc) and form factor (Rf) were computed in Arc GIS. Morphometric analysis of the 14 watersheds has been computed and summarized in Table 2. Following morphometric analysis, the Hazard degree method and PCAWSA are applied for the priority category for the 14-sub watershed in terms of flood potential (Fig. 2 and 3)

5 Linear variable

Horton (1945) and Strahler (1964) have elaborated on a different method for ordering. The Strahler method is slightly updated of Horton's scheme that has been implemented due to its simplicity. (Farhan et al., 2016) The smallest, unbranched fingertip streams are designated as 1st order, the confluence of two 1st order channels results in 2nd order channels, two 2nd order streams merge to form a 3rd order section, and so on. The higher order is maintained when two channels with differing orders are merged. The stream ordering of the study area has been classified from DEM in the GIS environment with the help of Google Earth. Higher Stream order leads to high water concentration inside the channels and higher potential of the flash flood. (Nasir et al., 2020). The stream order of the Teesta watershed is the 7th order, while other sub-basins have 3,4,5,6 orders. The total number of stream segments that drain a basin, is termed as stream number (Nu). Stream numbers are influenced by lithology and soil characteristics of the basin along with rainfall characteristics. Higher stream numbers can significantly increase the instant discharge (Mahmood & Rahman, 2019). The highest stream number was recorded in 6 and the lowest in 4.

Bifurcation ratio is the number of stream segments of a given order to the number of segments of the next higher order (Schumm, 1956). Strahler (1957) demonstrated that the bifurcation ratio shows a small range of variation for different regions or different environmental conditions, except where the geology dominates. The bifurcation ratio is about 2 for flat basins and up to 3 or 4 for mountains or dissected

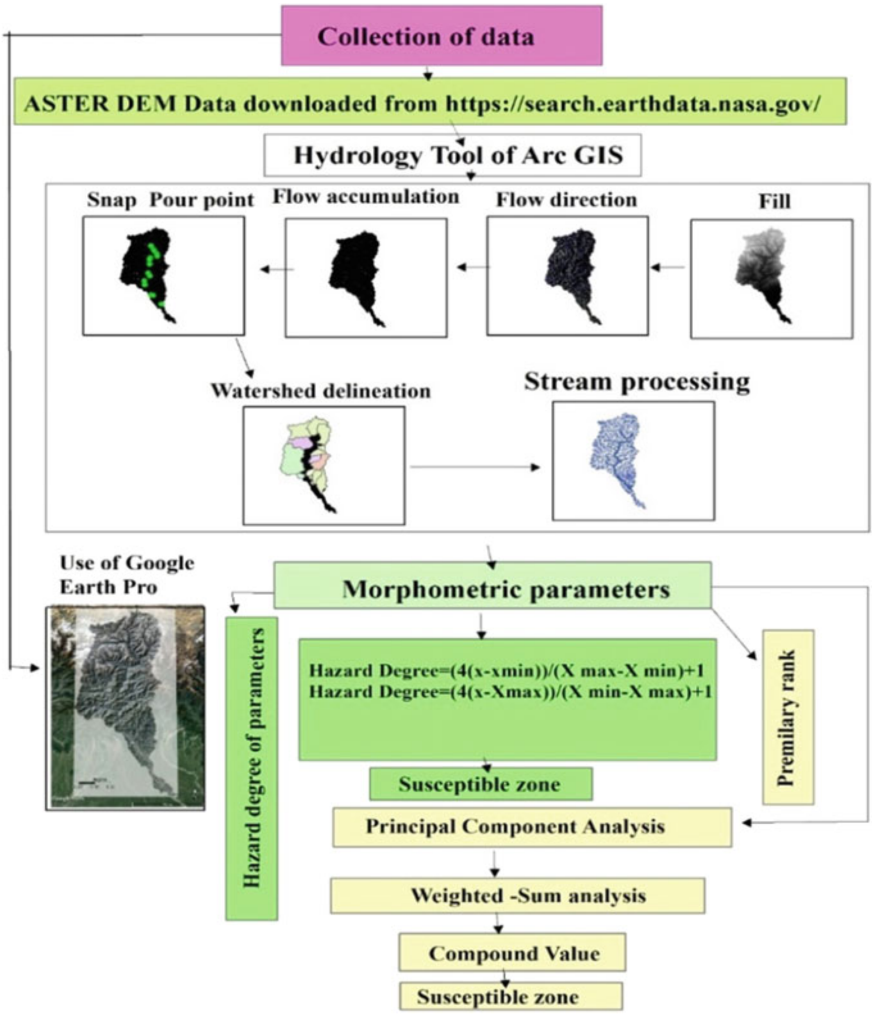

Fig. 2 Flow Chart Methodology

drainage basins (Farhan et al., 2016). It can be correlated with hydrological characteristics. Lower bifurcation values are the characteristic of structurally less disturbed basins without any distortion. (Nag, 2003). When the Rb value is high, it indicates that there is a lot of overland flow and a lot of potential for flash flooding during heavy rain. (Bajaba et al., 2014; Farhan et al., 2016). In the study area, bifurcation ratio varies from 1.51 to 4.41. Generally, all the watershed in Sikkim has higher values; this reflects high mountainous dissected areas (Fig. 4).

The stream length (Lu) has been computed based on the law proposed by Horton. Stream length is one of the most significant hydrological features of the basin as it reveals surface runoff characteristics (Bajaba et al., 2014). The stream of relatively

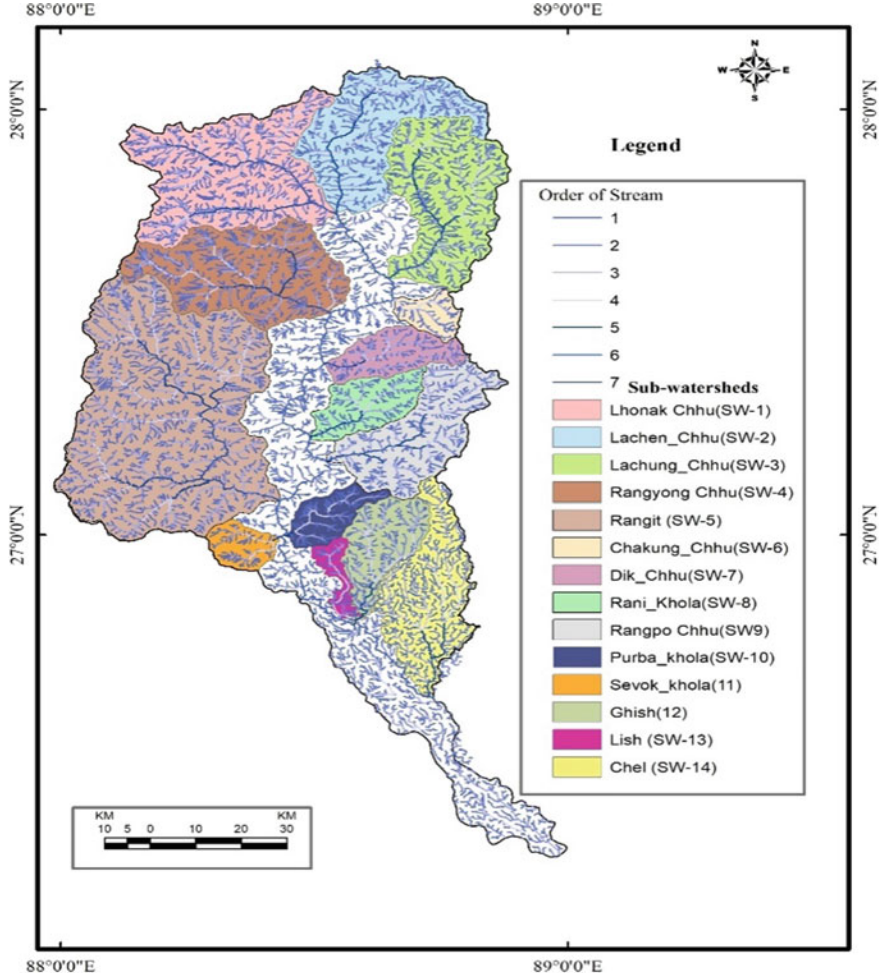

Fig. 3 14 Sub -watersheds of the Teesta River

smaller length is characteristics of areas with larger slopes and finer textures. Longer lengths of streams are generally indicative of a flatter gradient. Teesta is 3969.36 km while the stream length of the sub-basin ranges between 97.55 km to1995.58 km. The stream lengths revealed a directly proportional relationship with the number of streams and area for all the studied sub-basins. (Fig. 5).

We can estimate the stream number as well as stream length from the total area of sub watershed in the study area through the following equation

$$Y_1 = 0.4835x + 11.628$$

Table 2 Morphometric parameters of 14 sub watersheds of river Teesta

Sub-watersheds	U	N_u	R_b	Lu	L	W	R/W	Au	P	R_e	R_c	B_s	D_t	D_d	F_s
Lhonak Chhu (SW1)	6	1280	1.72	1121.71	49.33	29.05	1.7	986.4	193.46	0.72	0.33	0.58	6.62	1.14	1.3
Lachen Chuu (SW2)	5	896	1.9	736.4	31.55	15.64	2.02	687.77	166.07	0.94	0.31	0.37	5.4	1.07	1.3
Lachung Chhu (SW3)	6	1018	1.63	816.61	43.3	24.49	1.77	769.5	152.66	0.46	0.41	0.48	6.67	1.06	1.32
Rangyong Chhu (SW4)	5	1078	1.79	881.15	42.6	21.05	2.02	822.83	149.92	0.36	0.46	0.18	7.19	1.07	1.32
Rangit (SW5)	6	2734	1.51	1995.58	54.68	31.68	1.73	2130.51	239.48	0.77	0.47	0.6	12.97	2.46	1.46
Chakung Chhu (SW6)	4	108	2.03	102.38	13.8	9.78	1.41	112.18	49.09	0.29	0.34	0.43	2.99	0.91	0.96
Dikchhu (SW7)	5	320	2.01	222.83	26.79	11.25	203.8	245.86	81.78	0.41	0.46	0.48	3.91	0.91	1.3
Rani Khola (SW8)	4	399	1.4	226.75	28.46	13.48	2.11	254.69	78	0.46	0.53	0.56	5.12	0.89	1.57
Rangpo Chhu (SW9)	6	721	1.72	536.17	37.81	14.67	2.58	571.18	137	0.33	0.38	0.34	5.26	0.94	1.26
Purba Khola (SW10)	5	399	1.67	226.75	19.06	10.41	1.83	170.84	67.96	0.42	0.46	0.42	3.22	0.95	1.28
Sevok Khola (SW11)	4	185	1.65	128.88	13.9	13.29	1.05	130.13	47.85	0.62	0.71	0.63	3.87	0.99	1.42
Ghish (SW12)	5	394	1.7	345.43	32.8	14.75	2.22	318.4	112.75	0.4	0.31	0.4	3.49	1.08	1.24
Lish (SW13)	4	106	1.77	97.55	21.93	3.2	6.8	83.9	78.79	0.19	0.17	0.18	1.35	1.16	1.26
Chel (SW14)	6	764	1.91	745.76	56.78	17.53	3.24	589.18	188.73	0.25	0.21	0.3	4.03	1.27	1.3

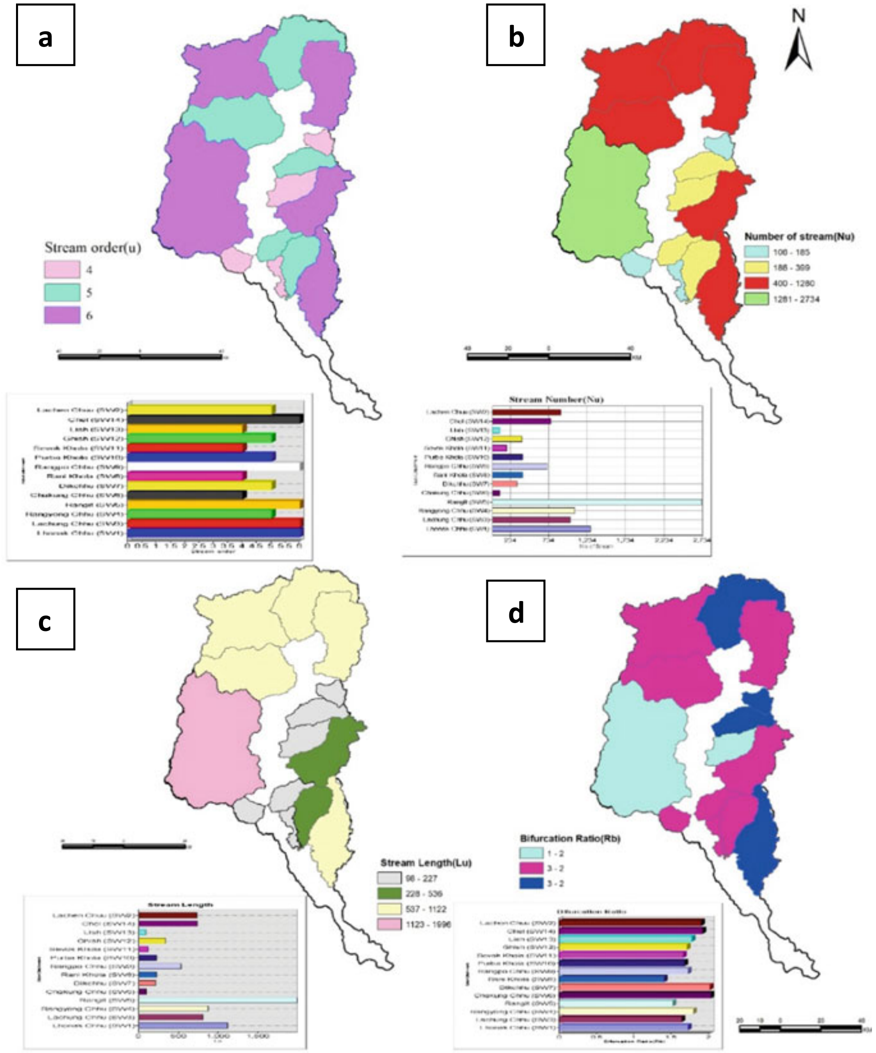

Fig. 4 Thematic representation of Linear parameters of the Teesta River watershed (**a**) Stream order (**b**) No. of stream (**c**) Stream length (**d**) bifurcation ratio

Where, Y_1 represents the stream length and X represent the area of the sub watershed.

$$Y_2 = 0.317x + -3.6974$$

Where, Y_2 represents the stream number and X represent the area of the sub watershed.

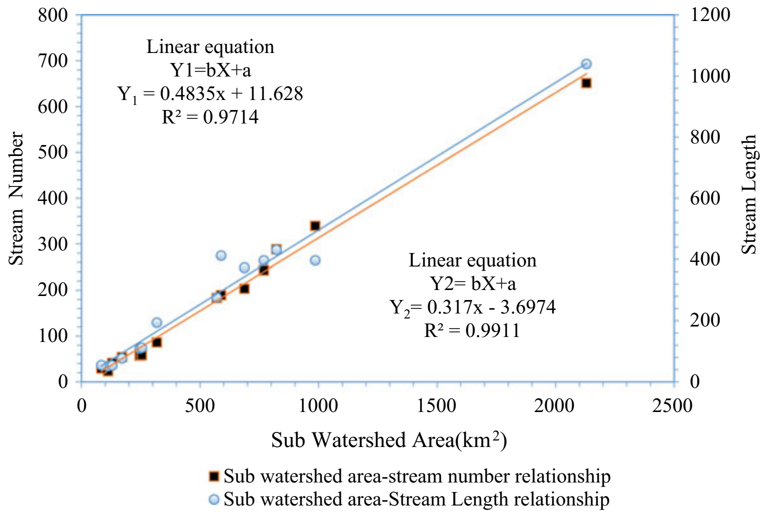

Fig. 5 Relation between the area, stream number and stream length of studied sub- watershed

Basin length is the longest dimension of a basin to its principal drainage channel. Lb is crucial in hydrological calculations because it rises as drainage rises and vice versa. (Patel et al., 2012) The study basin length is highly variable, as it varies from 13.8 km to 56.78 km. On the other hand, basin width ranges between 3.2 to 31.68 km (Fig. 6).

6 Areal Variables

Significant hydrological characteristics of a watershed are drainage perimeter and area**.** The sub-watershed ranges between 47.85 km in the Sevok Khola sub-watershed and 239.48 km of the Rangit sub-watershed. The basin area of the Teesta River sub-basins is highly variable, ranging from 83.9 sq. km for sub-basin Lish to 2130.51 sq. km for sub-basin Rangit. Compared to smaller basins, larger basins tend to trap more precipitation, resulting in higher peak discharge (Biswas et al., 2014). Stream order, stream numbers, length and width of the basin, basin length, and basin perimeter are all affected by larger basins.

The total number of stream segments of all orders in a basin per basin perimeter is known as drainage texture (Horton, 1945). More is the drainage texture more will be dissection and leads more risk (Nasir et al., 2017). Impermeable areas have a higher proportion of stream networks than permeable areas. Smith (1950) categorised drainage texture into five categories: very coarse (2), coarse (2–4), moderate (4–6), good (6–8), and very fine (> 8). The sub-watersheds SW1, SW2, SW3, SW4, SW8, and SW5have fine to very fine textures and are thus predicted for lower infiltration

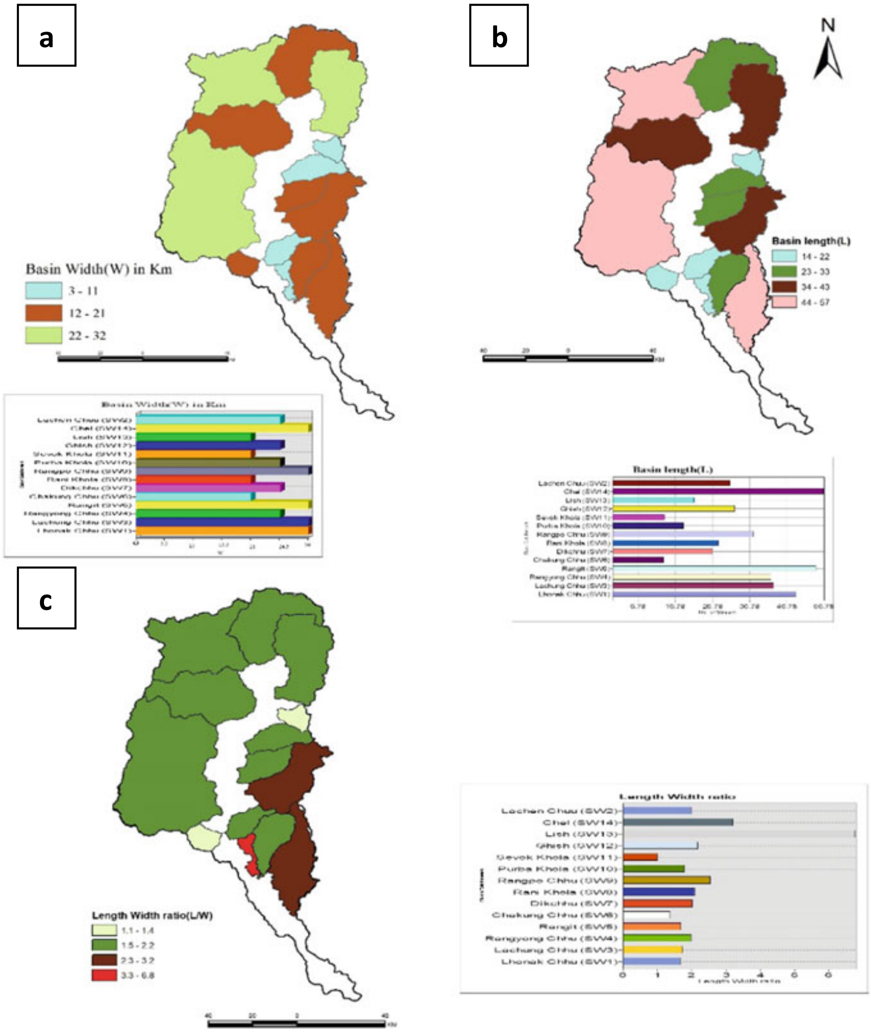

Fig. 6 Thematic representation of Linear parameters of the Teesta River watershed. (**a**) Basin width (**b**) Basin length (**c**) length–width ratio

and higher runoff. Horton (1945) defined it as the proportion of total stream length of all orders per unit basin area. The drainage density specifies an area's groundwater capacity, because of its relationship to surface runoff and permeability. In this case, the highest drainage density is found in the Rangit sub-watershed (Fig. 7 and 8).

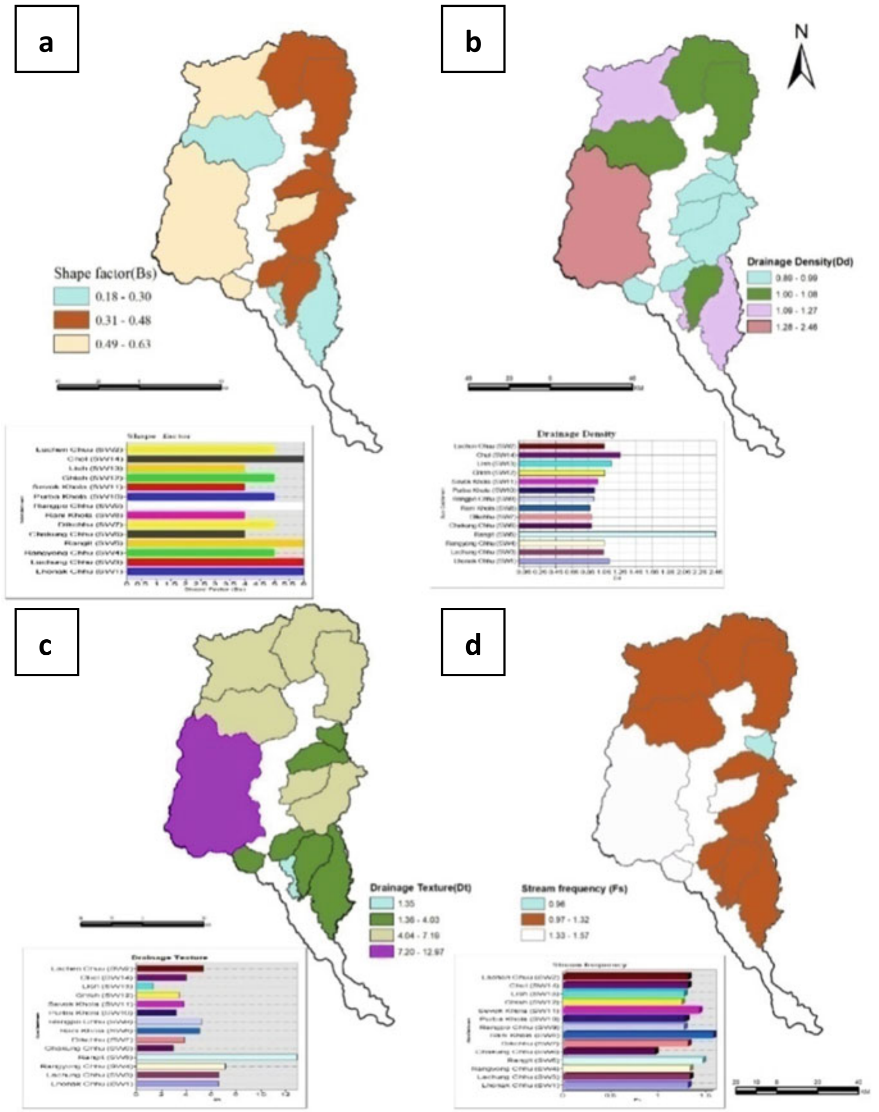

Fig. 7 Thematic representation of aerial parameters of the Teesta River watershed. (a) shape factor (**b**) drainage density (**c**) drainage texture (**d**) stream frequency

7 Shape Variable

It is the ratio between the diameter of the circle of the same area as the drainage basin and the maximum length of the basin and is found generally from 0.6 to 1 (Schumm, 1956). Re is classified into four categories: > 0.9 for circular, 0.9–0.8 for

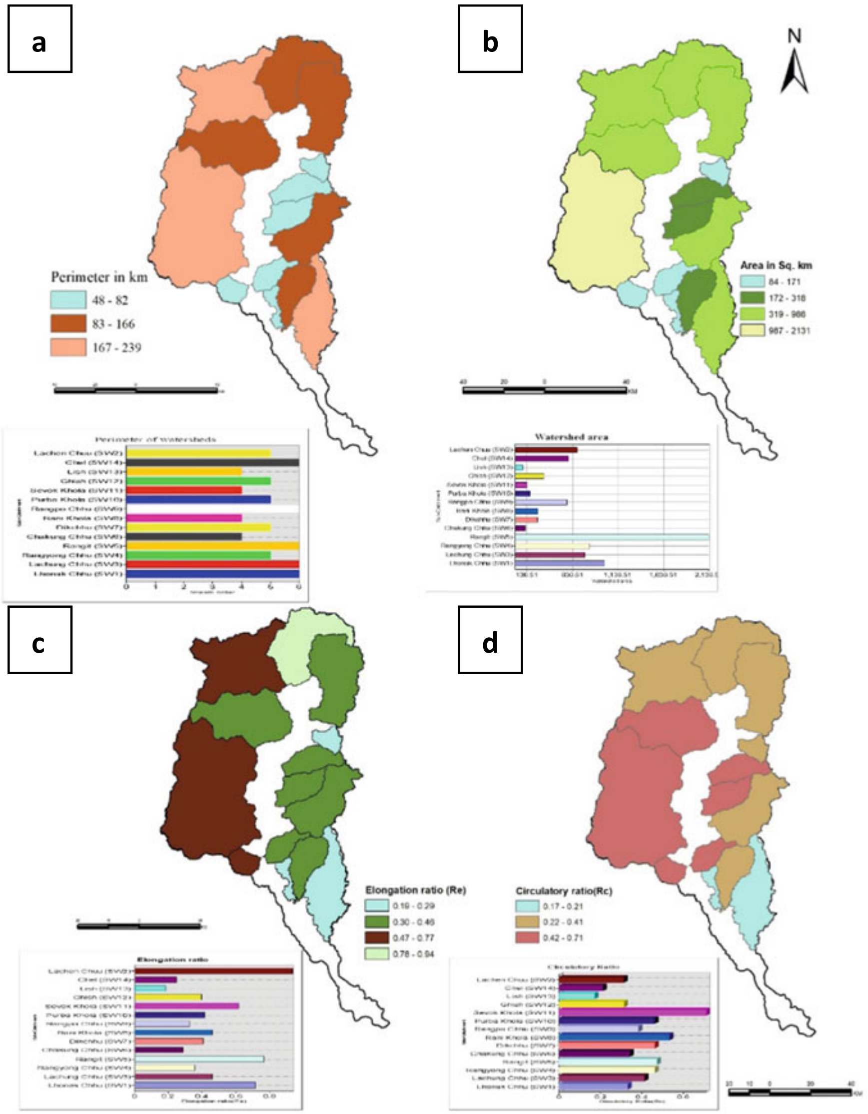

Fig. 8 Thematic representation of aerial parameters of the Teesta River watershed (**a**) perimeter (**b**) Watershed Area (**c**) Elongation ratio (**d**) circulatory ratio

oval, 0.7–0.8 for less elongated, 0.5–0.7 for elongated, and 0.5–0.7 for more elongated (Strahler, 1964). The range of Re value is 0.19 to 0.94. The sub-watershed Lachen chuu (SW2) has the highest elongation ratio (0.94), making it the least susceptible to flood hazard, whereas sub-watershed Lish (SW13) has the lowest elongation ratio (0.19) and it is more susceptible to flooding. The elongation ratio ranges from 0.0.46

to 0.94, indicating that watersheds are located at a high altitude (Nasir et al., 2020). Higher values of SW5 and SW6 show high infiltration capacity and low runoff, whereas lower Re values indicate high susceptibility to erosion (Reddy et al., 2004).

It's a measure that is similar to the elongated ratio. It is the ratio of the area of the basin to the area of the circle having the same circumference as the basin perimeter (Miller, 1953). The circulatory ratio is another important form characteristic of the basin that is helpful for the assessment of flood hazard. Higher Rc values suggest a higher risk of flooding and a low circulatory ratio indicates a low risk of the flash flood (Malik et al., 2019; Nasir et al., 2020). The circulatory ratio varies from 0.17 to 0.71, indicating an elongated to oval shape. Sevok khola (SW11) has a circular shape. Sub-watershed 14 has the lowest value (0.21) and is least susceptible to flood. Flooding is most likely in sub-watershed 11, which has the highest value (0.71). The shape factor observed in the study area is minimum in the case of WS3 ($Rs = 0.46$) and maximum in the case of WS16 ($Rs = 0.79$), as shown in Table 6. It gives an idea about the circular character of the basin. The greater the circular character of the basin is, the greater is the rapid response of the watershed after a storm event (Altaf et al., 2013).

8 Flood Priority Rank Based on Hazard Degree Method Result

Prioritization of watersheds based on morphometric analysis is crucial for understanding the river's flood dynamics and executing the requisite flood mitigation measures (Farhan et al., 2016). Using Arc GIS, the spatial distribution of 14 watersheds of the Teesta river is shown based on Morphometric ranking values in Fig. 9. The hazard degree method is employed to assess the degree of flash flood vulnerability for 14 sub-watersheds. The method was used by integrating scores of various morphometric characteristics. Using the Hazard degree (Table 3), each basin was measured in terms of flood priority. The aggregated hazard degree scores divide the Teesta River sub-watersheds into three susceptibility zones. The higher the aggregated hazard degree score of the morphometric variable, the more vulnerable the sub-watersheds are to flash floods, and vice versa (Elmoustafa & Mohamed, 2013). The drainage patterns in the study area are dendritic, indicating less percolation and maximum runoff in high areas.

High Hazard Zone (47.84–58.19):
Out of the 14 sub-watersheds of the Teesta River, 1sub-watershedcomes under high priority (Fig. 9). It denotes higher degree of risk.

Medium Hazard zone (37.44–47):
Sub-Watersheds Are Found to Have Moderate Flood Priority. These Sub-Watersheds Are 1, 3, 4,9 and 14.

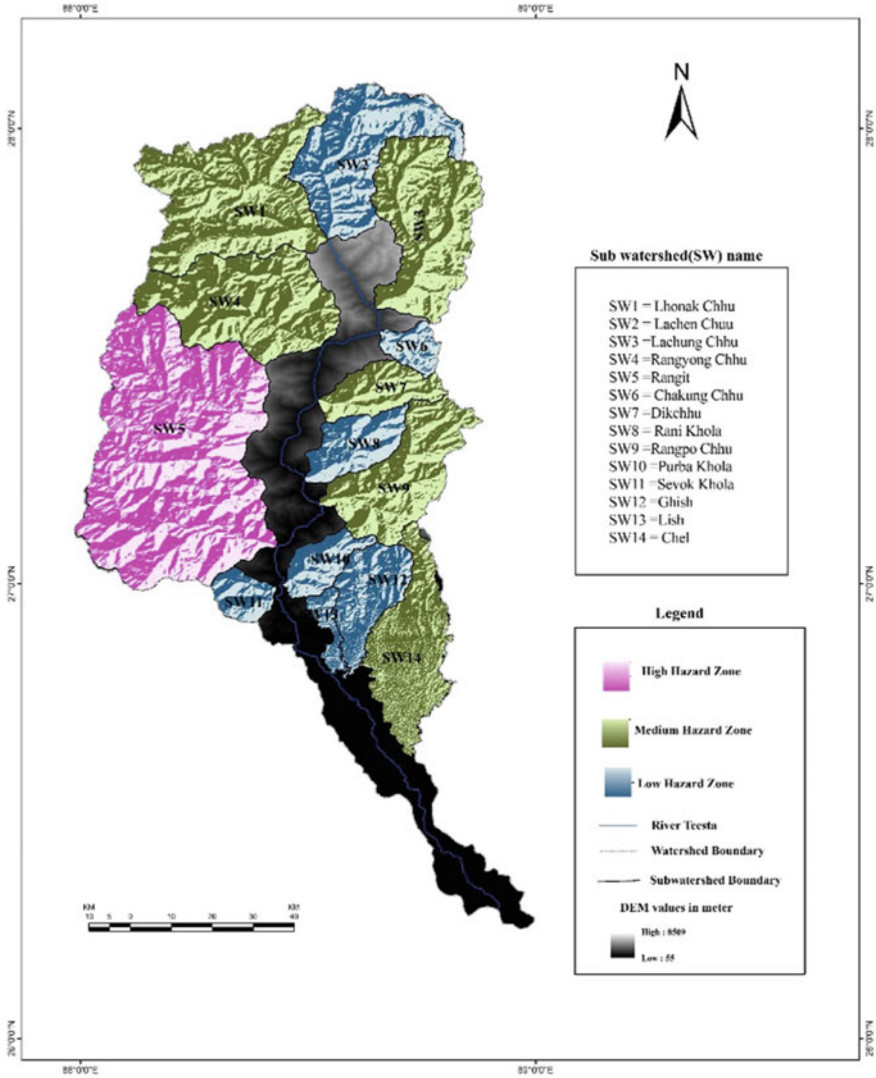

Fig. 9 Flood priority of the 14 watersheds based on Hazard Degree

Low hazard zone (37.13–37.44):

The third category of sub-watersheds is assigned low priority. It consists of seven sub-watersheds as follows: 2, 6, 8, 10, 11, 12, and 15.

Table 3 Score of different morphometric parameters of 14 sub watershed of Teesta River by Hazard degree

Sub-Catchment	Hazard Degree of the Parameters																Priority	Basin Hazard degree
	U	Nu	Rb	Lu	L	W	L/W	Au	P	Re	Rc	Bs	Dt	Dd	Fs	Total		
Lhonak Chhu (SW1)	5	2.79	3.03	3.16	4.31	4.63	1.01	2.76	4.04	2.17	2.19	1.44	2.81	1.64	3.23	44.21	M	3
Lachen Chuu (SW2)	3	2.2	4.17	2.35	2.65	2.75	1.02	2.18	3.47	1	2.04	3.31	2.39	1.46	3.23	37.22	M	2
Lachung Chhu (SW3)	5	2.39	2.46	2.52	3.75	3.99	1.02	2.34	3.19	3.56	2.78	2.33	2.83	1.43	3.36	42.95	M	3
Rangyong Chhu (SW4)	3	2.48	3.48	2.65	3.68	3.51	1.02	2.44	3.13	4.09	3.15	5	3.01	1.46	3.36	45.46	M	3
Rangit (SW5)	5	5	1.7	5	4.8	5	1.01	5	5	1.91	3.22	1.27	5	5	4.28	58.19	H	5
Chakung Chhu (SW6)	1	1	5	1.01	1	1.92	1.01	1.06	1.03	4.47	2.26	2.78	1.56	1.05	1	27.15	L	1
Dikchhu (SW7)	3	1.33	4.87	1.26	2.21	2.13	5	1.32	1.71	3.83	3.15	2.33	1.88	1.05	3.23	38.3	L	2
Rani Khola (SW8)	1	1.45	1	1.27	2.36	2.44	1.02	1.33	1.63	3.56	3.67	1.62	2.3	1	5	30.65	L	1
Rangpo Chhu (SW9)	5	1.94	3.03	1.92	3.23	2.61	1.03	1.95	2.86	4.25	2.56	3.58	2.35	1.13	2.97	40.41	M	3
Purba Khola (SW10)	3	1.45	2.71	1.27	1.49	2.01	1.02	1.17	1.42	3.77	3.15	2.87	1.64	1.15	3.1	31.22	L	2
Sevok Khola (SW11)	1	1.12	2.59	1.07	1.01	2.42	1	1.09	1	2.71	5	1	1.87	1.25	4.02	28.15	L	1
Ghish (SW12)	3	1.44	2.9	1.52	2.77	2.62	1.02	1.46	2.35	3.88	2.04	3.04	1.74	1.48	2.84	34.1	M	2
Lish (SW13)	1	1	3.35	1	1.76	1	1.11	1	1.65	5	1	5	1	1.69	2.97	29.53	L	1
Chel (SW14)	5	2	4.24	2.37	5	3.01	1.04	1.99	3.94	4.68	1.3	4.73	1.92	1.97	3.23	46.42	M	4

9 Flood Priority Rank Based on Principal Component Analysis with Weighted-Sum Approach Results

The PCA is a multivariate statistical technique for reducing data by minimizing the number of parameters to a small number of components (Farhan & Shaik, 2017). PCA was applied on linear, areal and shape morphometric variables to compute co-relation matrix and obtain principal component and to find out the most important variable that is responsible for hazard Zonation (Malik et al., 2019; Arefin & Alam, 2020). PCA was conducted on 14 morphometric parameters to express the relationship between morphometric variables for the Teesta watershed. The 10 morphometric parameters were reduced to two significant components. The result of inter-correlation analysis among 10 parameters related to the Teesta watershed is displayed in Table 4 Inter-correlation among different geomorphic parameters was detected to reduce the length of the parameters. Inter-correlation matrix shows that the diagonal element has correlation value one. According to Meshram and Sharma (2018), correlation coefficient among elements in inter-correlation matrix > 0.9 is strongly correlated, when correlation coefficient > 0.75 to 0.9, good correlation exists, when correlation coefficient > 0.6 to 0.75, moderate correlation exists. It is observed from the table that a strong correlation (>0.9) exists between Au to Lu; Dt to Au; P to Lu; P to L; Dt to Lu; and between W to Lu. Correlation among Fs to Rb; L to Lu; Dd to Lu; W to Lu, Au to W; P to W; Dt to W; P to Au; Dt to P and Dd to Dt has a good correlation. However, Dt to L; Dd to W, Dd to P; Bs to Rc a have moderate correlation. The rest of the correlation coefficient of the inter-correlation matrix is very low (Table 5).

Table 5 shows the Eigen value obtained during PCA analysis. It was observed from Table 5 that the first three components have an Eigen value greater than 1, and together account for 81.62% of the total variance in the original data, suggesting that they are significant. Table 6 shows that unrotated matrix of linear, areal and shape morphometric variables which indicate that the first component was strongly correlated with Lu, Au, P and in a good correlation with L, W, Dt, Dd, whereas component 2 has a good correlation with Rc, Bs and moderately correlated with Fs. component 2 has a good correlation with LW.

Table 6 shows that the most important Morphometric variables are Basin length (L), Circulatory ratio (Rc), Drainage Texture (Dt). These variables are used for the Weight sum Analysis and Mapping of the Hazard group.

10 Weighted-Sum Analysis

To assess the flash hazard group of 14 sub-watershed of Teesta 3 significant morphometric (L, Rc, Dt) parameters were used. The cross correlation between the three parameters is shown in Table 6. The compound factor was used as a factor to determine the flood susceptibility zone. The computation of CF for sub-watershed hazard zonation was done thus (Table 7 and 8)

Table 4 Correlation matrix of morphometric parameters of 14 sub-watersheds of Teesta

Morphometric Parameters	Rb	Lu	L	W	LW	Au	P	Re	Rc	Bs	Dt	Dd	Fs
Rb	1.000												
Lu	−0.287	1.000											
L	−0.171	**0.826**	1.000										
W	−0.349	**0.907**	**0.798**	1.000									
LW	0.434	−0.204	−0.142	−0.205	1.000								
Au	−0.324	**0.991**	**0.773**	**0.880**	−0.175	1.000							
P	−0.145	**0.926**	**0.939**	**0.836**	−0.208	**0.884**	1.000						
Re	−0.239	0.532	0.193	0.552	−0.097	0.536	0.443	1.000					
Rc	−0.443	−0.033	−0.293	0.145	0.117	0.025	−0.291	0.313	1.000				
Bs	−0.435	0.213	−0.035	0.410	0.094	0.250	0.016	0.568	**0.628**	1.000			
Dt	−0.436	0.9**32**	**0.674**	**0.883**	−0.139	**0.958**	**0.768**	0.566	0.271	0.374	1.000		
Dd	−0.324	**0.836**	0.569	**0.614**	−0.164	**0.871**	0.6**86**	0.375	−0.024	0.227	**0.787**	1.000	
Fs	**−0.759**	0.317	0.295	0.338	−0.016	0.338	0.253	0.383	0.501	0.391	0.449	0.311	1.000

Table 5 Total variance explained of 14 sub-watersheds of Teesta

Component	Initial Eigen values			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	6.751	51.929	51.929	6.751	51.929	51.929	6.164	47.412	47.412
2	2.585	19.884	71.813	2.585	19.884	71.813	2.921	22.466	69.878
3	1.275	9.807	81.620	1.275	9.807	81.620	1.526	11.741	81.620
4	0.852	6.552	88.172						
5	0.553	4.251	92.424						
6	0.461	3.545	95.969						
7	0.356	2.742	98.710						
8	0.118	0.905	99.616						
9	0.028	0.216	99.832						
10	0.016	0.122	99.954						
11	0.005	0.038	99.992						
12	0.001	0.007	99.999						
13	0.000	0.001	100.000						

Table 6 Rotated Component Matrix

	Component		
	1	2	3
Rb	−0.157	−0.558	0.761
Lu	**0.983**	0.116	−0.096
L	**0.879**	−0.179	−0.139
W	**0.885**	0.274	−0.091
LW	−0.132	0.172	**0.818**
Au	**0.963**	0.175	−0.091
P	**0.965**	−0.124	−0.090
Re	0.487	0.569	0.093
Rc	−0.164	**0.886**	−0.036
Bs	0.141	**0.851**	0.092
Dt	**0.874**	0.379	−0.113
Dd	**0.799**	0.139	−0.137
Fs	0.236	**0.644**	−0.418

Table 7 Cross- corelation matrix of L, Rc, Dt parameters of 14 sub-watersheds of Teesta

Morphometric Parameters	L	Rc	Dt
L	1.000	−0.33	0.674
Rc	−0.293	1.000	0.271
Dt	0.674	0.271	1.000
Sum of corelation	1.381	0.941	1.945
Grand total	4.267	4.267	4.267
Weight	0.323	0.221	0.456

CF = (0.323 × PPR of L) + (0.221xPPR of Rc) + (0.456xPPR of Dt).

For the priority of the watersheds, compound factor value was used. Finally, a compound factor values were used to assess flood potential zone. The low values indicated a high flood priority, while the high compound values indicated a low flood priority. The 14sub-watersheds have been grouped into three priority categories 1. High (1.2–4.2) 2. Medium (4.23–8.24) 3. low (8.21–12.41). Figure 10 shows the sub-watersheds SW-1, SW-3, SW-5under the very high category, SW-4, SW-2, SW-6, SW-7, SW-8, SW-9, SW-14 under medium, SW-6, SW-10, SW-11, SW-12 under low category.

Table 8 Score of Sub Watershed by Compound Factor

Sub watersheds	Compound Factor	Priority
Lhonak Chhu (SW1)	5.003	5
Lachen Chuu (SW2)	7.295	9
Lachung Chhu (SW3)	4.207	3
Rangyong Chhu (SW4)	3.411	2
Rangit (SW5)	1.765	1
Chakung Chhu (SW6)	12.439	14
Dikchhu (SW7)	8.218	10
Rani Khola (SW8)	6.541	7
Rangpo Chhu (SW9)	6.442	6
Purba Khola (SW10)	10.232	13
Sevok Khola (SW11)	9.864	12
Ghish (SW12)	9.708	11
Lish (SW13)	4.23	4
Chel (SW14)	6.844	8

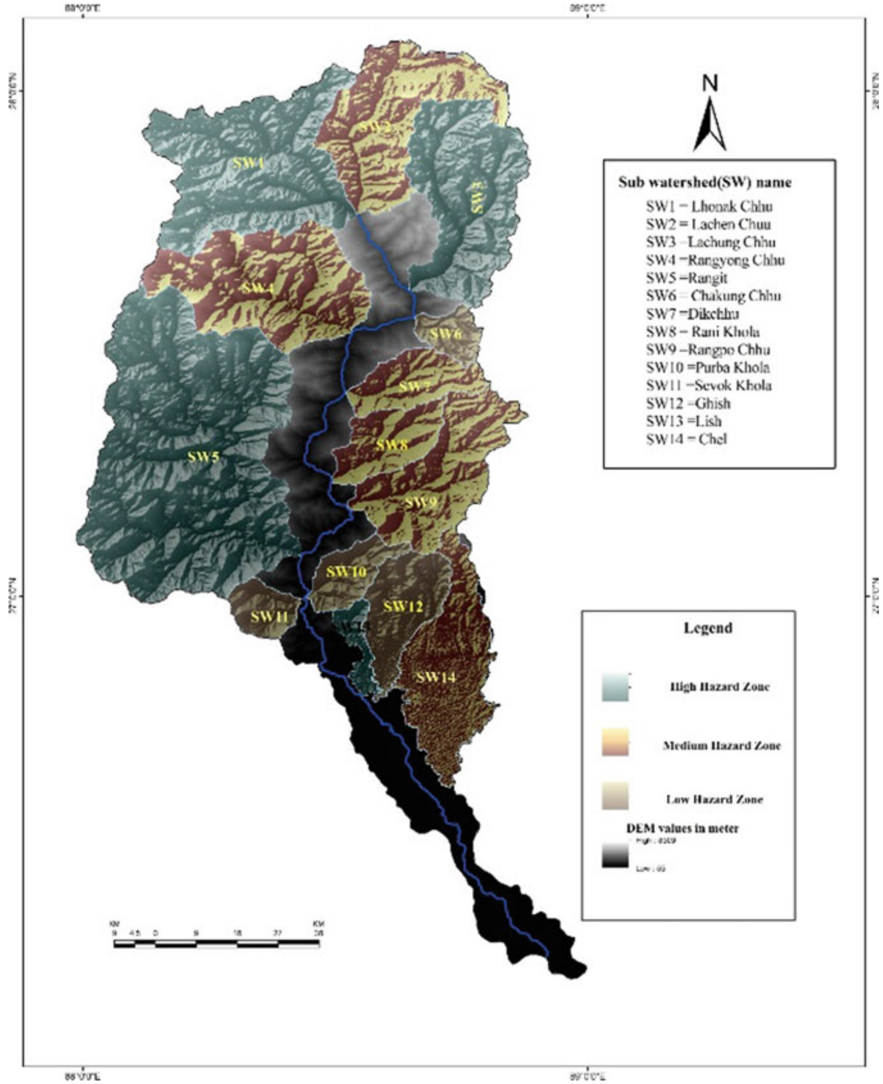

Fig. 10 Flood priority of 14 watersheds based on PCAWSA

11 Conclusion

GIS and Remote sensing were employed in the study to evaluate flood priority using15 different morphometric parameters including linear, areal, shape. The outcome of the research is the spatial potential of flood mapping. The research demonstrates that decision-makers can use GIS combined with statistical approaches for an ungauged watershed to provide effective watershed management in terms of water resources. The study reveals that Rangit (SW-5), Lachung Chhu (SW-3) fall into the very high susceptible zone. Elevation difference, drainage density, stream frequency and texture ratios are all extremely high. PCAWSA map displays those 3 sub-watersheds have a high priority, 7 sub-watersheds have moderate priority, and 4 sub-watersheds have low priority (Fig. 10). On the other hand, Hazard degree Score shows, 1 sub-watershed has high priority, 6 watersheds are found to have moderate priorities and 7 sub-watersheds have low priority. These results reveal that two different prioritization methods give almost similar results. The top priority assigned to these and followed by SW-4, SW-2, SW-6, SW-7, SW-6, SW-10, SW-11 and SW-12. It may be concluded, using remote sensing and GIS, a systematic study of morphometric parameters within the watershed provides valuable information for understanding basin characteristics and the study shows flood prone sub-watershed across the study area. This contributes to the long-term sustainability of the watershed by appropriate soil and water conservation initiative.

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An Appraisal of Spatio—Temporal Occurrence of Fluvial Hazard: Case Study of Flood in the Districts of Jalpaiguri and Alipurduar (West Bengal, India)

Moitrayee Das

Abstract Flood is the most common and widespread fluvial hazard. Flood in Erstwhile Jalpaiguri (now Jalpaiguri and Alipurduar) district occurs almost every year with unfailing regularity but the geographical area affected by flood varies largely from one year to another. About 2000 km^2area of land are prone to floods in Jalpaiguri-Alipurduar district which is about 32% of the land area of the district. Throughout the decade the occurrence of the flood shows a positive increase [$Y = 22.29x + 460.15$] and also insignificant $R^2 = 0.18$). In spite of various engineering river training method, the misery of flood still continues. In the present paper, the author tried to analyse the detailed temporal variation of flood scenario of the district along with hypothesis testing whether the flood event is reducing in the present context and it is an annual event in the district.

Keywords Spatial flood · Temporal flood · Hypothesis testing

1 Introduction

Bank failure, river shifting and river deposition, flash flood, common flood are the different forms of fluvial hazards. Among them flood is the most common and wide spread fluvial hazard. The entire North Bengal has been suffering from the agony of floods especially during monsoon months. Erstwhile Jalpaiguri district, the study area, presently divided into Jalpaiguri and Alipurduar districts of West Bengal, is one of the annual flood-hotspots in India (Dutta, 2016) (Roy, 2011). The study area is situated on the humid foothills and piedmont plains drained by numerous large and small rivers originating in the Eastern Himalaya (Chatterjee, 1949). Flood occurs during the period of the South-West monsoons primarily due to high rainfall and high discharge from the Eastern Himalayan Rivers of the region (Biswas, 2016). Other physical controls like slope, relief and soil further encourage occurrence and vulnerability of flood in Jalpaiguri district, though its magnitude varies from one

M. Das (✉)
Department of Geography, Chandernagore College, Hooghly, West Bengal, India
e-mail: moitre_alap@rediffmail.com

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administrative block of the district to the other and also over time (GoI, 2002).Flood caused by these rivers is a source of misery of the people and a factor of backwardness of the area (Uttarbanga Unnayan Parisad, 2001). As the district is dominated by rural settlements and associated farming activities including tea plantations, there is an all pervasive negative impact of flood. Several hard-engineered river training measures have been taken from time to time to check flood related damages that run into several million rupees in monetary terms every year in the district. But flood continues to occur (Hunter, 1876).

Flood varies in intensity and extent over time and space. Temporal and spatial variation of flood here refers to disparities in the areal extent of flood that is variation in the size of flood affected areas in different flood-years across the administrative blocks of the district. Identification of temporal and spatial variation—and its patterns, if any - is important for well-being of people, management and planning for the region, as well as for administrative purposes.The present study has been taken up, therefore, to find out the significance of spatio-temporal variation of flood scenario in the study area through some hypothesis testing.

2 Study Area

Jalpaiguri district of the state of West Bengal, India, which has been divided into Jalpaiguri and Alipurduar districts in 2014, is the present study area. It is geographically situated from 26º16′35″ North to 26º59′30″ North and from 88º04′59″East to 89º55′20″ East comprising an area of 6227 sq. km. The study area occupies the southern flanks of the foothills of the Darjeeling Himalaya, consisting of the Terai and the Duar. The study area is bounded on the north by Darjeeling and Kalimpong districts of West Bengal, India, and the sovereign country of Bhutan. On the south, it is demarcated by Uttar Dinajpur and Kochbihar districts; on the west by Uttar Dinajpur and Darjeeling districts of West Bengal as well as Purnea district of Bihar, while the state of Assam occurs on the east. The R.Sankosh separates the study area of Jalpaiguri district from the Goalpara district of Assam (Fig. 1).

Administratively, as per the 2011 Census records, Jalpaiguri district consists of three sub-divisions, viz. Sadar, Mal and Alipurduar.These sub divisions consist of 13 Community Development (CD Blocks), 17 police stations, 756 mouzas and 4 Municipalities. (Census Report, 2011). From 2014, the erstwhile Jalpaiguri district has been divided into—Jalpaiguri and Alipurduar districts.

Jalpaiguri—Alipurduar district have an almost longitudinally disposed varied terrain lying over a part of the Extra- Peninsula of the Himalayan foothills and the Ganga–Brahmaputra plains, drained by a web of large and small rivers (Fig. 2b). There is steeply sloping Sub-Himalayan hill range in the North (lying above 900 m), followed by mega alluvial fans (300-900 m) and flood plains (<50 m -300 m) across the foothill piedmont zone to the South (Burrard & Hayden, 1933) (Sarkar, 2003) (Fig. 2a). There is plentiful orographic rainfall from SW monsoons that load the rivers with high seasonal discharge ((Dhar & Nandargi, 2003). Flood is, therefore, a

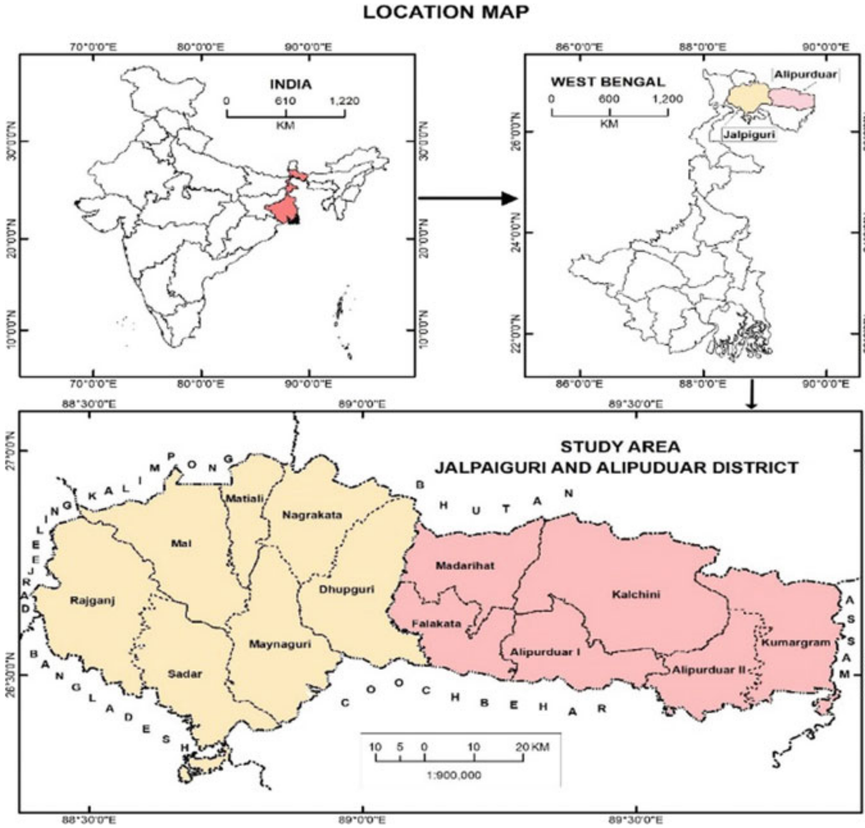

Fig. 1 Location Map

common occurrence here ((Froehlich,et.al, 2000). Not only that, all the blocks in the district is more or less affected by the flood. There is constant and noticeable change of land use and land cover. Dense rich forests of the locality is fast receding. Vast maze of farming land and tea gardens interspersed with settlements are emerging instead (GoWB, 2001). These dynamic physical and socio-economic environments directly and indirectly control the occurrence and duration of flood in the area under study. (Dash, 1947) (Mukhopadhyay, 1979).

3 Objectives

Present paper is to explain the various dimensions of spatial and temporal distribution of flood areas in the district of Jalpaiguri and Alipurduar. The dimensions are:

- To analyse the spatial (block level) distribution of flood affected area in the district.
- To assess the temporal variation since 1970 to 2019.

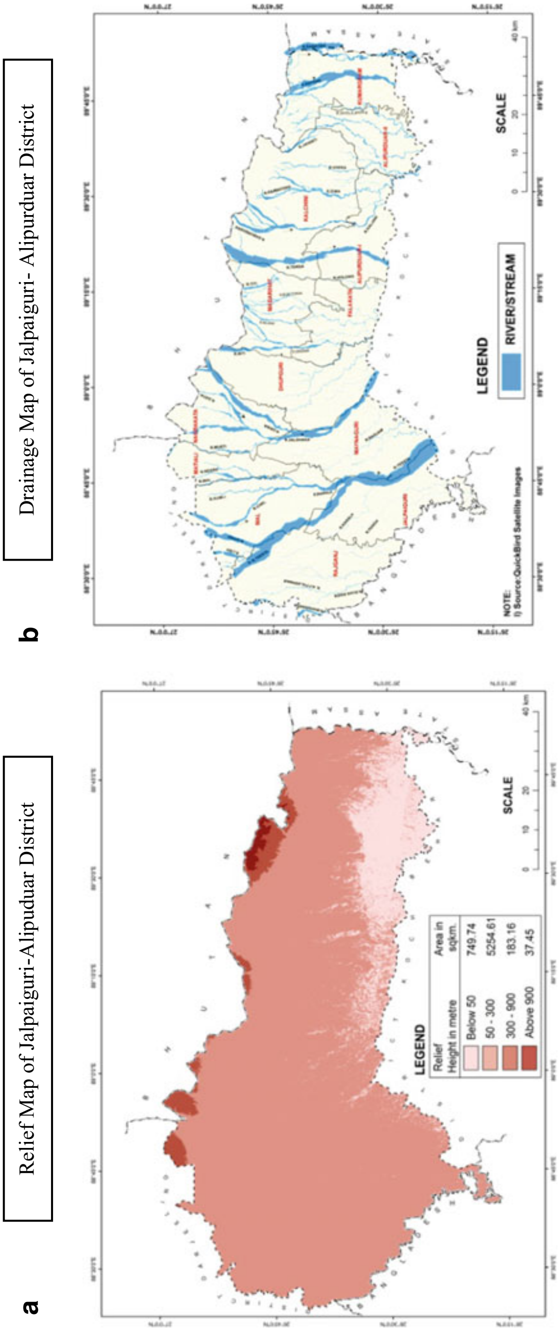

Fig. 2 **a** Relief Map; **b** Drainage Map

On the basis of the objective the author also tried to solve two hypotheses which have been derived. Those are: (i) Hypothesis Test: area affected by flood is diminishing in Jalpaiguri-Alipurduar districts. (ii) Hypothesis Test: flood is a regular event in Jalpaiguri- Alipurduar district.

4 Data Base and Methodology

To success the present work the data has been taken from various government agencies. The agencies are Central water Commission, Lower Brahmaputra Division and Disaster Management Section of District Magistrate Office, Jalpaiguri. The data provided by the both agencies are basically area coverage data of flood year to year, from 1970 to 2019. To exercise the temporal variation simple trend line and moving average curve has been taken into consideration. For the execution of hypothesis analysis two different hypothesis test are taken over the project.One is 't' test and another one is 'chi' square test. In the section of chi test expected and observed frequency has been analyse by Relative Frequency and Cumulative Relative Frequency. The Cumulative Relative Frequency has been considered as Observed Frequency. To find out the Expected Frequency (or Theoretical Frequency) Cumulative Distribution Function (CDF) [1-e^-(x_i/mean)] has been worked out.

5 Analysis and Assessment

There is an overall positive temporal and areal trend of occurrence of flood between 1970 and 2019 (Fig. 3). In abiding regularity floods not only occurred in the district during the said period but also seized in wider areas under their damaging effect. This long duration of 50 years there has been a positive trend [$Y = 22.29x + 460.15$] but the $R^2 = 0.18$ which indicates the positive trend is insignificant.

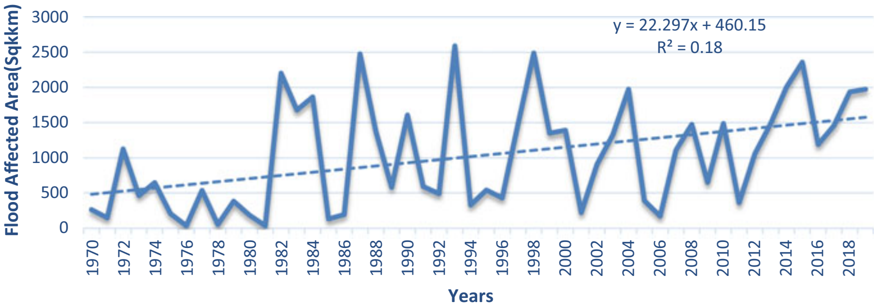

Fig. 3 Temporal and Spatial variation of flood affected areas in Jalpaiguri-Alipurduar district (1970–2019) (*Source* CWC, LBD & Irrigation and waterways, Jalpaiguri)

Within the total span of 50 years the maximum area affected by flood was in 1993 (2589.38 sq. km) which covered 41.58% of total geographical area of the district followed by the 1998 flood (2489.23 sq. km of flood affected area i.e. 39.97%of total area of the district) and the 1987 flood (2477.763 sq. km of flood affected area i.e. 39.79% of total area of the district). If the extent of the flood affected area from 1970–2019 is classified into six size classes (km^2) and the frequency of flood affecting such areas are worked out, then it appears that the study area is extremely responsive to small sized floods having areal extent of less than 500km^2. The district saw such floods occurring for 18 times during the period under review (Table 1). On the other hand, it was only in a single occasion that flood was so colossal that it spread over more than 2500 km^2. It occurred in 1993 as a result of excessive rain on the Bhutan Himalayan front when Hasimara recorded a rainfall of 850 mm/24 h and protective embankments of Alipurduar town was nearly washed away (Table 1.)

The average of flood affected area during the span of 50 years (1970–2019 CE) is 1028.73 km^2. Within the said period flood situation crossed the area-average (1028.73km^2) for 18 times and more particularly seven times from 1970 to 1990, and eleven times between 1991 and 2019. During the said period of 43 years, at least 31.45% area of the district on an average has been inundated It may further be noted that the percentage distribution of mean flooded area to the total geographic area is 1028.73*100/6227 = 16.52%.

On the basis field data obtained from field survey (2006–2012) and administrative data regarding flood obtained from 13 Block Development Offices in Jalpaiguri, it appears that out of the 756 mouzas comprising the study area, 337 mouzas are flood prone (Table 2). There are two mouzas viz. Mal (53.39%) and Jalpaiguri Sadar (49.93%) where about 50% or more area is affected by flood. In 40%-50% flood affected area category lies Alipurduar II having 42.61% area flood prone. Within 30%-40% category several administrative blocks are included such as Alipurduar I, Madarihat, Dhupguri, Nagrakata, and Maynaguri. Again, the 20%-30% flood-area class is comprised of Kumargram, Falakata, and Matiali blocks. The least flood affected blocks in the district are Kalchini (18.66%) and Rajgunj where only 13.82%

Table 1 Frequency of floods and size of flood affected area in Jalpaiguri-Alipurduar (1970–2019)

Flood affected area (Sq km)	Frequency	Year of occurrence
Below 500	18	1970, 1971, 1973, 1975, 1976, 1978, 1979, 1980, 1981, 1985, 1986, 1992, 1994, 1996, 2003, 2005, 2006, 2011
500–1000	7	1974, 1977, 1989, 1991, 1995, 2002, 2009
1001–1500	13	1972, 1988, 1997, 1999, 2000, 2003, 2007, 2008, 2010, 2012, 2013, 2016, 2017
1501–2000	6	1983, 1984, 1990, 2004,2018, 2019
2001–2500	5	1982, 1987, 1998, 2014, 2015
Above 2500	1	1993

Source Data provided by CWC, LBD, and Irrigation& Waterways and Compilation by Author area is flood prone. In so far as percentage of high flood frequency is concerned Maynaguri (60.8%) and Mal blocks (57.8%) are most affected (Fig. 4)

Hypothesis Test: Area affected by flood is diminishing in Jalpaiguri-Alipurduar:

It has been observed that the mean flood affected area of the district is 1028.73 sq. km. But it is expected that the average area due to flood has decreased in the last 15 years (2004–2019). The Null Hypothesis is therefore as follows:

$$\mathrm{H_o}:\ \mu = 1028.73\text{sq. km}$$

$$\mathrm{H_1}:\ \mu < \ 1028.73\text{sq. km}$$

$$\mathrm{t} = \frac{x-\mu}{s/\sqrt{n}}[\mathrm{n}-1]$$

Where, x = mean flooded area of given year (2004–2019), μ = mean flooded area,

s = standard deviation of said year (2004–2019), n = no. of years.

Table 2 Spatial diversities of distribution of flood in Jalpaiguri -Alipurduar district

Name of administrative block	Total number of mouza	Number of flood affected mouzas	Size of flood affected area in km^2	% of flood affected area to total geographical area	% of flood affected mouza to total no. of mouza	% of mouza experiencing high flood frequency
Rajganj	29	5	85	13.82	17.24	40
Jalpaiguri Sadar	29	9	250	49.93	31.03	33.3
Mal	106	64	291.5	53.39	60.37	57.8
Maynaguri	86	23	161.82	30.49	26.74	60.8
Matiali	31	10	42.99	20.98	32.25	70
Nagrakata	34	24	141.81	35.67	70.58	44.4
Dhupguri	103	42	176.68	31.26	40.77	26.1
Madarihat	50	29	121.74	32.31	58	51.7
Falakata	63	21	104.01	29.38	33.33	47.6
Kalchini	43	24	166.56	18.66	55.81	54.1
Alipurduar I	48	24	125.15	33.05	50	33.3
Alipurduar II	79	34	136.9	42.61	43.03	47
Kumargram	55	28	153.97	29.74	50.90	50
N = 13	756	337	1958.43	31.45	44.57	47.73

Source Data Compiled by author

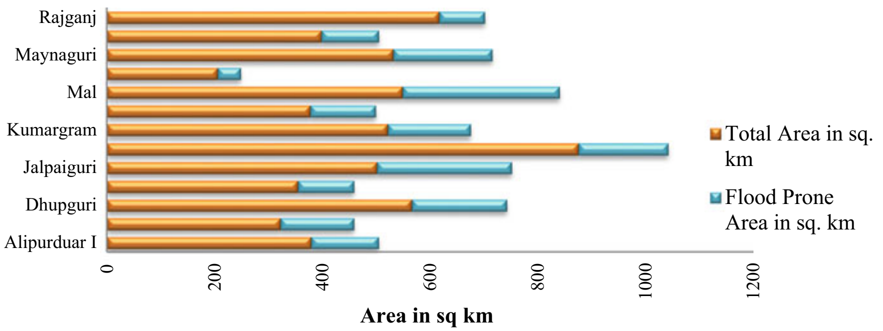

Fig. 4 Block wise distribution of flood affected area (1970–2019) (*Source* Data provided by CWC, LBD, and Irrigation& Waterways)

$t = \frac{1406.22-1028.73}{660.98/\sqrt{15}} = 2.210$ Calculated value

0.05 Level of Significance For14 Degree of Freedom, Two Tailed Test, Tabulated Value is 1.76.

Here, Tabulated value ≥ Calculated value. Therefore, $H_1{:}\mu < 1028.73$.

Thus it is concluded that during the last 15 years (2004–2019), flood affected area in the district has diminished in respect of the 50 year average.

Chi-square Good Fit and Hypothesis Test: flood is a regular event in Jalpaiguri-Alipurduar:

From the above test of hypothesis (t) though it has been concluded that in respect of 50 years' average (1970–2019 CE), the mean flood area is diminishing in Jalpaiguri-Alipurduar, yet another important aspect of flood remains to be tested that is whether flood is a regular event in the district. To analyse regular occurrence of flood, another hypothesis has been tested, therefore, on the basis of Chi-square good fit test. The chi-square good fit test is able to explain how the assumed theoretical distribution (Binomial, Poisson or Normal) fit with the observed data. The fit is considered to be good when calculated value of chi (χ^2) is less than the table value at certain level of significance.

Accordingly, Flood Affected Area of Jalpaiguri- Alipurduar district has been classified into six categories and the frequencies has been analysed (Table 1). Further, the Relative Frequency and Cumulative Relative Frequency have been calculated (Table 3). The Cumulative Relative Frequency has been considered as Observed Frequency. To find out the Expected Frequency (or Theoretical Frequency) Cumulative Distribution Function (CDF).

[1-e^(x_i/mean)] has been worked out (Table 3). Cumulative Relative Frequencies and Expected Frequencies of flood affected area have been shown in Fig. 5.

Table 3 Flood Probability Distribution

Classes Flood affected area (sqkm)	x_i	Frequency (f)	Probability (Relative Frequency	Cumulative Relative Frequency (O_i)	$F(x) = 1 - e^{-xi/\mu} = E_i$ CDF
Below 500	250	18	0.419	0.4186	0.2436
500–1000	750	7	0.16	0.58	0.5634
1000–1500	1250	13	0.233	0.81	0.7474
1500–2000	1750	6	0.093	0.91	0.8554
2000–2500	2250	5	0.07	0.98	0.9165
Above 2500	2750	1	0.023	1	0.9522
Total = 6		50			

Source Computed by Author

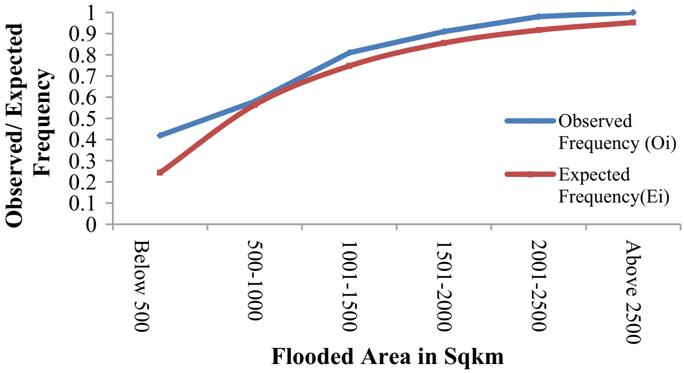

Fig. 5 Distribution of Area-wise Cumulative Relative (Observed) Flood Frequency and Expected Flood Frequency

It appears from Fig. 5 that Theoretical Frequency or Expected Frequency is less than Cumulative Relative (Observed) Flood Frequency. Particularly for floods inundating areas between 500–1000 km^2 the Observed frequency and Expected frequency are approximately same, if compared to other flood-area classes.

Hypothesis Test:

In practice, Expected Frequencies are computed on the basis of Null Hypothesis (H_0). If under this hypothesis the computed value of χ^2 given by (1) is found greater than some critical value (such as $\chi^2_{0.95}$ *or* $\chi^2_{0.99}$, which are the critical values at the 0.05 and 0.01 significance levels respectively), it can be inferred that the Observed Frequencies differ significantly from Expected Frequencies. Thus H_0 is to be rejected at the corresponding level of significance and hence the Alternative Hypothesis (H_1) is accepted. Here, (H_0) stands for flood being a regular event of the district. Thus,

$$\chi^2 = \frac{(o_1 - e_1)^\wedge 2}{x} e_1 + \frac{(o_2 - e_2)^\wedge 2}{e_2} + \cdots + \frac{(o_k - e_k)^\wedge 2}{e_k} = \sum_{j=1}^{k} \frac{(o_j - e_j)^2}{e_j} \quad (1)$$

$\chi^2 = 0.126 + 0.00049 + 0.0052 + 0.0035 + 0.0044 + 0.0024 \qquad (N - 1) = 5$ [Degree of freedom].

$\chi^2 = 0.141(N - 1) = 5$ [Degree of freedom].

Here, computed value of chi square (0.141) is less than the table value (the table value of chi for 5 degree of freedom at 0.01 significance level is 0.554) of chi square. This establishes that flood is a regular event in the district of Jalpaiguri- Alipurduar.

6 Conclusion

All physical factors contributing to flood in the study area such as high rainfall, high river-discharge, piedmont topography etc. are inexorable. Within a total span of 50 years (1970–2019) the maximum area affected by flood was in 1993 (2589.38 sq. km) which covered 41.58% of total geographical area of the district followed by the 1998 flood and the 1987 flood.

The districts are extremely responsive to small sized floods over areas less than 500km^2. The district saw such floods for 18 times during the period 1970–2012. It further appears that out of the 756 mouzas comprising the study area, 337 mouzas are flood prone. During the given period of 50 years (1970–2019), 31.45% area of the district on an average has been inundated by each event of flood. Test of hypothesis proves that during the last 15 years (1998–2012), flood affected area in the district has decreased in respect of the 43 year average. In spite of the fact of diminishing trend, it is also true that flood in the district of Jalpaiguri-Alipurduar is a regular event.

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Spatiotemporal Dynamics of a Poldered River System in Lower Bengal Delta, Bangladesh

Md Mujibor Rahman and Souvik Sarker

Abstract River response to numerous natural forces and human activities is vital for effective river management. This research deals with the dynamic morphological properties of a river, namely the Hari River and six of its tributaries. This study exclusively looks at a portion of the Hari River, which flows within polders 24–25 of the Lower Bengal Delta in Bangladesh's Khulna division situated in the country's southwest coastal zone. Three of the six tributaries flow through polder 24, while the other three flow through polder 25. Understanding the changes that occur in these rivers, as well as their responses to the different drivers of such changes that work on them, is crucial for improving the lifestyles of the polder dwellers. Spatiotemporal dynamics of Hari River and its tributaries were investigated using nine multitemporal Landsat satellite images from 1975 to 2021. Sinuosity ratios of the Hari River and its six tributaries were measured, and the results suggest that all the seven rivers have become more sinuous through the passing of time. Channel width of Hari River was measured at multiple spots and found to be decreasing. It was also revealed that the Hari River shifted slightly towards the east throughout the 46-year study period. The shifting is not abnormal, and hence it does not pose a threat to local people's existence. However, the narrowing of the already narrow Hari River poses a serious threat to its existence. Such information may assist the local river management body in planning and formulating an effective management strategy.

Keywords Spatiotemporal dynamics · Polder · Sinuosity · Channel migration · Satellite imagery · River management

1 Introduction

River courses are dynamic in nature. They are significantly sensitive to various natural and man-made changes. Any persistent effect created by such changes results in changes in the channel flow. These changes have significant impacts on both the main

M. M. Rahman (✉) · S. Sarker
Environmental Science Discipline, Khulna University, Khulna 9208, Bangladesh
e-mail: mujib@es.ku.ac.bd

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channel and the neighboring landforms. (Ollero, 2010). River course changes are considered hazardous as they promote a multitude of disturbances such as flooding, bank erosion, and tributary detachment (Mani & Patwary, 2000; Naik et al., 1999). The dynamic behavior of a river course has a morphological relation with the geology of the area (Gupta et al., 2013). Morphology of a river differs depending on its geographical location.

Natural factors such as climate changes, and tectonic and seismic activities have always played critical roles in changing water and sediment inputs. Moreover, in the Anthropocene, many of these changes are accelerated by human activities such as dam construction, bank revetments, sand mining, deforestation (Das et al., 2007), and several other activities such as polderization. Leys and Werritty (1999) found that fluctuations in river width are linked to engineering activities such as bridge construction. According to Surian and Rinaldi (2003), engineering works within a river course promotes morphological changes, which in turn affects the surrounding environment and civilization. Any natural or anthropogenic modification can cause the river to deviate from a phase of dynamic equilibrium (Petts & Gurnell, 2005; Winterbottom, 2000), resulting in channel instability and changes in channel structure and pattern (Yang, 1999).

Polders are areas protected by embankments, that are disconnected from the main river system. Over a hundred polders were constructed during 1960s and early 1970s in the coastal areas of Bangladesh by the then East Pakistan Water and Power Development Authority (EP-WAPDA), currently named as Bangladesh water Development Board (BWDB), to make sure the coast is protected from tidal flooding and to reduce salinity intrusion. They prevent long-term flooding and waterlogging caused by cyclonic storm surges. They are also used for agricultural cultivation. However, by restricting runoff of the southern river courses, these polders have disrupted the natural flow of the rivers. Furthermore, some very strong cyclones and storm surges has caused significant damage to the polders, resulting in severe external siltation (BWDB, 2013). This led to additional changes regarding water and sediment fluxes.

Several studies have shown that alteration in water and sediment flux trigger changes in river channel morphology. For example, a study on the Lower Colorado River (Tiegs & Pohl, 2005) revealed that its width varied with discharge throughout time and space. Furthermore, a study on the Yangtze River (Li et al., 2007) found that a rise in discharge might cause excessive bank erosion, leading the channel to widen. Yao et al. (2011) observed that sediments from bank erosion led to bar formation, and bank erosion appeared to have a significant connection with the average flow of China's Yellow River.

According to Yang et al. (1999), bankline migration is a channel response to many local and regional mechanisms, and recording channel migration is important for river management and planning, as well as flood protection planning. The aim of assessing the spatial extent of bankline changes via remote sensing is to gain a deeper understanding from the viewpoint of sinuosity and channel width, as well as the effects of human interventions, such as placing hard points on the river (Hossain et al., 2013).

The analysis of morphological changes of rivers with time and space is crucial for reducing potential damage from floods, bank erosion, and disasters. The findings will assist decision makers in designing river management strategies (Tiegs & Pohl, 2005), controlling navigation, recognizing changes in aquatic and riparian ecosystems (Li et al., 2007), planning engineering works in rivers (Yao et al., 2011), and developing ways to address climate change (Sarker et al., 2014).

An understanding of morphological changes of coastal river channels in poldered ecosystems of the Lower Bengal Delta in Bangladesh would be useful for their successful planning and management. But no such work was found to be done previously in this region. The present work is the first of its kind in this region. However, the present study does not deal with all the morphological parameters of a river. All the channels studied under this research are small rivers with narrow width. Stratigraphic analysis and sediment discharge analysis can provide more insight into bed geomorphology and fluvial flow regime. But these parameters were not studied due to budget limitation as it was a self-funded study. Satellite images for the older years of the study period were not of much high resolution which, coupled with the rivers being too narrow, led to difficulties in presenting the images.

The objectives of this research are to investigate the morphological changes of Hari River and its six tributaries, all of which are in a poldered region of the Lower Bengal Delta, in-terms of sinuosity, channel width and bankline shifting during 1975 to 2021 using satellite imagery; and to provide a geomorphological interpretation of this changes.

2 Study Area

The majority of Bangladesh is a delta formed by three major rivers—the Ganges, the Brahmaputra and Meghna—as they transport huge masses of water and sediment into the territory of the country each year from the Himalayan ranges. A delta lowers slowly as compaction of sediments occurs, but more sediment is deposited every year. Rapidly flowing water can still erode river banks. However, when the flow of water slows down and expands across river banks, it releases the sediments, particularly along the banks of rivers and channels, building up natural levees and balancing for sediment compaction (Hanlon, 2020).

There is a substantial difference between the upper (northern) and lower (southern) parts of the delta. During the rainy season, sediment deposited by rivers forms river floodplains in the upper part of the delta. In the lower part, however, the opposite is the case, as sediment is carried out to the sea by rapidly flowing rivers during the rainy season, but then transferred back to the land by the tides during the dry season. Silt is deposited on the land when the water slows. The water then rushes out with increasing speed as the tide falls (Hanlon, 2020).

This study was conducted in polders 24–25 of the Lower Bengal Delta in Bangladesh's Khulna division situated in the country's southwest coastal zone. There has been a significant change in the landscape of the area during the last around sixty years as a result of polderization, implementation of other water management projects, and natural forcing. The area, being located in a fluvio-marine environment, has a physical setup that is continuously changing and the changes influences the social-ecological setting of the area.

Polder 24 lies within Keshabpur upazila of Jashore district and polder 25 comprises portions of Dumuria and Phultala upazilas of Khulna district. The Hari River forms the border between these two polders and many of its tributaries run through the polders. Changes in the courses of these rivers have contributed to changes in the physico-social environment of the polders.

Geographically, the area is located in a floodplain region in the southern part of the Bengal Basin and lies at 22°47′45″N to 22°57′45″N latitude and 89°13′45″E to 89°31′30″E longitude. The two polders cover a 10.19 km length of the Hari River which lies at 22°49′45″N to 22°55′15″N latitude and 89°20′35″E to 89°21′35″E longitude. Figure 1 shows the study area in a location map.

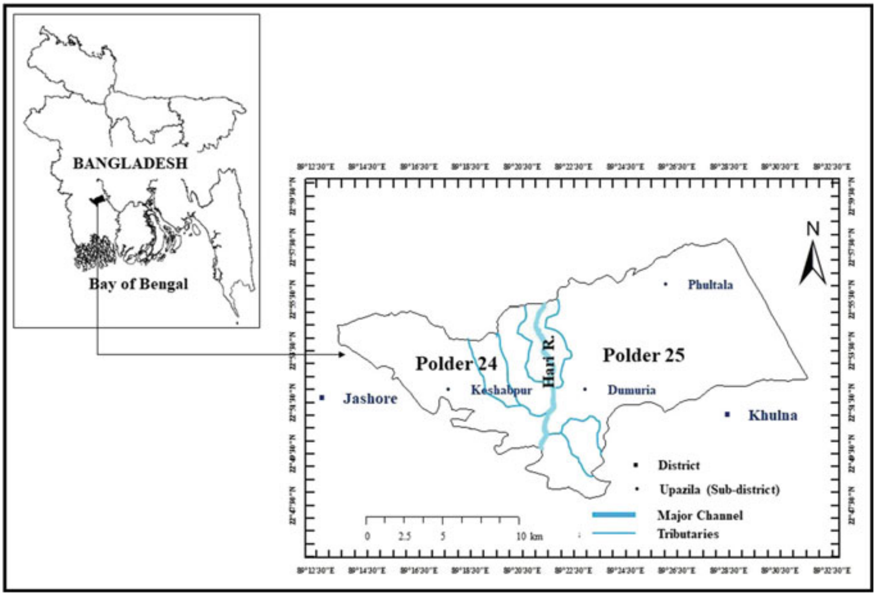

Fig. 1 Location map of the study area

Table 1 Satellite images used for this study

Sl No	Date of acquisition	Satellite ID	Sensor ID	Resolution (m)	Path	Row
1	03.05.1975	Landsat 2	MSS	80 × 80	148	44
2	21.02.1980	Landsat 3	MSS	80 × 80	148	44
3	30.01.1990	Landsat 5	TM	30 × 30	138	44
4	28.01.1995	Landsat 5	TM	30 × 30	138	44
5	26.01.2000	Landsat 5	TM	30 × 30	138	44
6	07.01.2005	Landsat 5	TM	30 × 30	138	44
7	21.01.2010	Landsat 5	TM	30 × 30	138	44
8	08.03.2015	Landsat 8	OLI/TIRS	30 × 30	138	44
9	04.02.2021	Landsat 8	OLI/TIRS	30 × 30	138	44

3 Materials and Methods

3.1 Data Acquisition

Multispectral and multitemporal satellite images were used in this research. Landsat 2 MSS (multispectral scanner system), Landsat 3 MSS, Landsat 5 TM (thematic mapper) and Landsat 8 OLI/TIRS (operational land imager/thermal infrared sensor) images were collected from United States Geological Survey (USGS) Earth Explorer. Images for 1975, 1980, 1990, 1995, 2000, 2005, 2010, 2015 and 2021 were collected. All of them were in World Geodetic System (WGS) 1984 datum and Universal Transverse Mercator (UTM) zone 45N projection. Table 1 lists the satellite images that were used in this research. Dry season images were collected to avoid cloud in order to get a better view and accuracy.

Level 1 images were collected as level 1 is a collection of all available bands with geographic reference of a particular sensor system. Each of Landsat 2 and Landsat 3 has 4 color bands along with a quality assessment band. Landsat 5 has 7 color bands along with a quality assessment band. While Landsat 8 has 11 color bands along with a quality assessment band. According to Worldwide Reference System (WRS), the study area lies in path 148 and row 44 in WRS1 system in case of Landsat 2 and 3 images, and path 138 and row 44 in WRS2 system in case of Landsat 5 and 8 images.

3.2 Data Processing

Different color bands of an image package provide different types of information. Hence, for greater accuracy, it is better to work with all the bands. Therefore, composite band images were created from each of the image packages using ArcGIS 10.7.

48 ground control points (GCPs) were collected from the field using GPS. The shape file of the study area was drawn manually in Google Earth Pro 7.3.2 and was then exported to ArcGIS platform. That shape file was used to extract the actual study area from the composite images.

3.3 Data Analysis

The sinuous lengths of Hari River and its tributaries were measured through the channel centerlines and the shortest path lengths were determined by measuring the straight-line distances between the centers of the two endpoints of particular channels. This was done for all the nine images of nine specific years to detect the change using ArcGIS. The following equation was used for calculation:

$$Sinuosity = \frac{Actualchannelpathlength}{Shortestpathlength}$$

Channel width was measured at seven different spots of Hari River using Google Earth platform. The tributaries are too narrow to measure their width using the collected images. Images before 2000 were not so good of quality to be used for measuring the width of a very narrow channel like the Hari River. Hence, channel width change detection was done only for a period of 21 years from 2000 to 2021. Three images were used for this purpose—those of the two terminal years and of 2010.

For detecting bankline migration, a spatiotemporal superimposition was done using ArcGIS 10.7. Channel migration map was produced only for Hari River and not for the tributaries due to their high narrowness.

Figure 2 shows the Hari River and its tributaries in a Landsat 8 composite band image of 2021. Here, a false color band combination of 7-4-2 was used which is shortwave infrared-2 (SWIR 2), red and blue bands in Landsat 8.

4 Results

To accomplish the research aims, sinuosity indexing, channel width measuring, and channel migration mapping were performed. These three features are unique, but they are interconnected. The erosion-accretion of river banks is associated with sinuosity. Erosion in one bank leads to deposition in the opposite one. When this happens, the river bends in a sinuous curve at that spot. The width of the river changes as well when erosion-accretion proceeds. As a response to the changing sinuosity and channel width, the bankline then migrates from its original location.

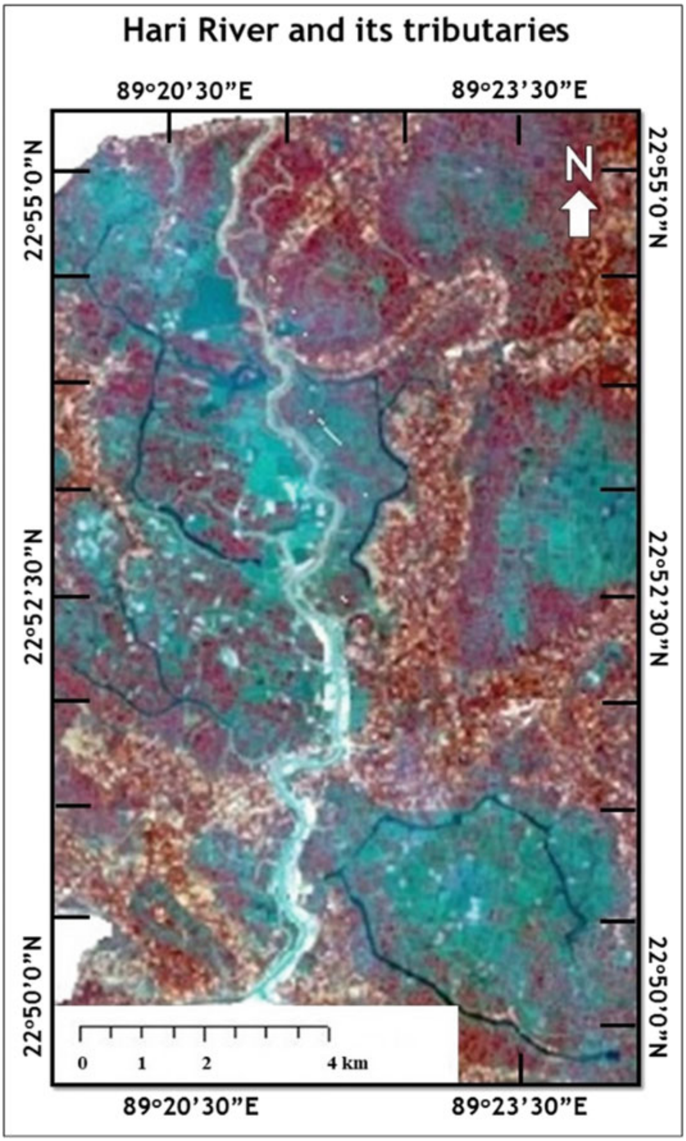

Fig. 2 Hari River and its tributaries

4.1 Sinuosity

The Hari River and all of its six tributaries studied in this research follow sinuous paths. Their sinuosity ratios have been continually changing. It is necessary to record past sinuosity ratios of these channels in order to predict future changes. Table 2 shows sinuosity of Hari River and the tributaries for nine different years.

Sinuosity of Hari River increased gradually from 1975 to 2021. Its sinuosity ratio was 1.191 in 1975 and it reached 1.262 in 2021. Figure 3 shows the changing trend of sinuosity of Hari River and its tributaries. From the figure it is understandable that in terms of increasing trend, there were two phases of change. The pace of increase was substantially slower from 1975 to 2000, then slightly greater from 2000 to 2021.

Table 2 Sinuosity index for Hari River and its tributaries

	1975	1980	1990	1995	2000	2005	2010	2015	2021
Hari River	1.191	1.193	1.198	1.198	1.200	1.215	1.229	1.254	1.262
Tributary 1, Polder 24	1.260	1.264	1.274	1.280	1.285	1.293	1.295	1.301	1.316
Tributary 2, Polder 24	1.424	1.429	1.435	1.467	1.469	1.454	1.466	1.480	1.495
Tributary 3, Polder 24	1.219	1.219	1.222	1.227	1.233	1.236	1.247	1.250	1.274
Tributary 1, Polder 25	1.461	1.465	1.488	1.501	1.508	1.525	1.532	1.576	1.579
Tributary 2, Polder 25	1.622	1.624	1.639	1.646	1.654	1.654	1.658	1.663	1.669
Tributary 3, Polder 25	1.255	1.255	1.264	1.267	1.279	1.286	1.296	1.296	1.302

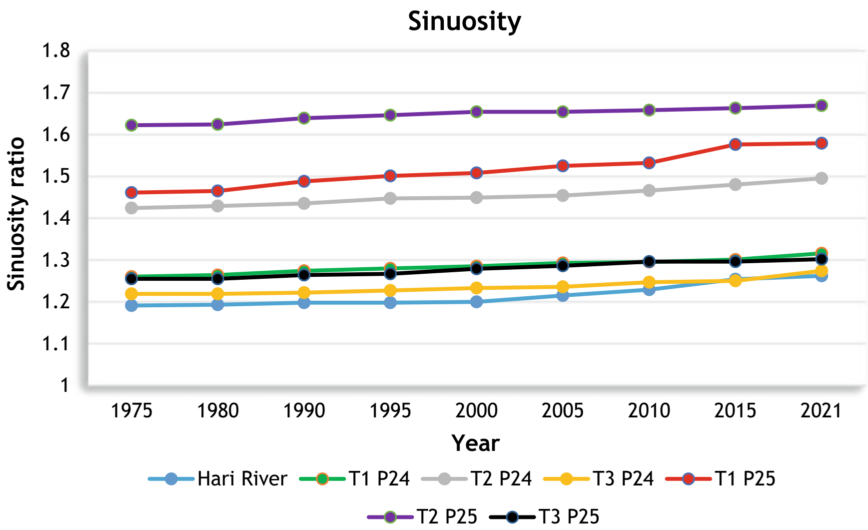

Fig. 3 The trend of change of sinuosity of Hari River and its tributaries during 1975–2021

Sinuosity of tributary 1 of Hari River that flows within polder 24 also shows an increasing trend. In 1975 it was 1.260 and in 2021 it is 1.316. The pace of increase was fairly constant throughout the 46-year study period. Tributary 2 of Hari River that flows within polder 24, also follows a similar increasing trend. However, it is more sinuous than tributary 1, with a sinuosity ratio of 1.495 in 2021. Tributary 3 of Hari River that flows within polder 24, also shows a gradual increasing trend. This one, with a sinuosity ratio of 1.274 in 2021, is less sinuous than the preceding two.

Sinuosity of tributary 1 of Hari River that flows within polder 25 also shows an increasing trend. In 1975 it was 1.461 and in 2021 it is 1.579. Figure 3 reveals that the pace of increase was consistently gradual from 1975 to 2010, and then got a small rise from 2010 to 2015 (1.532 to 1.576). Its sinuosity remained nearly constant over the last six years of the study period. Sinuosity of tributary 2 of Hari River increased in a similar pace as those ones of polder 24. It is, however, the most sinuous of the seven channels analyzed in this study, with a sinuosity ratio of 1.669 in 2021. Tributary 3 of Hari River that flows within polder 25, shows a gradual increasing trend of sinuosity. It is the least sinuous tributary among the three that flows within polder 25.

4.2 Channel Width of Hari River

Channel width of Hari River was measured for 2000, 2010 and 2021. The width was estimated at the river's beginning and end points within the polders, as well as five other selected sinuous spots within those two points. Then the average width was measured for each year. Table 3 shows the channel width of Hari River at selected spots for 2000, 2010 and 2021.

The channel is narrowest at its beginning point within the polders, and widest at its end point. The sinuous spots were chosen starting from the upper to the lower reaches. Interestingly, the lower reaches are wider than the upper ones as shown in Table 3.

Table 3 Channel width of Hari River

	2000 (meter)	2010 (meter)	2021 (meter)
Beginning point	23.19	34.22	31.51
Sinuous spot A	24.37	36.40	33.15
Sinuous spot B	23.86	34.27	32.08
Sinuous spot C	27.32	46.74	34.61
Sinuous spot D	67.07	68.53	46.58
Sinuous spot E	61.64	65.39	45.65
End point	70.65	72.71	61.56
Average width	42.59	51.18	40.73

Channel width increased from 23.19 m in 2000 to 34.22 m in 2010 at the beginning point. The width then began to shrink, reaching 31.51 m in 2021. Although it is not substantially lower than that of 2010, it is about eight meters higher than that of 2000. So, the beginning point of the channel within the polders was widest in 2010 and narrowest in 2000.

The upper reaches of the river were narrowest in 2000. The lower reaches were narrowest in 2021. However, compared to 2000 and 2021, the entire channel was wider in 2010.

Channel width increased from 70.65 m in 2000 to 72.71 m in 2010 at the end point. It is just a two-meter increase. However, during 2010 to 2021, width shrank significantly, reaching only 61.56 m, the lowest of the last 21 years.

As shown in Table 3, the average width of Hari River was highest in 2010 and it is reduced to only 40.73 m in 2021. This reveals how narrow the river is.

4.3 Channel Migration of Hari River

A spatiotemporal superimposition of the channel was done using images of 1975, 2000 and 2021 to detect the channel migration of Hari River. Figure 4 shows the superimposed channels.

It is revealed from Fig. 4 that the river has slightly migrated towards the east during this 46-year study period. However, a sinuous stretch of the channel's lower reaches has shifted slightly to the northwest direction. And the lowest reach has slightly shifted to the west.

Hari River is a very narrow channel and the shifting of the channel is not of a high extent. It might seem to be difficult to understand the shifting from Fig. 4. For this reason, another superimposition was done for the same years showing the channel as an arc, dividing the channel into three segments as shown in Fig. 5.

Figure 5 shows the three segments of the channel—A, B, and C. Most sinuous patches are in segment A, less than that in segment B, and segment C contains the lowest number of sinuous patches. Figures 6, 7 and 8 shows the course shifting of the three segments during the study period.

5 Discussion on the Findings

The Hari River and all of its six tributaries studied in this research exhibit increasing sinuosity tendencies. Their sinuosity ratios were never found to be decreasing over the course of the 46-year study period.

This study reveals that all the six tributaries that flow within polders 24–25 are more sinuous than the major channel. With a sinuosity ratio of 1.669 in 2021, the second tributary within polder 25 is the most sinuous river in the entire study area. Among the six tributaries, the third tributary within polder 24 is the one with the

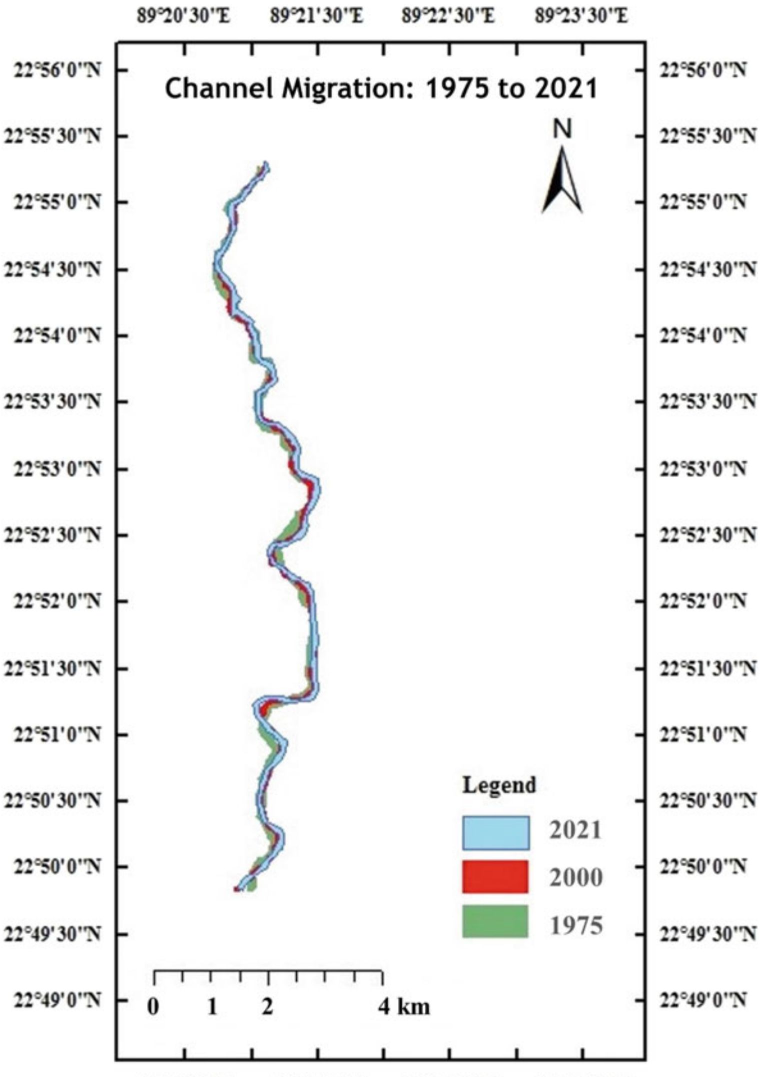

Fig. 4 Channel migration map of Hari River from 1975 to 2021

lowest sinuosity ratio that is 1.274 in 2021. Yet it is more sinuous than the major channel—Hari River (1.262 in 2021).

This unique condition hints that some geomorphological forces might be more active within each of the polders, forcing the tributaries to become more sinuous than the major channel. However, in the borderline area between the two polders, those forces might not be quite as active in forcing the Hari River, which forms the border between the two polders, to become as sinuous as its tributaries. In addition, some

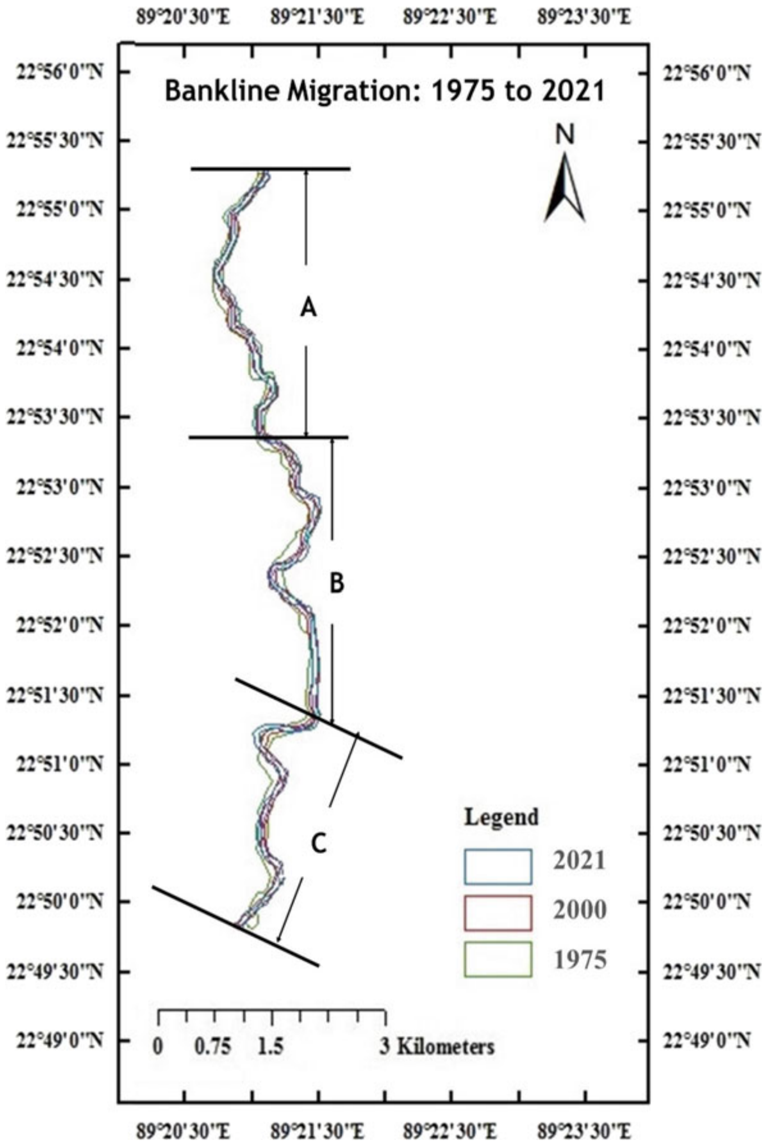

Fig. 5 Superimposed bank lines of Hari River segmented

geomorphological forces might be a little more active in polder 25 than in polder 24, because two of the tributaries that flow within polder 25 are the most sinuous of the seven channels analyzed.

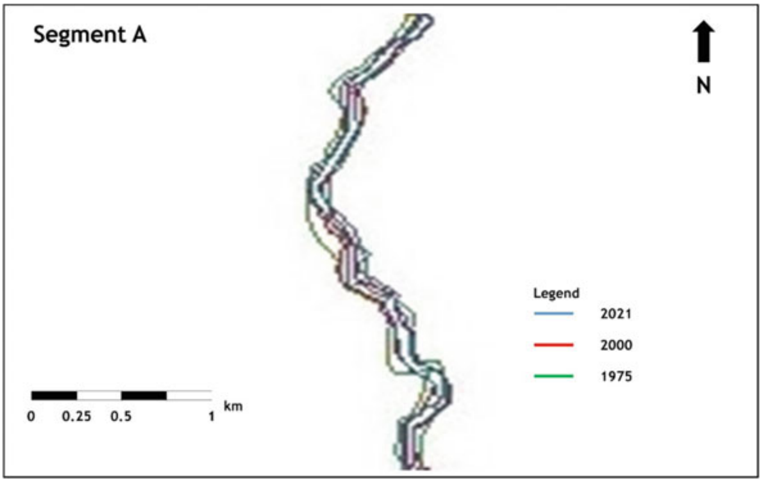

Fig. 6 Course shifting of Hari River in segment A

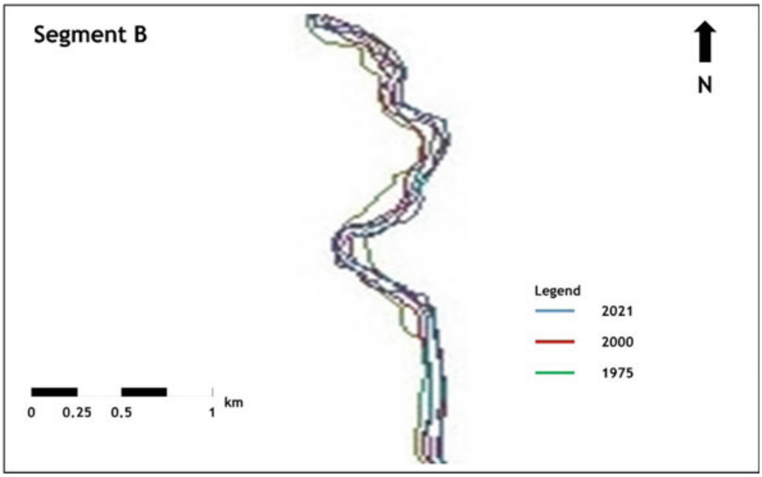

Fig. 7 Course shifting of Hari River in segment B

5.1 Classification of the Channels on the Basis of Sinuosity

To categorize channels, many scholars have penned different sinuosity ranges. For example, less than 1.3 is sinuous and greater than 1.3 is meandering, according to Mueller (1968). Schumm (1963) used further terms—straight, transitional, regular, irregular and tortuous, to improve upon the already recognized categories of straight, sinuous and meandering channels. Morisawa (1985) used another term "anastomosing" to define those channels with sinuosity greater than 2.0.

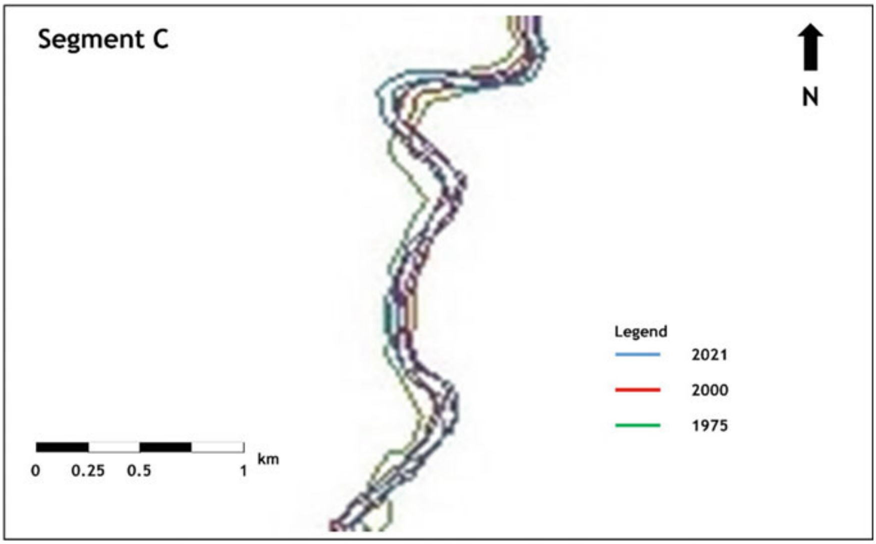

Fig. 8 Course shifting of Hari River in segment C

For this study, the classification of Leopold et al. (1964) is followed. That classification on the basis of sinuosity ratio, SR, is as follows (Leopold et al., 1964):

- SR < 1.1: straight;
- 1.1 ≤ SR ≤ 1.5: sinuous; and
- SR > 1.5: meandering.

Based on Leopold's classification, Hari River is simply a sinuous river, not meandering, as it currently has a sinuosity ratio of 1.262 (was 1.191 in 1975).

The three tributaries of Hari River that flow within polder 24 also show similar behavior. They are all sinuous channels, with sinuosity ratios of 1.316, 1.495, and 1.274, respectively.

One of the tributaries that flow within polder 25 had a sinuosity ratio of 1.461 in 1975. It was 1.488 in 1990. The channel was simply a sinuous one up until that point, as per Leopold's classification. However, its sinuosity rose to 1.501 in 1995, indicating that the channel had begun to meander. At present, its SR is 1.579 and the channel is a meandering one. Another tributary that flows within polder 25 has been found to be meandering since the early years of the study period, with a sinuosity ratio of 1.622 in 1975. It is 1.669 at present.

A third tributary of Hari River that is flowing within polder 25 is simply a sinuous channel as per Leopold's classification, having a sinuosity ratio of 1.302 at present.

5.2 *Factors Associated with Sinuosity of Hari River*

Channel sinuosity is influenced by soil lithology, regional geomorphology, slope features, riparian vegetation, water flow velocity, sediment discharge rate, erosion-accretion rates, and a variety of other factors. In turn, sinuosity may also influence these features. The current study is largely computer-based, aided by additional multiple field visits. It did not go for any ground-level investigation. Therefore, some of the aforementioned factors are addressed combining visual observation and existing literature on sinuosity of other small river channels.

5.2.1 Soil Lithology

The Hari River is less sinuous than its tributaries, but it does have more sinuous patches in the upper and upper-middle reaches. Soil lithology of a particular region has a large influence on sinuosity of channels of that region. Sinuosity varies with response to channel geology and riparian soil lithology. It increases when channel gradient decrease (Rosgen, 1994). Sinuosity also increases if there is more silt–clay content in the banks (Schumm, 1963). Therefore, this indicates that the upper and upper-middle reaches of Hari River have higher silt–clay contents as there are more sinuous patches in those reaches than the lower ones. Using Google Earth platform, presence of a substantial volume of alluvium was observed in the upper and upper-middle reaches of the river. Alluvial rivers, according to Schumm et al. (2000), are hardly influenced by bedrock and they run through sediments that have been eroded or deposited many times before. Therefore, relating the findings of Schumm and Rosgen to the present study, it can be argued that the presence of a large volume of alluvium highly influenced the sinuosity of Hari River, whereas the underlying lithology hardly had any influence.

5.2.2 Regional Geomorphology

Sinuous patches are more common in floodplains, where rivers may be forced to follow highly sinuous courses (Aswathy et al., 2008). This comment is justified for present research as the study area is situated in a floodplain region of the lower Bengal Basin. Hari River has several sinuous patches in its 10.19 km length within the polders, as mentioned earlier. Floodplains possibly forced the river to follow such course.

5.2.3 Slopes

Rivers often flow straight where there are more slopes. When slope increases, river velocity increases as well, and water quickly reaches the lower region. There are more sinuous patches on gentle slopes, areas where the slopes have less angular dimension. Rivers situated in such places tend to erode the banks and continuously travel in opposite directions across the land areas (Aswathy et al., 2008). Therefore, it can be argued for present study that there are less and gentle slopes in the upper and upper-middle reaches of Hari River where there are more sinuous patches.

5.2.4 Riparian Vegetation

Riparian vegetation stabilizes the unstable sinuous reaches by trapping sediments in their root system. More sinuous reaches are found in areas where there is an abundance of riparian vegetation (Aswathy et al., 2008). During field visit and on Google Earth platform, large amount of vegetation was observed in the upper reach of Hari River where more sinuous patches exist. This could have had a significant influence on the development of the sinuous patches.

6 Conclusion

Since the area comprises a good number of small rivers, Polder 24–25 in Bangladesh's southwest coastal region is an attractive site for fundamental research on small river channel dynamics. The purpose of this study was to investigate the channel dynamics of seven rivers in that poldered ecosystem over time and space. The Hari River and its six tributaries in polders 24 and 25 are typical sinuous rivers with a somewhat dynamic nature. Findings reveal that the magnitude of morphological changes in this area is not so high, although there are some as a result of altering the fluvial flow regime through polderization. Satellite images reveal that sinuosity ratios of Hari River and its six tributaries are increasing continuously in a steady pace. The Hari River is already extremely narrow, and its average width is furthermore shrinking. The tributaries are even narrower. If width continues to shrink, all the channels might be dead at some point of future. So there is a need of some planning to save these channels. In addition, the Hari River has shifted slightly eastward in recent decades. These findings from the 46-year study period reveal the behavior of the seven channels, particularly the Hari River, and could be used to predict future changes. This, in turn, will aid in the planning and implementation of river management projects, construction projects, and adoption of protective measures in the area.

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Anthropogeomorphic Understanding of the Damodar Fan Delta, India

Pradip Kr. Polley, Ujwal Deep Saha, and Arghyadip Sen

Abstract This study envisages the nature of anthropogenic encroachment within the major paleochannel systems of the Damodar River in the Fan delta region. Different perspectives of anthropogenic processes through 'EPA – excavation, planation and accumulation' processes have been applied in selecting the factors related to anthropogenic encroachments and alterations of the paleochannel systems. The Anthropogeomorphic theme of this study has been portrayed firstly, through the analysis of channel planform and topographic properties of the paleochannels demarcated through identifying the geomorphic markers and satellite image interpretation and lastly, through measuring the factors of anthropogenic alterations. The *Banka*, Gangur-Behula, Old Damodar, Kana-Ghia-Kunti, zone of overlaps between Old Damodar and the *Kana*-Ghia-Kunti system, and the *Kana* Damodar system are the seven major sub-systems studied covering the fan-deltaic region of the Damodar River. Here, local slope governed paleocourse development has registered an increasing trend of mean channel sinuosity towards the south with increasing mean chord length and decreasing meander wavelength. The direct anthropogenic processes; paleochannel fragmentation due to excavation (settlement growth), paleochannel fragmentation due to agricultural practices, paleochannel fragmentation due to installation of bridges and culverts, total fragmented channel units, percentage of agricultural and settlement occupancy around the paleochannels have registered a region-specific overview of the anthropogenic encroachment's intensity within the studied sub-systems. Moreover, the nature of anthropogenic processes was found more intense in the southern part of the fan delta due to the development of multiple urban bodies. This study portrays the nature of channel discontinuities that has a potential impact on the flood management and irrigation facilities in this region.

P. Kr. Polley
Department of Geography, University of Calcutta, Kolkata, India

U. D. Saha (✉)
Department of Geography, Vivekananda College for Women, Kolkata, India
e-mail: sahaujwal.geo@gmail.com

A. Sen
Banaras Hindu University, Benaras, India

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1 Introduction

The debate on the inclusion of the *Anthropocene* in the geological time-scale is a long-running event till date (Monastersky, 2015). However, alongside the existence of opposite thought, researchers from various fields of study have agreed that human actions (both directly and indirectly) have placed significant signals of human dominance as a geological agent on every sphere of the Earth's atmosphere. Since the very beginning of civilization, human activities have had an obvious tendency to take place near the courses of running water. Among all the fluvio-geomorphic units, floodplains, in particular, are subjected to the most prominent imprints of anthropogenic encroachment, as they provide several natural resources, such as fertile soil, food, and water and help to sustain ecosystems within it (Charlton, 2008). The Ganga–Brahmaputra Delta (GBD), was formed in the eastern part of the Indian subcontinent by the sedimentation of river Ganga, Brahmaputra, their tributaries and distributaries during the Quaternary period (Kuehl et al., 2005), is the largest Delta of the world that covers a surface area of West Bengal and Bangladesh. Apart from the contribution of these fluvial systems, several east-flowing rivers originating in the Indian cratonic segment also contribute to the development of the deltaic land (Bandyopadhyay & Bandyopadhyay, 1996; Jha & Bairagya, 2011; Kuehl et al., 2005; Rudra, 2018). The low gradient coupled with a large amount of deposition of alluvium during the Quaternary period caused avulsion of the channels within and around the part of their reach at the different periods (Rudra, 2006). Among the east-flowing tributaries, Damodar is the most important one in terms of volume of discharge and sediment. The Damodar Fan Delta (DFD), an inland delta formed due to sediment deposition of Damodar is located in the interfluvial part of lower Damodar and the Bhagirathi-Hooghly system (Bagchi, 1944) denoting the western margin of GBD that transits into the Lateritic Rarh Plain further westward (Acharyya & Shah, 2007; Mallick & Niyogi, 1972). Right at the beginning of its lower stretch near the Chachai village in East Barddhaman (Choudhury, 1990), the Damodar takes a sharp southerly bend almost at its right angle. It is regarded as the apex of the inland delta where several tracks of palaeochannels have radiated eastward following the general slope of the land towards the Bhagirathi-Hooghly River. The depositional unit of the Damodar fan-delta was formed by the sedimentation of these channels in the past, as those channels used to drain the area by carrying the flow of Damodar eastward. The highly fertile land with no particular relief restrictions, a network of rivers and climatic conditions attracted a steady growth of population as well as man-made modifications in the natural environment of the eastern part of India (Alam, 2015; Chattopadhyay & Roy Chowdhury, 2017).

The River Damodar has been subjected to an enormous amount of river training since the colonial period when the construction of earthen embankments on either side of the banks results in the beheading of the eastward distributaries from the main flow (Bhattacharyya, 2011; Rudra, 2008) and hindered the natural processes of avulsion and spill on a floodplain (Majumdar, 1941). Thus, presently the fan deltaic part is way distant from getting a fresh supply of alluvium except through the negligible amount of surface runoff and occasional high floods. The dwellers constantly adjust their livelihood to the riverine hazards and landscape produced by the palaeo-courses of the Damodar River which results in excessive modifications of the natural riparian landscape of the abandoned channels (Chandra, 2003; Lahiri-Dutt, 2003). The naturally fertile corridors of the palaeochannels with alluvium that although only get recharged after the occasional floods, have been converted into farmlands and farm ponds (Ghosh, 2016).

The palaeochannels are the natural corridors of flood diversion and suitable locations for groundwater recharge (Samadder et al., 2009). It also helps in sustaining inland riparian ecosystems and is often considered with high ecological values. Degradation of these flow arteries leads to blocking the surface sand due to concretization and growth of shrubs. Lateral blocking (bridges and culverts) and agricultural practices at certain pockets often result in flow fragmentation and disconnection. The presently ongoing nexus between the anthropogenic interventions and the abandoned fluvial trajectories on the DFD leads to the implementation of excessive anthropogenic stress on the palaeochannels resulting in an aggressive rate of degradation. Past studies conducted by Bhattacharyya (2011), and Sen et al. (2020) have mentioned phenomena related to the human-nature nexus in this area but they have failed to project the entire scenario holistically. Certain praiseworthy attempts have also been done in delineating the palaeochannels on the DFD (Ghosh, 2011; Sen et al., 2020) where intensive field verification was found lagging. Acharyya and Shah (2007) had identified the courses of the abandoned channels of the DFD but it lacks resolution. Thus, taking up these existing research gaps, this study is focused on demarcating the palaeochannels of the region relying upon the high-resolution satellite images and band algorithms with intensive field verifications conducted in 2019 and 2020. A considerable part of this study deals with identifying the factors that help to corroborate the true facets of anthropogenic interventions along with their intensity in different sub-systems developed by the paleochannels of the Damodar River on the DFD.

2 Study Area

The Damodar Fan-Delta is formed due to sedimentation envisaged by the old distributaries of Damodar during late Quaternary flood episodes (Sen, 1985; Ghosh, 2017; Rudra, 2010). Sediments eroded from the exposed quartz-rich Archean gneiss and Gondwana sandstone of Chotonagpur plateau fringe at the headwaters and middle stretch of Damodar River respectively were deposited by its old courses flowing eastward to form the fan within the Bengal basin (Bhattacharyya, 2011). The eastern margin of this Quaternary alluvial unit has been truncated by the Bhagirathi-Hooghly

River and is present with relatively newer alluvium on the top (Bandyopadhyay, 1996; Ghosh, 2017; Majumder & Shivaramakrishnan, 2014). Physiographically, this Fan-Delta is a deltaic floodplain, consisting of two parts. The Memari fan forms the eastern part while the Tarakeswar fan consists south-east and south of the fan delta (Acharyya & Shah, 2007; Mallick & Niyogi, 1972). The entire fan-delta has showcased numerous geomorphic signatures in the form of abandoned channels, palaeo levees and scars which are evidence of frequent avulsions. In this deltaic floodplain, the average slope is extremely low (less than 1°), which supports frequent channel shifting. The orientation of two fans and the history of avulsion had established the scenario of the fan-delta building process which possibly had taken place from the off-take of one of the old courses of Damodar near *Kana* up to the present off-take located 128 km southward near Garchumuk. The DFD lies over the Southeastern part of the east Bardhhaman district, the eastern and central part of Hooghly district and the northern tip of the Howrah district of West Bengal located in the eastern part of India (Fig.1). The entire area is inhabited by a fairly large amount of population, both urban and rural. The rapid growth of the population has been supplemented by a large number of people who migrated from Bangladesh after 1971 and inhabited these places (Guchhait & Dasgupta, 2012). At present, the administrative blocks covering these areas have moderately high to high population density, ranging from 600 to 1500 person per km^2, which create pressure on land for food, occupation and other natural resources (Census, 2011). These demands push the inhabitants more for exploiting the abandoned fluvial corridors of this region (Fig. 1). This region has been subjected to continuous anthropogenic changes since the later part of the last century (Bhattacharyya, 2011; Ghosh, 2012; Rudra, 2008) where settlements grew mostly on the levee to avoid flood inundation (Sen et al., 2020), excessive growth of road network, particularly in the eastern part of the fan delta (Siddique & Mukherjee, 2017).

3 Data Used and Methodology

3.1 Database

A series of satellite images of Landsat 8/OLI acquired in the post-monsoon season of 2019 have been used in delineating the spatial traces of paleochannels primarily. The excess moisture content of paleochannels was tried to utilise for delineating abandoned channels, feeble courses, old bank lines and cut-offs. The fine resolution of Sentinel 2 images captured in April 2019, Orb view 3 images of 2003 captured on different dates and Google earth (image dated 20.01.2019) have been utilized for spatial verification of demarcated palaeo courses and other geomorphic as well as land use attributes (Table 1). All the satellite images used in this study were collected free of cost from the web-based platform of USGS (http://glovis.usgs.gov).

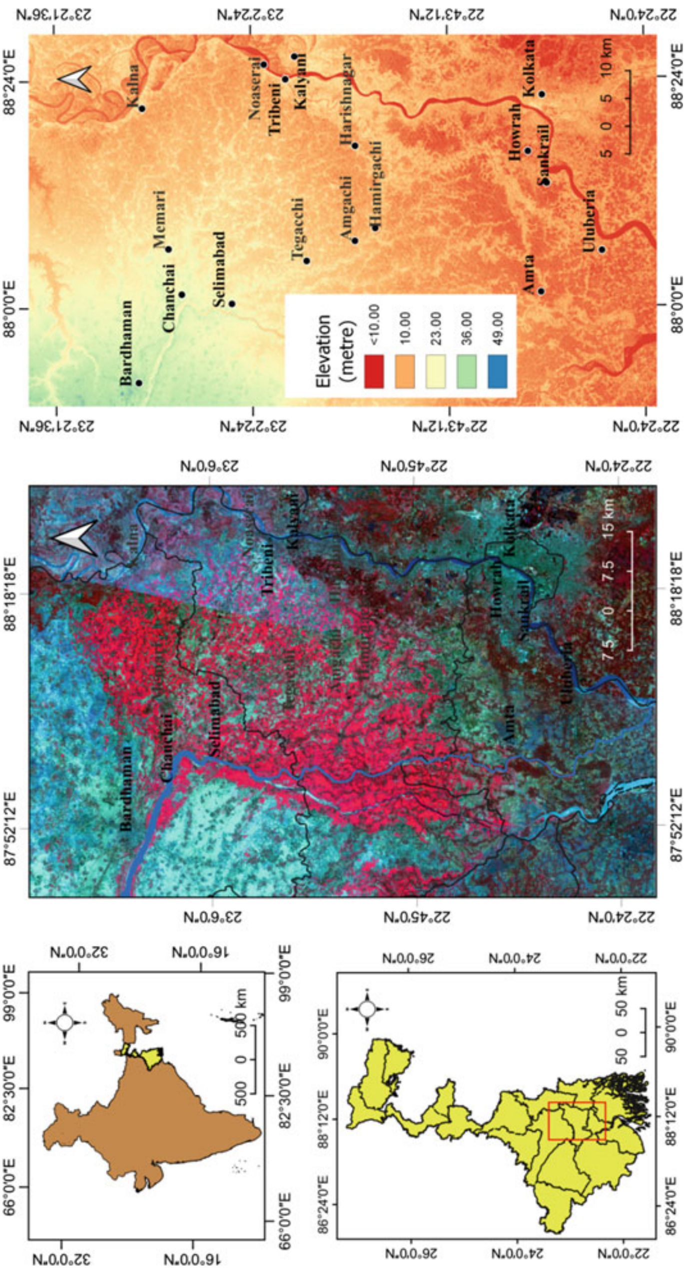

Fig. 1 Location of the study area; Damodar Fan Delta (DFD) has developed in the interfluvial part of the Damodar River and Bhagirathi-Hooghly system; the elevation (from SRTM Dem 30 m) of the DFD decreases towards Bhagirathi-Hooghly system and southwards

Table 1 Satellite dataset used in this study

Date of acquisition	Satellite	Sensor	Path/row	Resolution
30.11.2019	Landsat -8	OLI	138/044	30 m
30.11.2019	Landsat -8	OLI	138/045	30 m
30.11.2019	Landsat -8	OLI	139/044	30 m
25.04.2019	Sentinel 2	MSI	T45QXF N02.07	10
16.11.2003	Orb view 3	Orb view 3	22.86820000 88.36550000	1
05.12.2003	Orb view 3	Orb view 3	22.86850000 88.29910000	1
08.12.2003	Orb view 3	Orb view 3	22.87080000 88.03400000	1

3.2 Data Processing and Verification

Palaeo-fluvial environments are usually associated with several surface geomorphic tracers in the form of cut-offs, levees, distinct palaeo-bank lines and connected channels (Saha & Bhattacharya, 2019; Sen et al., 2020). Locations of the levee, abandoned channels and cut-offs were confirmed and traced from high-resolution satellite images of recent dates and ground survey records of palaeo-bank lines were merged to extract the valid location of the paleochannels. An extensive field survey was conducted in 2019 using Garmin Map 64SC GPS with ±1 m of vertical accuracy to locate the significant fluvio-geomorphic markers at different locations. Abandoned channels are often impounded with sediments to separate individual plots and for aquaculture practices. Location of ponds and other water bodies in a more or less continuous-linear fashion has been utilized to trace the palaeo channels too. The primary approximation of the paleochannel locations was done from the Normalised Difference Water Index (NDWI) map prepared using the Landsat 8 datasets.

$$\text{NDWI for Landsat8} = \frac{(\text{Band3} - \text{Band5})}{(\text{Band3} + \text{Band5})}$$

3.3 Channel Planform Properties

Only the demarcated paleochannels at least of any considerable length were considered to calculate its sinuosity. The ratio of channel midline length and the straight line distance was used to measure sinuosity (Friend & Sinha, 1993). The average sinuosity of the sub-systems was computed using the sinuosity values of the individual channels of the respective sub-systems. The chord length of the meander bends was computed using the ratio of actual length and straight line distance between two inflexion points (Sümeghy & Kiss, 2012). 35% of the total bends observed were used to compute the mean chord length and wavelength of each sub-system.

3.4 Extraction of Criteria

Szabó (2010) elaborates the direct process of human encroachment on natural landscape deals in three distinct processes; EPA—Excavational, Planation and Accumulation. The types of intervention depend on different activities. The defined modes of interventions were studied within the study area to understand what are the processes of human interventions within the paleofluvial corridors of the Damodar River are evident under the stated types by Szabó (2010). The selected factors have been elaborated in Table 2. The paleochannels were found fragmented into ponds usually used for aquaculture or farm ponds, fragmented at multiple sites due to agricultural practices and the development of agricultural terraces. Apart from those installations of culverts or construction of bridges have significantly blocked channel flow and width also. For diverting the floodwater of DVC and for agricultural practices during the non-monsoon period, multiple paleochannels have been converted into irrigation canals. Sen et al. (2020) has identified areas lying within 300–500 m from the banklines on either side of the paleochannels that are under intensive use of agricultural practices and levees are intensively used for the growth of settlements. A buffer of 300 m has been drawn on either side of the demarcated paleochannels to calculate % the occupation of the agricultural practices and settlement. Separately, % length of settlement patches on the levee to the total length of the measured channels has been computed as a parameter of human encroachment. The catchments of the different paleocourses of the Damodar River were demarcated using the SRTM 30 m Dem in the watershed-viewshed property of TNT Mips 2015. All these mentioned criteria of human encroachment were measured for each of the sub-systems on the DFD (Fig. 2).

4 Fluvial Sub-systems of the DFD Region

The Damodar Fan Delta unit is associated with several palaeo-systems of Damodar which were once active in the past as the major passageways of monsoonal floodwater (Sen, 1978; Bandyopadhyay, 2007a, 2007b) (Table 3). Based on the flow direction and connectivity between the palaeo channels along with considerations of DEM derived watershed boundaries, 6 individual palaeo-fluvial systems were delineated within the fan delta unit (Fig. 3).

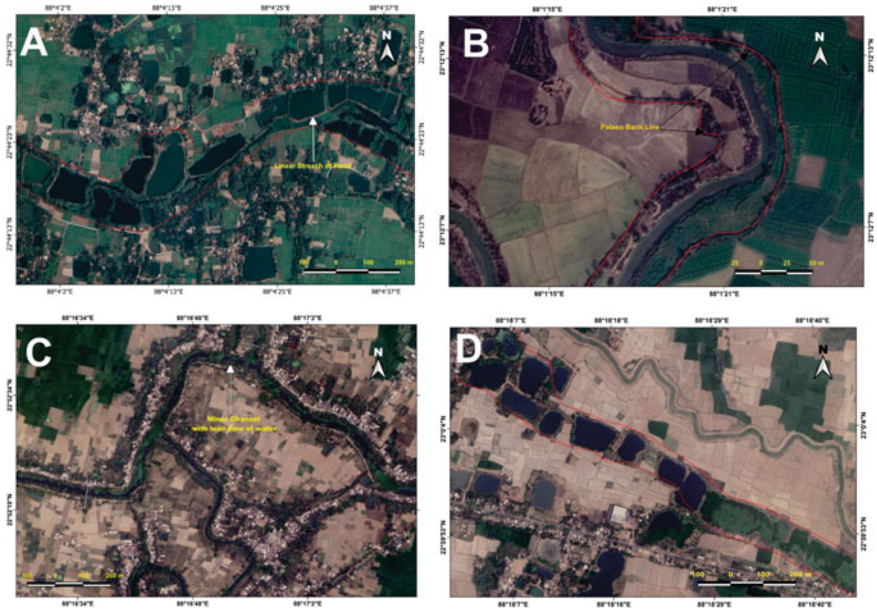

Fig. 2 Traces and techniques employed to delineate paleochannels of the DFD region; **A** paleochannel got fragmented due to aquaculture practices; **B** Later certain paleochannels were dredged to transform it into irrigation canals; **C** Segments of paleochannels covered by shrubs and hydrophytes; **D** Intensive agricultural practices around the paleochannels results in break in channel continuity

4.1 The Banka Subsystem

The Banka Damodar subsystem has developed on the upper part of the Memari fan delta (Sen, 1976). The *Banka* is presently a beheaded distributary of the lower Damodar and is also similarly depicted in the old map prepared in 18th century. It was one of the two major outlets of the Damodar in the sixteenth and seventeenth centuries. A minor branch of Banka fall into the river Bhagirathi near Nayasarai, and it was discharged into the Bhagirathi at Ambowa. These locations are presently near Kalna in the Bardhaman district of West Bengal. In the early nineteenth century, due to the construction of a flood control embankment along the left bank of the Damodar River floodwaters got restricted from entering the *Banka* and other east-flowing channels. After the construction of the Haora to Bardhaman railway track during the mid-nineteenth century, the *Banka* was thus completely disconnected from its feeder and started functioning as an independent drainage system.

Table 2 Processes of anthropogenic modifications selected for this study (modified after Szabó, 2010)

Anthropogenic process	Selected parameters	Significance
Agrogenic	Fragmentation of the paleochannel beds due to excavation of ponds	Confines river within a narrow extent
Agrogenic	Fragmentation of the paleochannel bed due to agricultural practices	Disrupts channel linkage
Traffic	Fragmentation of the paleochannel linkage due to installation of culverts and bridge piers	Confines river within a narrow extent and flow stagnancy
Urbanogenic	% length of settlement development to the levee/channel length	Pressure on the paleochannels because of possible pollution points and over utilisation of the paleochannels
Agrogenic and urbanogenic	Total number of channel fragmentation	Intensity of channel discontinuity
Agrogenic	% of cultivated land within the buffer region on either side of the paleochannels	Pressure on the paleochannel environment due to excavations and utilisation of irrigation facilities
Urbanogenic	% of settlement within the buffer region on either side of the paleochannels	Pressure on the paleochannel environment
Water management	% length of the dredged channel segment	Modified channel segment

4.2 Gangur-Behula Subsystem

The Gangur-Behula subsystem is also developed on the Memari fan delta. The Gangur is one of the paleocourses of Damodar which originated near Panagarh in the Bardhaman district of West Bengal. Evidence from historical maps, literature and satellite images suggest that the ancient course of Damodar used to flow eastward through the course of the Gangur River and flushes out in river Hooghly near Kalna (Ghosh & Jana, 2019). The Vanden Broucke's map surveyed in 1660 (Fig. 3) shows the main channel of the Damodar flowing through the *Moja* Damodar and meeting the Rupnarayan River near the Bakshi Khal (Bhattacharyya, 2011). Around that time, a significantly prominent branch of the Damodar River used to flow eastward which is similar to the present course of the Gangur and Behula River (Sen, 1978). As picked out from the Bengali folk culture during the mid-seventeenth century a significant volume of the Damodar's discharge used to pass through this route.

Table 3 Outline of the channel shifting pattern (modified after Bhattacharyya, 2011; Ghosh & Mistry, 2012)

Duration	Time period	Major active course	Remarks
Sixteenth century	During 1550	Kana Damodar channel	Begins below Selimabad and fall into the Hooghly river near Uluberia
Seventeenth century	During 1658 to 1664	Moja Damodar	The main channel of the Damodar flowing through the Moja Damodar and met the Rupnarayan River near the Bakshi Khal
Eighteenth century	During 1776 to 1794	Banka (upper part)	Takes its rise from the Damodar river near Burdwan town, went eastwards and flushed into the Ganges near Krishanagar
		Amta channel (lower part)	The main flow was running in a southerly direction, passing through the Amta channel
Nineteenth century	During 1867 to 1871	Mundeswari River	During that time, most of the discharge passed through the Mundeswari River
Twentieth century	Present	Kana Damodar and Kanki-Mundeswari river	At present, the drainage condition of the lower Damodar basin is observed with multiple beheaded distributaries coming out of the present course, the Kanki-Mundeswari River. There are a few link canals and dredged channels known as *khals*

4.3 The Subsystem of the Old Damodar Course

South of the Gangur-Behula subsystem, the subsystem of the Old Damodar course was demarcated. As depicted in the old map of Ven-Den-Brouke (1658–1664), James Rennel (1776), Lauri and Whittl (1794) and Morse and Sidney (1848) the Old Damodar course is considered one of the main branches of the Damodar River (Fig. 4). Between the sixteenth and nineteenth centuries, the Old Damodar had played an important role in the agriculture production and prosperity of the Bardhaman

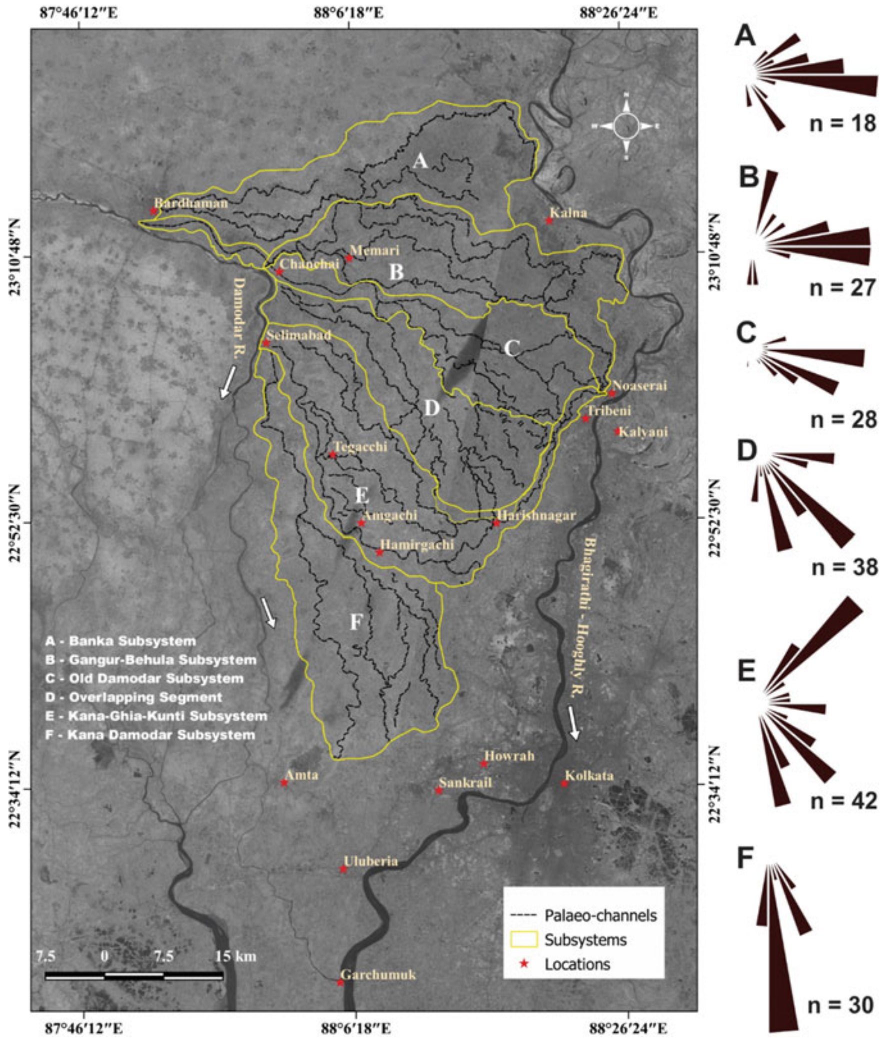

Fig. 3 Paleochannels on the DFD region; major courses of the sub-systems are only known by local names; a certain shift in the dominant channel direction is evident of a clockwise movement of the flow direction of the Damodar River in the downstream segment of the major avulsion apex

district. Morse and Sidney's map (1848) shows that during the mid nineteenth century the Old Damodar was wider than the present course. At present, the old Damodar channel is converted into a lean, abandoned spill channel.

Fig. 4 Drainage system of the DFD region during different time period (**A** Van-Den-Brouke 1658–1664; **B** James Rennel 1776; **C** Rennel, Lauri and Whittl 1794; **D** Morse and Sidney 1848)

4.4 Overlapping Segment

In between the Old Damodar subsystem and Kana-Ghia-Kunti subsystem, an intermediate zone is identified which is referred to as the zone of overlap, since no major palaeochannels are there and the only presence few minor paleochannels portray a shift in channel flow direction from eastwards to south-eastwards.

4.5 Kana-Ghia-Kunti Subsystem

Within the transitional zone of the Memari fan and Tarakeswar fan, the Ghia-Kunti subsystem has developed. The Kana and Ghia, both the channels flow from the north-west (NW) to south-east (SE) direction and join near Bainchipota on the eastern margin of the fan-delta. The unified channel flowed downstream with a new name Kunti that took an unusual bend towards the northeast following a parallel drainage lineament (Sen et al., 2020). The *Kana* and Ghia-Kunti had an arch-like path that used to flow towards SE and then diverted towards NE. Although, in the map prepared during 1767–1777 the present course of Damodar or Amta Channel was found carrying the major discharge while the Kunti River was found forming an important branch alongside. With the construction of DVC dams, the actual flow of Damodar was regulated and almost all the distributaries including Kana, Ghia and Kunti were delinked from the main course of Damodar.

4.6 Kana Damodar Subsystem

A major part of the *Kana* Damodar subsystem is developed on the lower part of the Tarakeswar fan delta. At present, the *Kana* Damodar is flowing almost parallel to the course of the present Damodar River. As depicted in the maps of De Barros (1550), the main flow of the Damodar in the sixteenth century was restricted to the *Kana* Damodar channel (Bhattacharyya, 2011). It was called the Jan Perdo River, i.e. a river for large ships. The map published by Laurie and Whittl in 1804 had shown Kana Damodar as a major distributary with no reference to Kana and Kunti, which was possibly due to a temporary shift of flow to the former channel (Table 3).

5 Topographical and Planform Characteristics of the Sub-systems

The general characteristics in terms of elevation, length of the paleochannels being measured, channel slope direction and channel morphometric properties have been inquired and measured for each of the subsystems of the Damodar Fan delta.

5.1 Banka Subsystem

The subsystem comprises Banka as its main channel that forms the northernmost part of the Damodar Fan-delta. The total measured channel length of different paleochannels in the Banka subsystem is 171.63 km, including 91.54 km of the total length of Banka. The elevation at the initial part of the course is around 30 m, which lowers to 9 m near its mouth. The general slope of the river is directed towards ENE; with its initial segment being directed towards ESE and its downstream segment having a sharp bend to the south as it leaves the Fan-delta before debouching into the Bhagirathi-Hooghly river. Banka, with a Sinuosity Index (SI) of 1.55, shows a highly meandering course. The overall paleochannel system in this sub-part is sinuous, with an average sinuosity index of 1.39. The mean chord length of the subsystem is 1.39; where the maximum and minimum chord length is 2.45 and 1.03 respectively. The Standard Deviation (SD), Coefficient of Variation (CV) and Inter-Quartile range (IQR) for chord length are 0.30, 21.70% and 0.28 respectively. The mean wavelength in the Banka subsystem is 608.97 m with the maximum and minimum wavelength being 2519.11 m and 121.72 m respectively and with the SD of 491.90; the CV of 80.78% and the IQR is 520.01 (Table 4).

5.2 Gangur-Behula Subsystem

In the south of the Banka subsystem, the Gangur-Behula subsystem exists. The two major channels of this fluvial unit are Gangur, flowing through the north and Behula, flowing through the south of the subsystem. Both of these channels have branched out from a single channel in the upstream segment. The total measured channel length of this unit is 232.41 km where Gangur itself comprises 87.14 km and Behula comprises 65.88 km of the total channel length. The general channel slope of Gangur is towards the east, while Behula flows in an ESE direction before debouching into the Bhagirathi-Hooghly River. The channel elevation is 29 m at the initial part and around 8–10 m at the mouth of both the rivers. The subsystem has a mean SI of 1.58, with the SI of Gangur being 1.68 and that of Behula being 1.57, which depicts a highly meandering nature of the palaeochannels due to the flat terrain and high variation in local slopes. The mean chord length of the Gangur-Behula subsystem is 1.30;

Table 4 Descriptive statistics of the channel morphometric properties on the DFD region

Morphometric properties		Banka (A)	Gangur-Behula (B)	Old Damodar (C)	Overlapping Segment (D)	Kana-Ghia-Kunti (E)	Kana Damodar (F)
Mean Sinuosity		1.39	1.58	1.34	1.54	1.48	1.44
Chord length	MEAN	1.39	1.30	1.19	1.21	1.16	1.17
	MAXIMUM	2.45	2.28	2.16	1.77	1.66	1.46
	MINIMUM	1.03	1.01	1.02	1.03	1.02	1.01
	SD	0.30	0.23	0.22	0.15	0.11	0.10
	CV	21.70	17.60	18.48	12.04	9.43	8.73
	IQR	0.28	0.24	0.17	0.19	0.15	0.15
Wave length	MEAN	608.97	877.97	1624.97	877.29	930	1093.61
	MAXIMUM	2519.11	3894.05	9971.99	2130.32	3719.14	3025.32
	MINIMUM	121.72	287.15	204.40	173.58	223.15	205.72
	SD	491.90	594.86	1810.04	427.92	773.77	691.58
	CV	80.78	67.75	111.39	48.78	83.20	63.24
	IQR	520.01	571.06	1347.86	550.21	886.78	785.05

with the maximum and minimum chord lengths being 2.28 and 1.01 respectively. The SD, CV and IQR for chord length are 0.23, 17.60% and 0.24 respectively. The mean wavelength of this subsystem is 877.97 m with the maximum and minimum wavelength being 3894.05 m and 287.15 m respectively, and with the SD of 594.86; the CV of 67.75% and the IQR of 571.06.

5.3 The Subsystem of Old Damodar

The paleocourse of Damodar that used to flow in the ESE direction, and its remnant cut-offs and spills form this subsystem. Currently, the principal course is devoid of any flow movement and fragmented into several water bodies. The total measured channel length of this subsystem is 163.98 km, including the measured length of the Old Damodar is 78.19 km. Near the upstream segment where the main paleocourse bifurcates, the channel elevation is around 26 m, whereas it varies between 8–11 m at different points in the east around its confluence with Behula and Kunti. Although the SI of the paleocourse of old Damodar is 1.26, the mean SI of the entire subsystem increase to 1.34 due to the high sinuous nature of the remnant paleochannels in this subsystem. The mean chord length of the old Damodar subsystem is 1.19; with a maximum chord length of 2.16 and a minimum chord length of 1.02 (Fig. 5). The SD, CV and IQR for chord length are 0.22, 18.48% and 0.17 respectively. The mean wavelength of this subsystem is 1624.97 m with the maximum and minimum wavelengths of 9971.99 m and 204.40 m respectively. The SD of wavelength is 594.86; the CV is 111.39% and the IQR is 1347.86.

5.4 Overlapping Segment

The subsystem of the overlapping segment between old Damodar and Kana-Ghia-Kunti is a zone comprising numerous remnants of the past avulsion, fragmented paleochannels and cut-offs that depict the clockwise shift of the Damodar course towards the south. These paleo-fluvial remnants are highly modified by intense human impoundment throughout the recent history and due to that, any definite course cannot be detected within this subsystem. The total measured channel length of the subsystem is 179.70 km. In the western part of the subsystem, there are two traceable unnamed palaeocourses, that traverse towards a south-east direction and further downstream it is connected with canals. In the western part of these channels, the maximum elevation is 24 m whereas in the eastern and southeastern parts the elevation varies between 7–14 m. The mean sinuosity index of the subsystem is 1.54. The mean chord length of this overlapping segment is 1.21; with a maximum chord length of 1.77 and a minimum chord length of 1.03. The SD, CV and IQR for chord length are 0.15, 12.64% and 0.19 respectively. The maximum wavelength of the subsystem is 2130.32 m and the minimum wavelength is 173.58 m with a mean

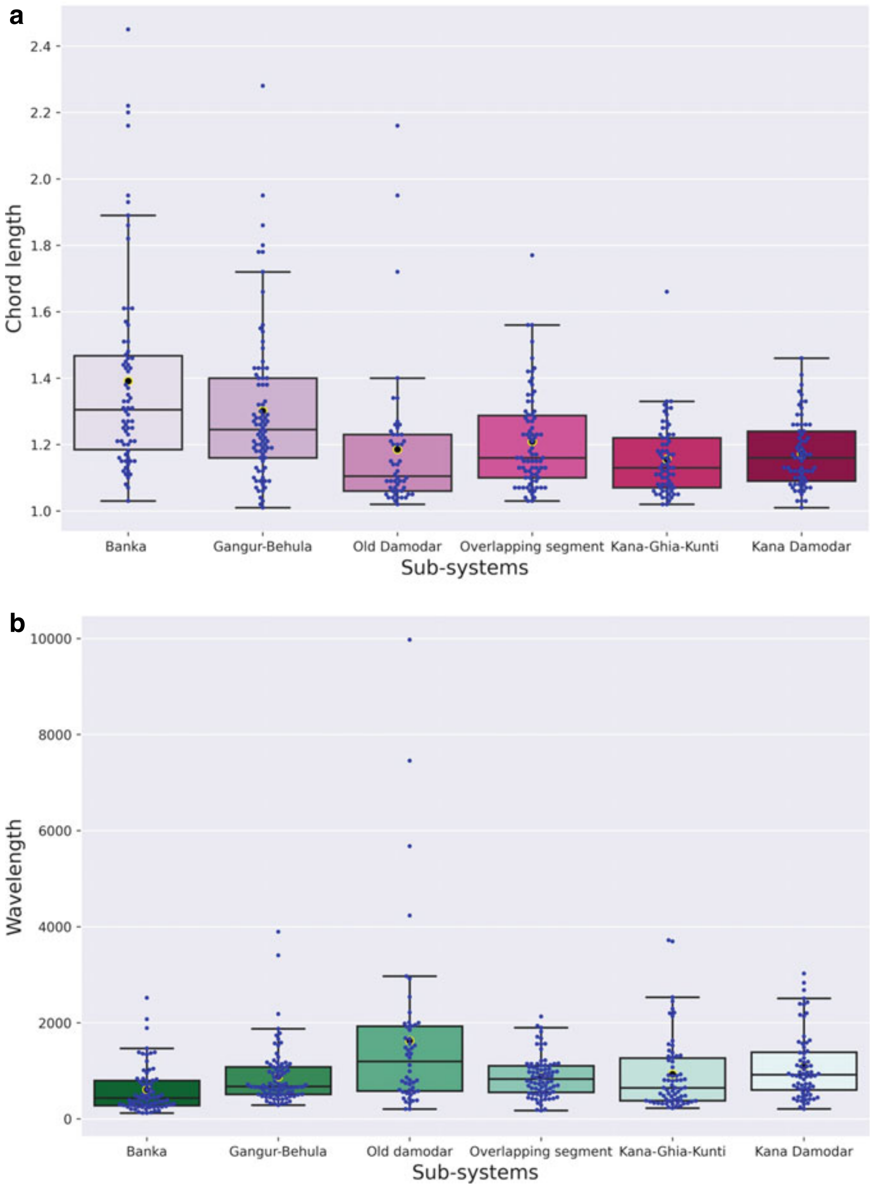

Fig. 5 Morphometric properties of channel form in different sub-systems of the Damodar River; **a** Chord length, **b** meander wavelength

of 877.29 m. The SD of wavelength is 427.92; the CV is 48.78% and the IQR is 550.21.

5.5 Kana-Ghia-Kunti Subsystem

This subsystem is composed of three major paleochannels of Damodar—Kana, Ghia and their combined flow named Kunti; and certain overlapping channels that connect these main channels. The total channel length measured in this sub-system is 263.54 km, which is the highest among the channel subsystems of the Fan-delta. The measured channel length from the origin of Kana to the confluence of Kunti and Bhagirathi-Hooghly is 91.38 km and the length of Ghia is 55.53 km. At the origin, the channel elevation of Ghia is 22 m and of Kana about 1.5 km south of Ghia, it is 23 m. The Kana and Ghia River both flow following a south-eastward slope and met each other at an elevation of 13 m near the eastern flank of the fan delta. From this conjunction, the unified flow named Kunti River takes a sharp left bend and flows in a north-east direction following the local slope. The Kana-Kunti channel displays an extremely high SI value of 2.04 while the Ghia channel registers a relatively lower sinuosity of 1.52. The mean sinuosity of this sub-system is measured 1.47. The maximum chord length of this subsystem is 1.66 and the minimum is 1.03; with a mean of 1.16. The SD, CV and IQR of chord length are 0.11, 9.43% and 0.15 respectively. The maximum wavelength of the subsystem is 3719.14 m and the minimum is 223.15 m with a mean of 930 m. The SD of wavelength is 773.77; the CV is 83.20% and the IQR is 886.78.

5.6 Kana Damodar Subsystem

The subsystem of Kana Damodar is the southernmost subsystem and also forms the southern and south-western parts of the DFD. The Kana Damodar is the only channel with a continuous course in this subsystem. The subsystem has a cumulative channel length of 197.61 km. With a measured length of 97.09 km, the Kana Damodar channel happens to be the longest channel of the Damodar Fan-delta. The main channel, along with other minor paleochannels of this subsystem, follows the general slope towards the south, showing a clear shift in the slope direction compared to other sub-systems. The channel elevation near its headward part is 21 m. At around half of its course, the Kana Damodar has bifurcated into two branches, of which the east branch is presently modified and converted in many parts. The Kana flows mainly through the left branch having a sinuosity of 1.45, which is not very skewed from the mean SI value of 1.44 for the entire subsystem. At its mouth, the channel elevation drops down to 9 m. The maximum chord length of this subsystem is 1.46 and the minimum is 1.01; with a mean of 1.17. The SD, CV and IQR of chord length are 0.10, 8.73% and 0.15 respectively. The maximum wavelength of the subsystem is 3025.32 m and the minimum is 205.72 m with a mean of 1093.61 m. The SD of wavelength is 691.58 with a CV of 63.29% and IQR of 785.05.

6 Nature of Human Encroachment

Human encroachment within the sub-systems and on the paleochannels is evident in this concerned geomorphic unit. The channel bed and levee have been mostly converted to different land use patches. Intense agricultural practice and the growth of settlements and traffic routes are the main parameters of channel conversion. Channel bed is also fragmented by the practitioners of pisciculture and the drainage is either lost or diverted through canals.

6.1 Percentage of Channel Length Fragmented into Ponds

The Kana Damodar subsystem shows the highest share of channel length being fragmented into ponds compared to the total channel length measured within the sub-system (37.52%). Relatively a moderate share of the fragmented channel is displayed by both the subsystem of Old Damodar (27.58%) and the overlapping segment (27.57%). A low share of fragmented channel length is displayed by the Kana-Ghia-Kunti subsystem (13.47%), Banka subsystem (18.28%) and the Gangur-Behula subsystem (20.03%) where all three subsystems have a consistent and definite course for the major channels.

6.2 Percentage of Channel Length Converted to Agricultural Plots

The subsystems of the middle part of the Fan-delta have been subjected to the highest rate of channel conversion due to agricultural practices. The Overlapping segment with no distinct present course shows the highest share of channel conversion to agricultural plots in terms of total channel length (44.89%), followed by the Gangur-Behula subsystem (35.20%) and the subsystem of the Old Damodar course (30.76%). A moderate share of channels converted to agricultural plots can be found in the Kana-Ghia-Kunti subsystem (27.21%). A low share of channels converted to agricultural plots is featured by the northernmost subsystem of the Banka River (16.09%) and the southernmost subsystem of the Kana Damodar (15.57%) (Table 5).

Table 5 Computations of the nature of the direct anthropogenic processes on the paleochannel environment

Parameters	*Banka* (A)	Gangur-Behula (B)	Old Damodar (C)	Overlapping Segment (D)	*Kana*-Ghia-Kunti (E)	*Kana* Damodar (F)
Total length of channel measured (km)	**171.63**	**232.41**	**163.98**	**179.70**	**263.54**	**197.61**
Fragmented into ponds (% of total measured length)	18.28	20.03	27.58	27.57	13.47	37.52
Agricultural practice (% of total measured length)	16.09	35.20	30.76	44.89	27.21	15.57
Settlement on levee (% of total measured length)	11.94	18.39	19.11	20.01	11.04	17.35
No. of bridge piers and culverts	47	87	33	21	87	67
No. of fragmented segments	546	1128	722	1327	1281	1628
% of agricultural land within the buffer	73.92	73.01	62.75	74.85	63.71	46.41
% of settlement within the buffer	22.27	24.31	32.76	23.46	31.40	48.63

6.3 Percentage of Channel/Levee Length Converted to Settlements

In the entire fan-delta, levee sections are densely inhabited, as the lower flood plains are often subjected to inundation. In the present time, due to the higher pressure of population, even the channel beds have been converted to built-up areas at places, often where the channels are fragmented. Like that of agricultural plots, the percentage of conversion of the levee by settlement development in terms of total length is highest in the Overlapping segment (20.01%). A moderate share of the converted levee in settlement can be seen in the subsystem of Old Damodar (19.11%), Gangur-Behula subsystem (18.39%) and Kana Damodar subsystem (17.35%). The lowest share of levee settlement is found in the Banka subsystem (11.94%) and the Kana-Ghia-Kunti subsystem (11.04%).

6.4 No. of Bridge Piers and Culverts

Installations of bridge piers and culverts denote the impact of transport networks on channel fragmentation. Both the Kana-Ghia-Kunti subsystem and the Gangur-Behula subsystems have accounted for 87 bridge piers and culverts each, the highest among the subsystems (Table 6). Both these subsystems have multiple continuous channels extending from the western to eastern boundaries of the fan-delta. These sub-systems have multiple urban areas that act as nodal points for several rail and road networks. The subsystems of the Kana Damodar (67) and Banka (47) have a relatively moderate number of bridge piers and culverts, as they also host many towns as transport nodes, but they only have one major channel each. The subsystems of Old Damodar (33) and the overlapping segment (21) have the least number of bridge piers and culverts, as most of the channels are converted, fragmented and present with no significant flow.

6.5 Total No. of Fragmented Segments

The Kana Damodar subsystem has the highest number of fragmented segments, 1628. Most of these fragmented segments are located on the eastern side of the subsystem and along the main channel of the Kana Damodar. The moderate class in terms of the number of channels fragments The overlapping segment, the Kana-Ghia-Kunti subsystem and the Gangur-Behula subsystem have registered comparatively a moderate share of fragmented channel segments, 1327, 1281 and 1128 respectively due to a high number of spills and discontinued channels. The subsystems of Banka and the Old Damodar have registered the lowest share of fragmented channel segments among all the sub-systems (Fig. 6).

Table 6 The intensity of the direct anthropogenic processes on the paleochannel environment

Classes	Fragmented into ponds (% of total measured length)		Agricultural practice (% of total measured length)		Settlement on levee (% of total measured length)		No. of bridge piers and culverts		No. of fragmented segments		% of agricultural land within 300 mm buffer		% of settlement within 300 mm buffer	
	Range	Subsystems	Range	Subsystems	Range	Subsystems	Range	Subsystems	Range	Subsystem	Range	Subsystems	Range	Subsystems
High	>35	Kana Damodar	>30	Overlapping Segment, Gangur-Behula, Old Damodar	>20	Overlapping Segment	>70	Gangur-Behula, Kana-Ghia-Kunti	>1500	Kana Damodar	>70	Banka, Gangur-Behula, Overlapping Segment	>35	Kana Damodar
Moderate	25–35	Old Damodar, Overlapping Segment	20–30	Kana-Ghia-Kunti	15–20	Old Damodar, Gangur-Behula, Kana Damodar	35–70	Kana Damodar, Banka	750–1500	Overlapping Segment, Kana-Ghia-Kunti, Gangur-Behula	50–70	Old Damodar, Kana-Ghia-Kunti	25–35	Old Damodar, Kana-Ghia-Kunti
Low	<25	Kana-Ghia-Kunti, Banka, Gangur-Behula	<20	Banka, Kana Damodar	<15	Banka, Kana-Ghia-Kunti	<35	Old Damodar, Overlapping Segment	<750	Banka, Old Damodar	<50	Kana Damodar	<25	Banka, Gangur-Behula, Overlapping Segment

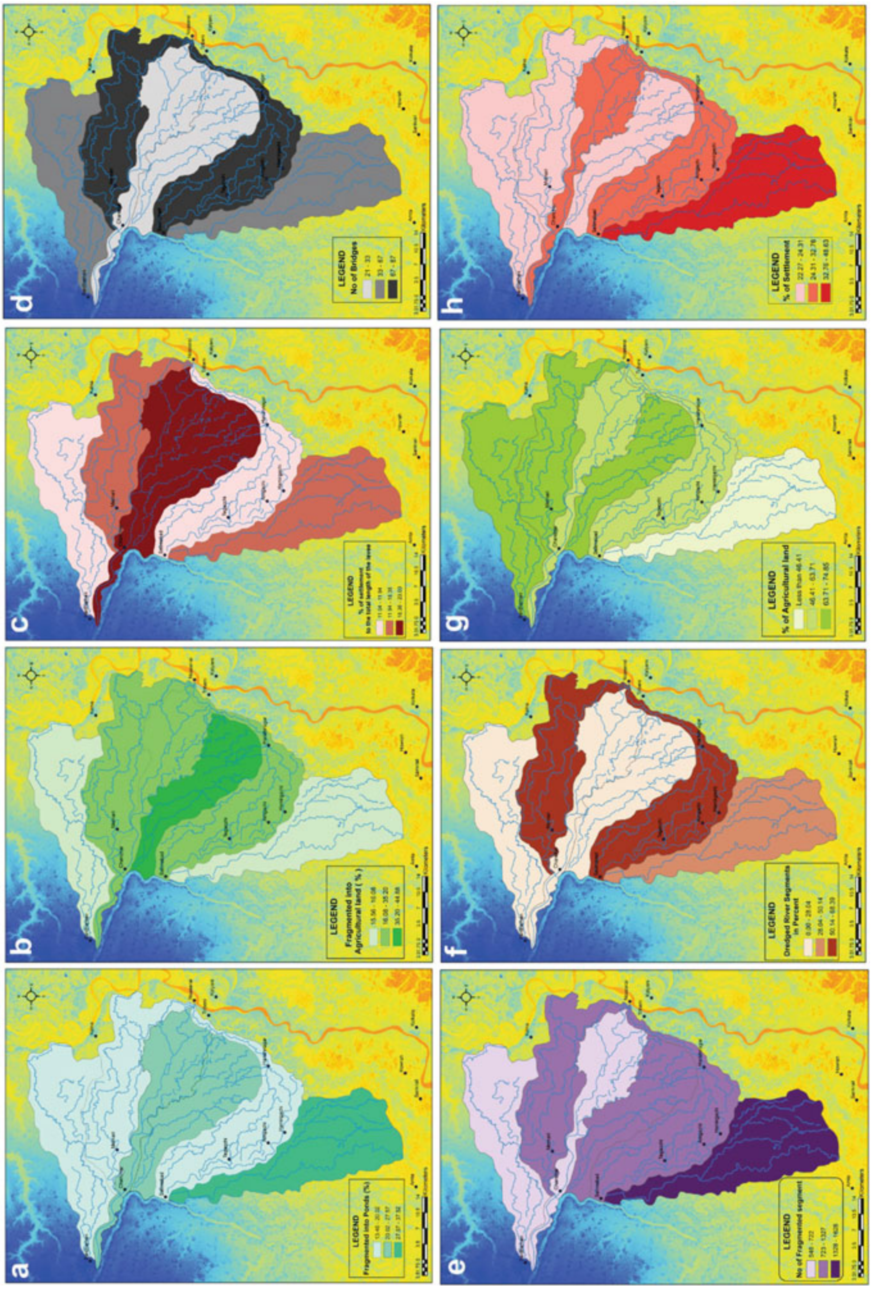

Fig. 6 Factors selected to analyse the nature of human encroachment within the paleochannel environment on the DFD; **a** Percentage of channel length fragmented into ponds; **b** Percentage of channel length converted to agricultural plots; **c** Percentage of channel/levee length converted to settlements; **d** No. of Bridge piers and culverts; **e** Total no. of fragmented segments; **f** Percentage of agricultural land within buffer; **g** Percentage of settlement within buffer

6.6 Percentage of the Dredged Segment to the Total Length Measured

Presently, many of the paleochannels are used as irrigation canals, locally known as *Khals*. The percentage of channel length converted to canals was calculated concerning the total length of the paleochannel being measured. The sub-system of Gangur-Behula River and Kana-Ghia-Kunti was found to register the highest share of channels being converted to *khals* or dredged to modify its flow capacity. Here, the canals already being mentioned by the DVC have been left apart from the calculation.

6.7 Percentage of Agricultural Land Within the Buffer

A buffer of 300 m was delineated on either side of the demarcated paleochannels to determine the pattern of agricultural activity that has the potential for alteration of the fluvialscape. Most of the fragmented channels in the subsystem of the overlapping segment are scattered within the vast agricultural fields, with 74.85% of buffer area occupied by agricultural practice followed by the *Banka* subsystem and Gangur-Behula subsystem with 73.92% and 73.01% of buffer area occupied by agricultural land use respectively. Relatively moderate shares of agricultural land use are found in the subsystems of the *Kana*-Ghia-Kunti (63.71%) and the Old Damodar paleocourse (62.75%) within the buffer area. The lowest share of agricultural land use within the buffer is found in the *Kana* Damodar subsystem, which is relatively densely occupied with settlements and shows only 46.41% of agricultural practice in total buffer area land use.

6.8 Percentage of Settlement within the Buffer

In terms of the percentage of area occupied by settlements and the built-up area within the 300 m buffer, the scenario is exactly opposite to that of the area occupied by agricultural practice. Since most of the settlement is developed on the paleochannel's levee, they notably fall within the buffer area. The general trend of an increasing number of settlements from north to south of the DFD is reflected in the percentage of settlement area within the buffer as well. The subsystem of Kana Damodar shows the highest buffer area shared by settlement growth, which is 48.63%, resulting in making this only subsystem to have more area covered by settlements than agricultural practice within the buffer. The subsystems of Old Damodar (32.76%) and the *Kana*-Ghia-Kunti (31.4%) show a relatively moderate share of buffer area under the settlement. The subsystems of the Overlapping segment, Gangur-Behula and Banka where most of the buffer area is occupied with agricultural practice, have only 23. 46%, 22.31% and 22.27% of buffer area respectively, under settlement cover.

7 Overview of Direct Anthropogenic Impact on Channel Confinement

Due to the intense human encroachment throughout the history, coupled with flow reduction caused by the change in the general slope direction from east to south and 0the construction of embankments on the left bank of the Damodar, the source from where the paleochannels of the Damodar fan-delta have been bifurcated, the existing channel width has significantly reduced from that of its previous period. Almost all channels, spread into different subsystems, show a relatively narrower channel width containing the active flow, often modified to canals, within a relatively wider extent of paleochannels, demarcated by its levee and old bankline.

The average ratio of Old floodplain width to existing channel width is 4.2. The older floodplain width of the *Banka* River varies from 60 m at the narrowest to 230 m at the widest, the existing channel width ranges between 30 to 90 m. In most of the parts, the existing course forms a misfit channel inside the older floodplain, which is often modified and restricted by channelization and flow redirection.

South to the *Banka* subsystem, Gangur has a floodplain width to the existing channel width ratio of 3.81. Whereas, in the case of Behula, the average ratio is 8.26, because of the greater disparity of floodplain width (70–400 m) and existing channel (15–40 m) in the Behula than in the Gangur channel. Gangur's floodplain width ranges from 30 to 135 m with existing channel width varying from 8 m at its narrowest to around 46 m at its widest. The present course of both Gangur and Behula resemble a misfit channel within the floodplain, often being confined by human activities such as channelization, agricultural practices and construction works on either side of the banks.

In the subsystem of *Kana*-Ghia-Kunti, due to intense human encroachment, flow redirection, and channel bed fragmentation have reduced the width of the existing channel of Ghia to around 3 m, particularly at its headwaters, with at its widest existing channel width it scales up to 20 m. The floodplain width of Ghia varies from 20 to 80 m, with an average floodplain width to the existing channel width ratio of 4.08. The present course of Ghia forms a misfit channel almost its entire length. In several places, both *Kana* and Kunti's courses are confined due to intense human impoundment. Around the off-take of their courses, they form a misfit channel. The *Kana* has an average floodplain width to existing channel width ratio of 3.14, with floodplain width varying from 35 to 115 m and existing channel width varying from 20 to 45 m. The Kunti channel, on the other hand, has the least variation in terms of floodplain width to existing channel width disparity, as the floodplain width of Kunti ranges from 45 to 65 m and the channel ranges from 20 to 25 m. The average ratio of floodplain width to channel width for Kunti is 2.56.

The *Kana* Damodar, the longest paleochannel and the only major southward flowing paleochannel of the DFD depict an average floodplain width to the existing channel width ratio of 3.61. From the beginning to the end of its course, the floodplain width of the *Kana* Damodar ranges from 38 to 270 m; whereas, the existing channel length ranges from 18 to 170 m. Within most of its course, the *Kana* Damodar forms a misfit channel within the floodplain, with an intense occurrence of channel confinement due to human impoundment at multiple areas on either side of the bank (Table 7).

8 Discussion

After the abandonment of any river course, it is bound to get restricted into a narrow zone due to a lack of inflow and a higher rate of sedimentation. Within a fertile land of dense population cover, excessive and uncontrolled interventions through direct and indirect anthropogenic interventions govern this rate of decay rigorously. The DFD region is well known for its substantial flood history within and around the catchment area of the DVC. Apart from that, it is also well known for its production of Rabi crops. Clogging the paleochannels and disruptions in paleochannel connectivity could result in neither an efficient flood management programme nor being capable of providing good irrigation facilities.

The paleochannels are often regarded as conduits of groundwater recharge since it carries sand lenses beneath the channel surface. Restrictions in channel width, over-exploitation of the rivers and different forms of pollution may lead to the growth of shrubs and an impervious layer of clay on the surface of the paleochannels. Since the sand bodies lying beneath the paleochannel surface pose higher hydraulic conductivity (Samadder et al., 2009) discontinuation of the paleochannels and growth of shrubs restricts its ability to percolate rainfall. Sen et al. (2020) has also found similar condition in a certain part of the DFD. Apart from the general understanding of the problems found, the parameter specific nature of anthropogenic interventions is also significant to understand. With an increasing number of urban localities, encroachment within the paleochannels and anthropogenic pressure along the paleochannels has increased significantly. The agricultural intensity, within or around the paleochannels significantly dropped southward while the occupation of the paleochannels or its levee nearby started getting intensely populated southward. Significantly, with greater intensity of urbanisation, installation of culverts, rail and road bridges increased within the sub-systems lying on the southern part of the DFD; Kana-Ghia-Kunti and the Kana Damodar channels. Discontinuation of the paleochannels was found highest on the southernmost part of the DFD too. Since no major courses were found within the overlapping segment, the total number of channel fragments was naturally high. The increasing rate of population growth, development of the connectivity networks and local utilisation of the paleochannels through modifications of the channel landscape have been intensively restricting and transforming the paleochannels into relict features. It is therefore not only increasing the cost of annual dredging of the *khals* but also chocking the floodwater spills and recharge

Table 7 Nature of channel confinement on the DFD region

Name of the palaeo-channel	Nearest location	Old flood plain width (m) (Wf)	Existing channel width (m) (Wc)	Ratio (Wf: Wc)	Average ratio	Remarks
Banka	Kalyanpur	164.60	43.52	3.78	4.20	Misfit channel
	Hiragachi	–	35.34	–		Confined due to human impoundment
	Palsit Station	94.29	42.29	2.22		Misfit channel
	Sekhpur	122.74	33.58	3.65		Misfit channel
	Grabupur	66.01	44.34	1.48		Misfit channel
	Lakshmipara	88.56	68.67	1.28		Misfit channel
	Nagargach and Malatipur	86.93	229.14	0.37		Misfit channel
Behula	Keja	222.51	37.74	5.89	8.26	Misfit channel
	Khyerpur and Nandiara	102.99	15.74	6.54		Misfit channel
	Arbelia	–	34.67	–		Confined due to human impoundment
	Banshi and Chaksimla	73.731	–	–		Decayed channel
	Char Noapara	494.23	40.05	12.34		Misfit channel
Gangur	Bharpota	–	28.20	–	3.81	Confined due to human impoundment
	Baharpur	91.22	30.74	2.96		Misfit channel
	Chaupira and Ichhabacha	33.75	8.74	3.85		Misfit channel
	Napara	110.25	37.00	2.97		Misfit channel
	Gaipara	73.221	19.19	3.81		Misfit channel
	Dhakchhara	57.184	9.42	6.07		Misfit channel
	Simualia	55.31	17.09	3.23		Misfit channel
Kana	Harirampur	135.79	46.63	2.91	3.14	Misfit channel
	Abdulpur	–	35.95	–		Confined due to human impoundment
	Chandpur and Bharamahapur	91.203	24.17	3.77		Misfit channel
	Daluigacha Gopalnagar	114.04	41.65	2.73		Misfit channel

(continued)

Table 7 (continued)

Name of the palaeo-channel	Nearest location	Old flood plain width (m) (Wf)	Existing channel width (m) (Wc)	Ratio (Wf: Wc)	Average ratio	Remarks
Ghia	Faimpur	21.88	4.42	4.95	4.08	Misfit channel
	Muidipur	49.83	14.49	3.43		Misfit channel
	Dakshin Babnan	78.14	20.20	3.86		Misfit channel
Kunti	Kamdebpur	45.44	20.39	2.22	2.56	Misfit channel
	Ampala	54.15	19.87	2.72		Misfit channel
	Bahirnagar	66.48	24.15	2.75		Misfit channel
Kana Damodar	Jotkrishtai	–	43.45	–	3.61	Confined due to human impoundment
	Paharpur	39.95	19.14	2.08		Misfit channel
	Shukpur	154.11	41.27	3.73		Misfit channel
	Antpara	145.46	39.41	3.69		Misfit channel
	Sahabazar	–	110.22	–		Confined due to human impoundment
	Mora Gopinathpur	–	167.68	–		Confined due to human impoundment
	Ichhabati	276.93	65.75	4.21		Misfit channel
	Nalada	171.16	39.23	4.36		Misfit channel

locations of groundwater. The lack of connectivity in the paleochannels occurred mainly due to the intensive mode of cultivation in the DFD region. Here the decayed part of the paleochannels are either converted into agricultural practices or made fragmented into ponds. Here, at multiple locations development of settlement has helped in decaying the paleochannel system where the connectivity got lost permanently and those certain locations often face waterlogging scenarios during heavy monsoon rainfall (Fig. 7).

9 Conclusion

The present study has significantly portrayed the nature and intensity of the anthropogenic encroachment within the paleochannel environment in the DFD region. The increase in the intensity of direct human interventions has popped up the uncertainty

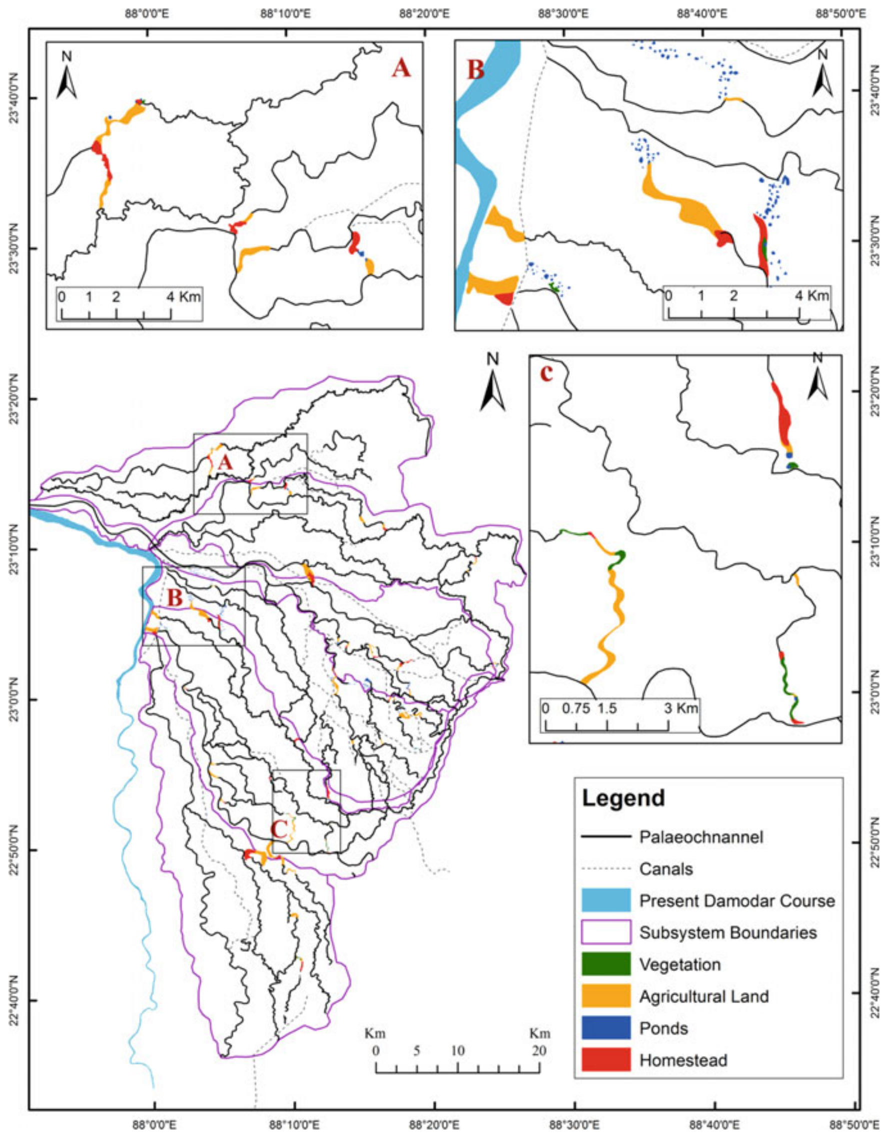

Fig. 7 Overview of direct anthropogenic processes within the paleochannel environment of the DFD region

of the flood management programme and efficient supply of irrigation water. The major findings of the study can be outlined as follows

a. The nature of human interventions varies significantly over the DFD region. In the northern part due to the development of intensive agricultural practices and in the southern part due to the growth of urban localities, the mode of intervention varies significantly.

b. Significant growth of major settlements has made the paleochannels fragmented into certain frequencies that it has significantly controlled the disconnectedness scenario of the paleochannels mainly on the southern part of the DFD.
c. The paleochannels of the Damodar River have left behind prominent markers of its past significance but the intensive mode of human interventions possibly could burry the surface signatures drastically. It would lead to problems for irrigation facilities, increase the cost of annual dredging of the paleochannel and an inefficient flood management programme.

This study leads to elaborations of the nature of human interventions on a natural environment and consequent channel confinement of the paleochannel drastically more than its probable natural rate. The finding bears a significant amount of importance in riverine planning in the DFD region or reconnascence survey of the existing channelization facilities here.

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Analyzing Historical Evolution and Decay of Jamuna River (West Bengal) Using Multi-temporal Satellite Images and GIS

Puja Ghosh

Abstract Moribund River is the river that is being in a state of dying or inactive. Jamuna River which was active in probably fourteenth and fifteenth centuries now is in the dying stage with multiple bends and meandering courses. The main objectives of this study are to provide an overview of basin geology and soil of Jamuna basin, to describe the origin of River Jamuna through details study of present evidence, to provide details of channel morphology and hydraulics, and to detect channel shifting, degradation, and present condition of Jamuna River. Mid-channel bar and paleochannel maps of the Bhagirathi-Hooghly River have been prepared using satellite images, Google Earth Image, and QGIS software to describe the origin of River Jamuna. Morphometric and hydraulic data of Jamuna River were also collected using Google Earth and QGIS software and from River Gauge data of River Research Institute. The maximum slope and average slope of Jamuna River are respectively 1.7% and 0.2%. The average Sinuosity Index of Jamuna River is 2.78 which indicates a meandering course. Oxbow lakes named Jalkar Magra (length—5.80 km, average width—0.22 km, average slope—0.7%), Bhomra Beel (length—6.25 km, average width—0.2 km, average slope—1.1%), Kankana Boar (length—4.66 km, average width—0.25 km, average slope—0.4%) and other beels all are situated at the left side and the multiple meander bed cutoffs at Chawberia provide evidence that River Jamuna gradually shifted towards the southern direction. August is recorded as the peak month for River Gauge at Gaighata station. Satellite images of different years have been collected to detect spatio-temporal changes of River Jamuna. Siltation in the river bed and increasing activity of human cause's serious problem in river regime leads thread like narrow channel with an average width of 36 m.

Keywords Jamuna River · River degradation · Meander-bed cutoffs · Siltation · Flow bifurcation

P. Ghosh (✉)
Department of Geography, Krishnagar Government College, Krishnanagar, Nadia, West Bengal, India
e-mail: pujaghosh745@gmail.com

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1 Introduction

An alluvial river is a river in which the bed and banks are made up of loose sediments or alluvium. Scale is an important consideration in fluvial geomorphology, with process-form interactions occurring over a huge range of space and time scales (Charlton, 2007). Spatial and temporal change of an alluvial river is a common phenomenon as the river flows abundantly with multiple meandering course. Waveform or meandering is obvious for all stream channels (Das & Islam, 2015). Different works have been done on alluvial channels (Das, 2019). A tentative classification of alluvial river channels have been reported by Schumm (1963). Channel sinuosity of alluvial river have been discussed by Brice (1964). " Jabunah" (Named by Rennell, 1780) locally known as Jamuna River originates from Bhagirathi-Hooghly River near Tribeni, flows 65 km eastward, and meets Ichhamati River near Tipighat. Jamuna River flows through Nadia and North 24 Parganas district. River Jamuna is characterized by a sinuous course with several bends and meanders. According to Chakraborty (1924, quoted in Rudra et al., 2018), Dhoyee in "pavanduta" in 1175 AD described Jamuna River as an active channel (Rudra et al., 2018). According to Ray (1979), Bipradas Piplai (1495 AD, quoted in Ray 1979) in "Manasamongla" described Jamuna River as a "bishal" river (Rudra et al., 2018). Hunter (1875) also described the Jamuna River as a navigable river (Rudra et al., 2018). However, the Jamuna River does not figure at all in Van den Brouck's map (1660). In Rennell's maps (1780), the name Jabunah persists from the Hooghly River to savashpour on the Isamot (the Ichhamati) river (Mukerjee, 1938). In Rennell's days, the river in the wet season was "deep enough for the largest boat" (Mukerjee, 1938). According to Rennell (1781), the Hooghly River has a much deeper outlet to the sea than the principal branch. Several works were done on different tributaries and distributaries (Das and Das 2020, Das and Bhattacharya 2020) of the Bhagirathi-Hooghly River. For examples—The confluence of two major river systems, Ganga and Brahmaputra have been described by Sengupta (2011). River systems of Ganga–Brahmaputra–Meghna delta have been described by Rudra et al. (2018). Combating flood and erosion in the lower Ganga plain in India was also discussed by Rudra (2020). Evolution of the Ganga Brahmaputra delta have been described by Bandyopadhyay (2007). Oscillation of meandering Bhagirathi on the alluvial flood plain of Bengal Basin have been discussed by Laha (2015). Role of hydrological regime and floodplain sediments in channel instability of the Bhagirathi River have been described by Guchhait et al. (2016) and Islam and Guchhait (2017a, 2017b). Social and psychological terrain of bank erosion victims along the Bhagirathi river have been analysed by Islam and Guchhait (2018). Social engineering as shock absorbing mechanism against bank erosion along Bhagirathi river have been also described by Islam and Guchhait (2021). The trend of sea level change in Hooghly estuary have been discussed by Nandy and Bandyopadhyay (2011). Two indices to measure the intensity of meander have been described by Das (2014). Identification of palaeochannels using optical images and radar data have been examined by Mahammad and Islam (2021). Detecting the facets of anthropogenic interventions on the palaeochannels of Saraswati and Jamuna River have been examined by Sahana et al. (2020) But this moribund channel seems to be much more detailed study from past decades to present time (2021). So, the present study emphasizes on the detailed study of the Jamuna River, its origin, degradation, and present condition. The main objectives of the study are as follows:

i. To details study of Jamuna river basin geology and soil characteristics.
ii. To description of origin of River Jamuna through the detailed study of present pieces of evidence.
iii. To provide details of channel morphology and hydraulics
iv. To detect channel shifting, degradation, and present condition of Jamuna River.

2 The Study Area

The Jamuna River flows through the Haringhata block of Nadia district and Gaighata, Baduria, and Habra-1 blocks of North 24 Parganas district. The total length of the river is 65 km. Latitudinal extension of the study area is from 22°51′N to 23°9′N and the longitudinal extension is from 88°24′E to 88°55′E. The total basin area of the Jamuna River is approximately 255 km^2. The total length of Jamuna River in the North 24 Parganas district is 41.923 km and the percentage of the area drained in this district is 0.22% (District Survey Report, 2018). The basin area is characterized by alternate layers of sands, silts, and dark gray clays of middle to upper Holocene. The lithology of the area is deltaic plain, Para deltaic fan surface, semi to unconsolidated sediments with intergranular porosity (District Survey Report, 2018). The lower part of Jamuna River Basin falls under the Hinge Zone. Hinge Zone is a striking structural feature of Bengal Basin, which can be marked by a line connecting Kolkata to Mymensingh, Bangladesh (Rudra et al., 2018). The upstream of Jamuna River is totally detouched from Bhagirathi-hooghly River. So the river becomes a rainfeed nala (brook). The climate of the region is monsoon climate. The river bank is bounded by agricultural land with high intensity (Fig. 1).

3 Materials and Methodology

Data on width, length, slope, and area have been collected on Jamuna River and oxbow lakes using Google Earth Image. River Gauge data at Gaighata have been collected from Hydromet River Gauge data of River Research Institute. Channel profile and features map have been prepared using Google Earth, satellite images, and QGIS software. Location maps have been prepared using Google Earth and QGIS software. Ancient maps of the bengal river have been collected from Google Books.

The sinuosity Index of each section of the left and right bank meander belt has been calculated using the sinuosity formula given by Brice (1964). Each section's

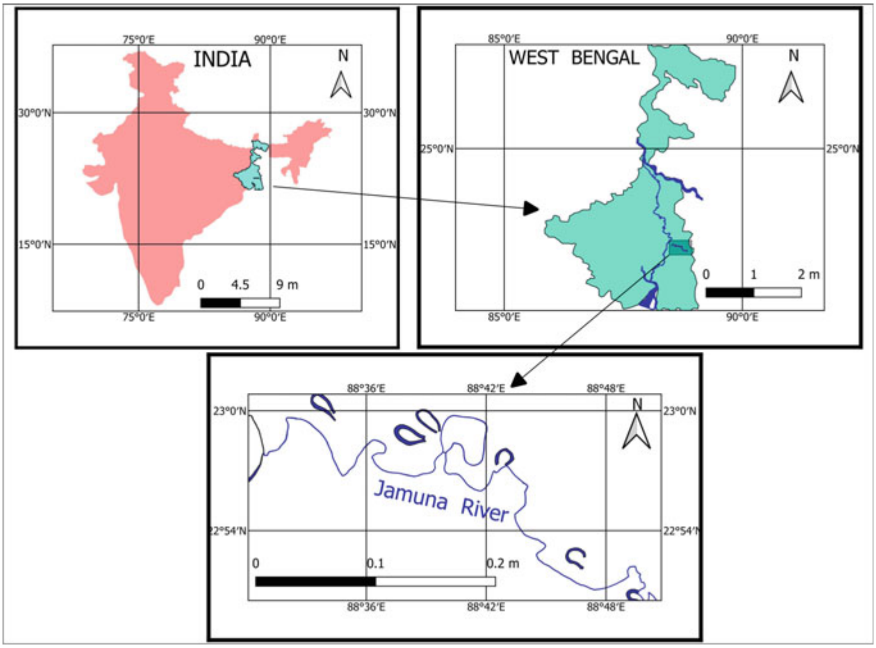

Fig. 1 Location of Jamuna River (West Bengal)

sinuosity is the ratio of actual river length to straight-line length. All section length has been averaged to get the Sinuosity Index of Jamuna River. Axis of meander belt is the centerline solid curve of meander belts (Brice, 1964). Axis of meander belt have been drawn with help of limits of meander belt using Google Earth Image. Then each sections of meandering course of Jamuna River have been marked as L1, L2, L3, L4, L5, L6 (for left bank) and R1, R2, R3, R4, R5, R6 (for right bank). Then the ratio of each section of meandering course to straight line length (axis of meander belt) have been calculated to get each sections sinuosity. Finally, the values of all sections have been averaged to get Sinuosity Index of Jamuna River. Satellite images, Google Earth Image, and ancient maps have been used to model the origin of the Jamuna River. Landsat 1–5 Multi-spectral scanner (MSS), Landsat 4–5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) satellite images have been collected from USGS to detect channel shifting and changes in the river basin. Here is the list of satellite images used for the study purpose. All images are in February Months (Table 1).

The satellite images have been processed by the following methods to get True Colour Composite (TCC) and False Colour Composite (FCC) images (Fig. 2).

Table 1 List of satellite images used in study

Image year	Satellite	Path and row	Source
1973	Landsat 1–5 MSS	138, 44	USGS
1990	Landsat 4–5 TM	138, 44	USGS
2000	Landsat 4–5 TM	138, 44	USGS
2010	Landsat 4–5 TM	138, 44	USGS
2021	Landsat 8 OLI	138, 44	USGS

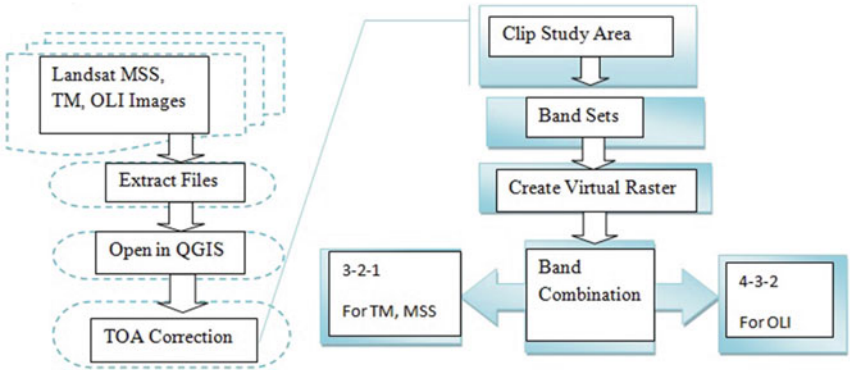

Fig. 2 Methodological framework for satellite image processing

4 Results and Discussion

4.1 Origin and Flow Direction

Bifurcations are commonly unstable but their lifespan varies greatly (Kleinhans et al., 2013). The majority of the cross-sections of lower Bhagirathi River have undergone significant changes (Islam & Guchhait, 2020). After Chakdah, there is multiple channel shifting evidences of Bhagirathi-Hooghly River course (Fig. 3). From Google Earth and satellite images, multiple paleochannel lines and chars (Srikishnapur char, Dumurdaha char, Raninagar char, Noasari char, char Ragunathpur, char Jajra, and char Jadubati, Majher char) have been identified along both banks (Fig. 3). These identities have been formed due to channel shifting of Bhagirathi-Hooghly River. It implies that the river is very active here from ancient times (Fig. 4). At the downstream of Chakdaha a mid-channel bar formed named sukhsagar which leads to bifurcation of main flow (Fig. 3). As we see historical time scale, after 1990 the mid channel bar started to grow and 2012 onwards the main flow passed through the left bank and with the growth of the mid channel bar flows at right bank reduced and other sub chars started to grow (Fig. 3). Now the question is how this process relates to the origin and evolution of the Jamuna River? Let's try to answer.

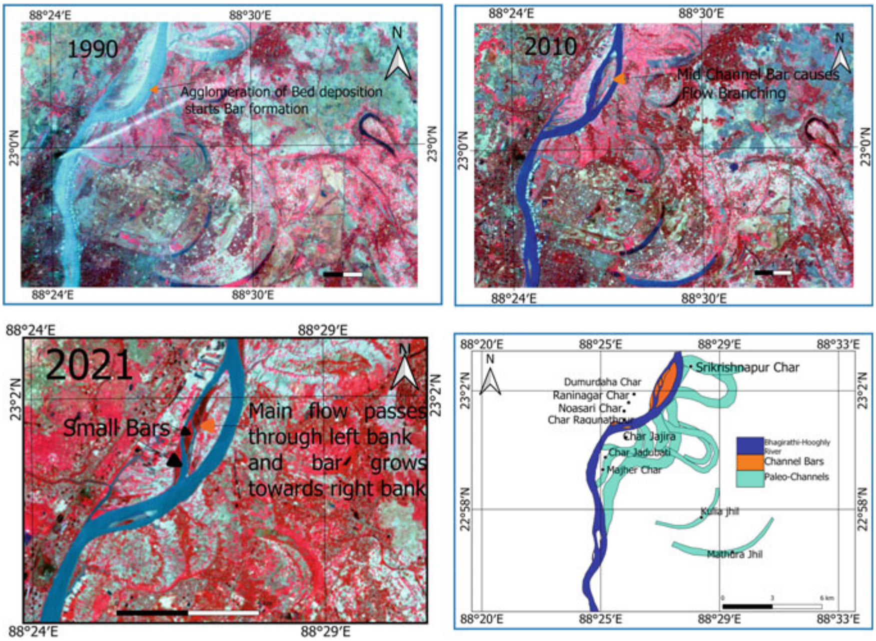

Fig. 3 Discussion on Jamuna River origin insight of present evidences; mid-channel bar formation, channel branching, and channel shifting

Here the curvature, alignment, and sequences of Mathura Beel, Kulia Beel, and other paleochannel lines in satellite and Google Earth Images give a hint that the main flow of Bhagirathi-Hooghly River struck over these paleochannels at some historical time scale(Fig. 3). After origin from the Ganga River, the Bhagirathi-Hooghly River started flowing towards the south direction. After crossing Ranaghat and chakdah, the river tooks a "U" turn and after that, the river flowed abundantly due to slope reduction. So the channel debris accumulated which gave rise of bars and chars. So channel branching occured near Tribeni. Saraswati River flows in a south-west direction, Jamuna River at the east and the main flow at the southern direction. As time passed with the maturation of chars and bars, the main flow shifted and gives rise of those paleochannels and other charlands (Fig. 4). As the main flow shifted towards the west, the source of Jamuna River dried up and now the original source of Jamuna River can't be identified. Only one thin line jointed Mathura Beel might be said as the source of Jamuna River.

4.2 Channel Morphology and Hydraulic

Jamuna River presently appears as a thread-like narrow channel with an average width of 36 m. The total flow is 65 km. River morphometry, as well as hydraulic regime changed due to growing human activity. The dying river now flows as nala

Fig. 4 Thornton's map of Bengal showing channel branching of ancient Bhagirathi-Hooghly River (Mukerjee, 1938)

(brook) with a meandering path. Some parts of the river bed are totally occupied by human activity (Fig. 5). Agricultural practices have been shown in many parts of river beds during the dry season. River width mainly increases in downstream. Here river width of nine stations has shown some fluctuations (Table 2) due to human activity, channel restriction and capture of the river bed for agriculture practice as well as for manmade reservoirs. After Gaighata ghat, the river Jamuna is restricted at both sides with small and big reservoirs. The river flows at a narrow channel (26.75 m) and got a width of about 38 m before meeting Ichhamati River. The maximum slope of the Jamuna River is 1.7% and the average slope is 0.2%. The main morphological features of the Jamuna River are oxbow lakes, flood plains, and meander cutoffs. Morphometry of oxbow lakes is widely used as a tool for knocking the evolutionary history (Das et al., 2020). The morphometry of oxbow lakes is shown in the table (Table 3). The entire oxbow lakes are mainly situated on the left side of Jamuna River (Fig. 5) and meander bed cutoffs at Chawberia give evidence that the river was gradually shifted towards the south direction. The highest meander cutoff is found at Chawberia whose meander radius is 1.49 km, total area is 1723 acres and circumference is 9.35 km. The total bed is mainly converted into lodge water nala (brook). However, after charghat water flows found and the rejuvenated river bed channelized to tipighat for economic purpose (Table 4).

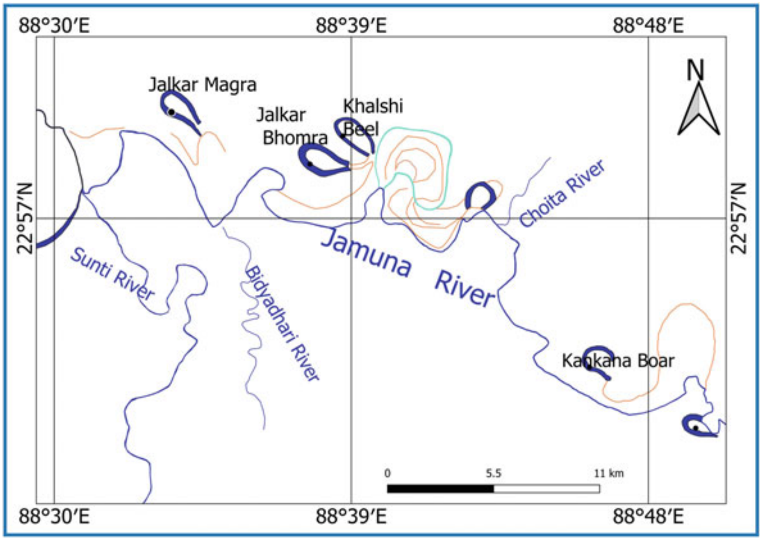

Fig. 5 Morphology of Jamuna River

Table 2 Jamuna River width in different places from up to downstream

Places	River width
Birohi Bazar Bridge	30.48
Haringhata Bazar Bridge	31
Kurambelia Bridge	37.46
Nagarukhra Jamuna Bridge	44.05
Canal Bridge (Chowberia)	31.77
Gopinathpur Bridge	25.58
Ghonja Road Bridge	32.82
Chandigarh Road Bridge	43.60
Gaighata ghat	50.44

Table 3 Geometry of oxbow lakes

Oxbow lakes	Length (km)	Average width (km)	Size (acres)	Maximum slope (%)	Average slope (%)
Jalkar Magra	5.80	0.22	171	4.4	0.7
Jalkar Bhomra	6.25	0.2	310	7	1.1
Khalshi Beel	4.73	0.15	156	2.0	0.5
Kankana Boar	4.66	0.25	223	5.7	0.4

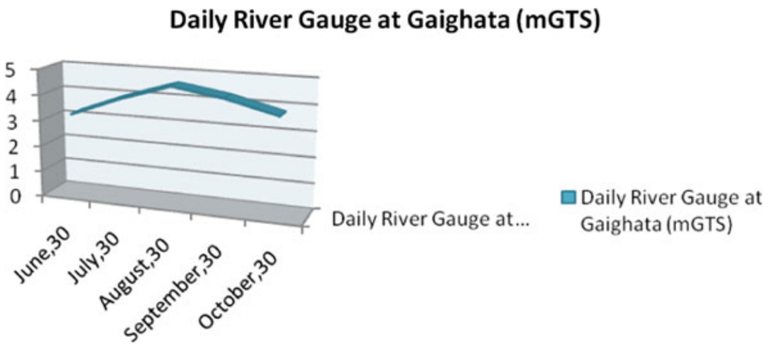

Fig. 6 Monthly variations in River Gauge data

Table 4 River Gauge data at Gaighata

Months (June–October, 2020)	Daily River Gauge at Gaighata in mGTS
June, 30	3.22
July, 30	3.97
August, 30	4.59
September, 30	4.28
October, 30	3.79

- **Sunti River:**

Sunti River is an important distributary of Jamuna River. In the northern part of the district, the river flows north–south direction and then to the east to be renamed as Harua Ganga and ultimately merges with Bidyadhari River in the southeast which goes across the Sunderbans. Here the off-takes of all these rivers have been silted up so that the rivers lost their heads. In their lower portions, they serve as drainage channels (District Survey Report 2018).

- **Choita River:**

The Choita River is part of the Ganga River system. The river is 40 km long and merges with the Jamuna River in Gaighata. The River crosses Gopalnagar, Talikhola, Khadaitala, Chaitapara, Kharua Rajapur, Kinarmath, Rampur, etc. in the way of flow.

- **Channel Planform:**

According to Brice (1964) channel sinuosity of a reach or Sinuosity index (S.I.), is the ratio of the length of the channel to the length of the meander-belt axis. According to him (Brice, 1964), if the sinuosity index of a reach is 1.3 or greater, the reach has described as meandering and a straight reach has a sinuosity index of 1 (Fig. 7). Also, the reaches that have sinuosity indices in between 1.05–1.3 are described as sinuous. Here using this formula channel sinuosity of each section of Jamuna River has been calculated. Each section of Jamuna River represents a sinuous to the meandering course (Fig. 7). The average sinuosity of the river is 2.78 (Table 5) which represents a meandering course. From each section value, it identified that the river course is more meandering at the left bank in comparison to the right bank. Although the sinuosity value at the last section in the right bank is very high. It is due to human interference near Tipighat where concrete river banks have been found and the river channelized economically.

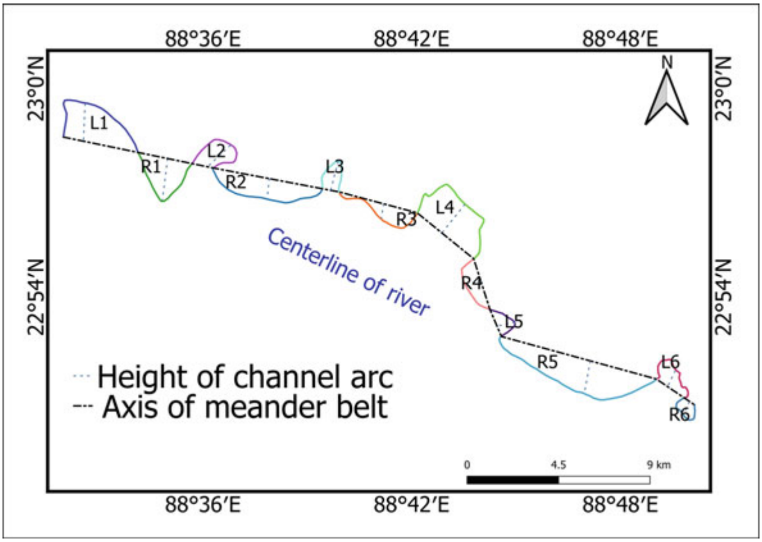

Fig. 7 Sinuosity Index in different sections of Jamuna River

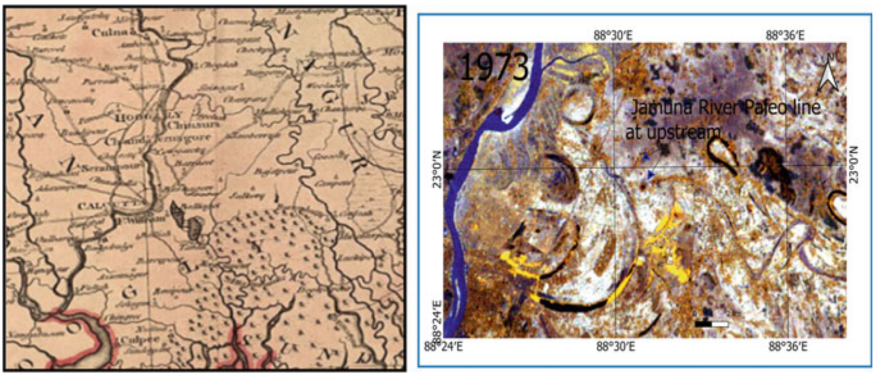

Fig. 8 Left map is Rennell's Map of 1786 showing the prominent channel of Jamuna River and right side map shows some parts of upstream paleochannel in 1973

Table 5 Sinuosity Index of Jamuna River

Section no	Actual river length (Km)	Length of meander belt axis (Km)	Sinuosity Index
L1	6.79	3.8	1.786842105
L2	4.71	1.08	4.361111111
L3	3.56	0.84	4.238095238
L4	7.3	3.69	1.978319783
L5	2.47	1.54	1.603896104
L6	4.06	1.71	2.374269006
R1	5.41	2.7	2.003703704
R2	6.4	5.48	1.167883212
R3	5.02	4.02	1.248756219
R4	3.48	2.8	1.242857143
R5	9.27	7.98	1.161654135
R6	2.62	0.63	4.158730159
Total			27.32611792
Average sinuosity of Jamuna River			2.277176493

4.3 Channel Shifting and Degradation

Jamuna was an active river in the past historic period and played an important role in the delta-building process. Ancient records descript that the Jamuna River was navigable by large boats (Mukerjee, 1938). The river degraded due to human as well as natural processes with the passing of time. From Rennell's map of Bengal (1780), it can detect that then the river was prominent and the river was navigable by large boats in the wet season. However, river decay was started. From the satellite image of 1973, some parts of the upstream paleo- line have been detected but the exact source of the river cannot be understood (Fig. 8). This is due to channel shifting and with the emergence of villages and towns the original source of Jamuna River washed out. There are two natural causes for river degradation—the first is bed deposition and maturation of delta and the second is siltation. As the main flow of the Ganga River passes through the Padma River and Bhagirathi-Hooghly River got a comparatively small amount of water leads channel shifting. Due to detachment from the source, the Jamuna River got silted.

From satellite images, multiple paleochannel lines have been identified. All the oxbow lakes (Jalkar Magra, Jalkar Bhomra, Kalshi Beel, etc.) are on the left side of the river making the paleochannel clear. The width of those oxbow lakes (Table 3) depicts that the Jamuna River was much larger in ancient times to present time (2021). Some paleochannel lines and a prominent meander cutoff around Chowberia have been identified (Fig. 9). Most of the paleochannels are on the left side proves that the river bed sifted towards the southern direction. From the satellite images, it can detect that the river line in 1973 and 1990 were wider than that of 2021 (Fig. 9).

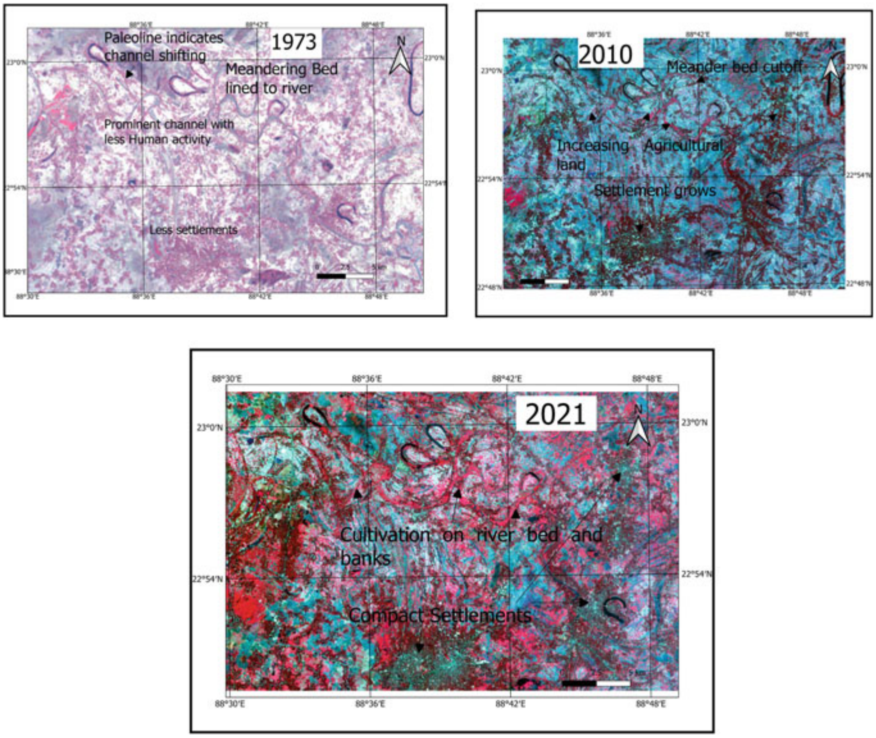

Fig. 9 Detection of increasing human activity and topography changes of river banks

Increasing human activity converted the river bed into a water lodge nala (brook). The riverbank of Jamuna River is mainly dominated by agriculture and reservoir. Agriculture is more dominant in the upper and middle regions. Some portions of river bed also converted into croplands during dry seasons. In the lower part of Jamuna River bed has been channelized and both banks are restricted by Big and Small reservoirs.

5 Conclusion

Channel branching is a common phenomenon in Bengal delta. The river was active in an ancient historical time scale before the seventeenth century. Jamuna River played an important role in the delta-building process. River Jamuna presently has an extremely sinuous course detached from Bhagirathi-Hooghly River is only traceable at downstream. It is a meandering course with the Sinuosity Index value of 2.78. Morphometry of oxbow lakes and identifiable paleochannels cleared the concept that the river was much wider in ancient times. The alignment and location of oxbow lakes and identifiable paleochannels proved that the river bed shifted towards the south. Now the moribund river is in dying condition. Now the channel is used as wastewater discharging nala (brook). The width fluctuations to downstream are mainly due to increasing human activity along the river bank. Siltation and degradation decreased river slope and the decreasing river slope changed the flow regime of Jamuna River. Due to these changes, heavy rainfall during the monsoon season causes floods in riverbank areas. Now the river bed is partly converted into agricultural land in many places. The economy of the area is agriculture and fishing-based. Cultivation in river bed have been found during the dry season. However, fishing practices are prominent during the monsoon season.

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Impact of COVID-19 on River Health in India

Shreyasi Singh

Abstract The COVID- 19 pandemic has wreaked havoc on the entire world, forcing all the great nations of the world to impose a lockdown and restricting people from coming together. Almost everything has been affected adversely by this pandemic, be it the schools, the workplace or the country's economy. The only thing that was seen to have improved was the natural environment. With fewer vehicles on the roads, the air quality of the metropolitan cities improved and with the closure of industries, the water quality of the rivers improved. However, the second wave of the COVID- 19 pandemic in India brought to us a very grim picture of these rivers. The increasing number of deaths in the country during April and May in 2021 led to the failure of proper cremation facilities. River Ganga, which is considered to be the holiest river in India, witnessed floating dead bodies. This paper thus aims to highlight the contrasting pictures of river health in India. In the first wave of the pandemic, river health improved due to lockdown, but in the second wave, the rivers had to carry bodies of the dead. Moreover, hospital wastes including non-biodegradable masks and gloves added to the misery of the rivers. This paper will hence, try to address some of these major problems of river pollution in India that have mainly come up due to the inefficient healthcare system in India, greatly exposed by the COVID-19 pandemic. Freshwater is a necessity. Lack of clean drinking water will lead to further dangerous diseases and if people continue to release all wastes into the rivers, there would be an extreme water crisis in the country and will also eventually lead the rivers to perish. This paper would also try to provide some solutions that could be adopted in order to maintain the health of the rivers even after the end of the pandemic.

Keywords COVID-19 pandemic · River health · Dead bodies · Hospital wastes · Freshwater crisis

S. Singh (✉)
Centre for the Study of Social Systems (CSSS), Jawaharlal Nehru University, New Delhi 110067, India
e-mail: shreyasisingh1@gmail.com

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1 Introduction

The coronavirus disease 2019 (COVID-19) was first observed in 2019 in the month of December in Wuhan city in China. Since then, nearly 210 countries of the world have been affected by this virus which has the ability to spread rapidly from person to person through aerosols of the affected person. The symptoms of COVID-19 were flu-like, but the disease is highly contagious as it is caused by severe acute respiratory syndrome coronavirus 2 (SARS-Cov-2). Owing to the rapid diffusion of the virus, WHO (World Health Organization) declared COVID- 19 as a pandemic on March 11, 2020 and instructed all the nations to adopt several restricting measures in order to curb the spread of the virus (WHO, 2020).

It was on 25th March 2020, that a nationwide lockdown was imposed in India for the first time. The infection rates were at a peak in mid- September which started to decline in January. However, a second wave arose at the end of March 2021, which was more devastating than 2020. The second wave of the Covid pandemic also exposed the flaws of the medical services in the country and also those of the government.

The COVID-19 pandemic wreaked havoc on the entire world, forcing all the great nations of the world to impose a lockdown and restricting people from coming together. Almost everything had been affected adversely by this pandemic, be it the schools, the workplace, or the country's economy. The only thing that was seen to have improved was the natural environment. With fewer vehicles on the roads, the air quality of the metropolitan cities improved, and with the closure of industries, the water quality of the rivers improved.

This paper would focus on the impact of the lockdown on rivers in India, especially on Ganga and two rivers of Eastern India, namely, Damodar and Hooghly. We all understand the importance of clean and fresh water for our survival, but in spite of that there is huge ignorance on the part of our government and all members of the society to maintain the quality of the rivers, which are one of the major sources of freshwater. Polluted rivers can have many detrimental effects on society and its people. Industrial and agricultural activities are the leading causes for this pollution, and when these activities came to a halt during the lockdown, the conditions of the rivers drastically improved.

The important question that arises here is, why do we need a lockdown to make us realize the importance of our riverine ecosystems? Why is it that we fail to maintain the quality of water in rivers alongside human activities? What are the problems and how can it be dealt with? Why did the holy Ganges turn into a place of dumping infected dead bodies during the 2nd wave of COVID-19 in the year 2021? These are the few pertinent questions that this paper aims to address.

This clearly indicates that rivers are now viewed as a place where one could dispose of wastes or even dead bodies simply to get rid of them, because it is believed that rivers are continuously flowing and hence it can cleanse itself. This is indeed a magical quality of the river itself, but we need to understand that rivers have their own limits. The rivers too need the time to process the waste (only biodegradable waste can be processed by the river and not harmful chemicals). Reports suggest that almost 40 million litres of wastewater enters rivers, but only 37% is treated (Singhal & Matto, 2020). Continuous increase in waste matter in the rivers would surely lead to the death of the river, and this is what needs to be prevented.

A lot has been written about the declining conditions of rivers due to human activities. This paper would focus upon the conditions of rivers in India in two main points of time. (1) During the peak of the first wave of COVID, when nationwide lockdown was imposed, and (2) During the peak of the second wave of COVID, when India witnessed the greatest number of deaths. While in the first case, river health improved, in the latter case, rivers were largely polluted due to rise in medical wastes. Hence, this paper would make an attempt to understand the conditions of the river in different phases of the COVID-19 pandemic and try to suggest some measures that would help us to maintain the water quality of rivers in India.

Research Questions:

- How did COVID- 19 affect river health in India?
- What were the positive and negative impacts of COVID- 19 lockdown on rivers?
- What are the measures that can be taken to maintain river health?

Research Objectives:

- To study the importance of river health to mankind and society.
- To study the reasons for contrasting images of Indian rivers during first and second waves of the COVID- 19 pandemic.
- To highlight the positive and negative impacts of the COVID- 19 lockdown on rivers in India
- To suggest some measures that can be implemented to improve and maintain river health.

1.1 Research Methodology

This paper explores the changes in different rivers due to the lockdown imposed due to the lockdown. It is based upon secondary sources drawn from journals, magazines and newspapers articles. This paper also uses research findings of famous geographers and chemists to understand the changing chemical composition of the river before and after lockdown.

2 Positive Impacts of COVID- 19 Lockdown on Rivers in India

All of us are aware that water is one of the most essential life-supporting components for all living beings on the planet. The hydrosphere, including lakes, rivers, oceans, and groundwater environments, has been vehemently polluted by various human activities such as industrialization, urbanization, agricultural practice and over-exploitation in normal times (Chakraborty et al., 2020). But it was examined that the pollution level of the aquatic environment remarkably dropped because of no mixing of industrial waste-water, solid waste, heavy metals, etc., during the lockdown period (Hader et al., 2020).

2.1 River Ganga

A recent study on the water quality of river Ganga near Kolkata city indicates a much higher level of dissolved oxygen (DO) in the lockdown period compared to previous years. Another study on Hooghly estuary near Haldia port, West Bengal demonstrates the enrichment of ichthyoplankton species due to no mixing of industrial waste-water and crude oil in the water. Investigation on bacterial load as total coliform (TC) on river Ganga at lower course reveals a significant drop of the bacterial community in this river ecosystem because of absence in activity of industrial, tourism, or traffic sector in lockdown. The river Ganga (In India) appears in a very clear and transparent picture in many places during the lockdown period (Mani, 2020).

Based upon the data of Biological Oxygen Demand (BOD), the report of Central Pollution Control Board (CPCB) showed that the number of polluted river stretches have increased from 302 to 351 between 2016 to 2018. Among 70 monitoring stations, only 5 contained water fit for drinking and 7 for bathing. River Ganga is considered to be an important part of India's identity, economy and religious beliefs. But unfortunately, due to deposition of untreated sewage and industrial wastes for years, the river became a dumping zone. River Ganga enters UP in the district of Bijnor and flows across several other districts in U.P. such as Kanpur, Varanasi, Meerut, Allahabad, etc. Through real- time monitoring by the CPCB, it was found that out of 36 monitoring units placed at different points of the river, the water quality improved for around 27 regions after only 10 days of lockdown. The level of dissolved oxygen was also observed to increase from 3.8 mg/l to 6.8mg/l in just one month (6 March, 4 April), showcasing a rise of 79%.

According to a CPCB assessment report, most stretches of river Ganga from UP to West Bengal were not fit for drinking before lockdown as there was very little amount of dissolved oxygen (around 0.5) and high levels of coliform bacteria that usually comes from animal wastes. However, it was observed that on April 19, the BOD was less than 3 mg/l, DO was more than 4 mg/l and the pH value belonged to the range of 6–9. These areas included Fatehpur Bridge, Varanasi bathing ghats and barrage in Kanpur, Murshidabad and Howrah Bridge, West Bengal. At some places, 'achaman' (ritual sipping of holy water) also became possible (Singhal & Matto, 2020).

According to Singhal & Matto, more than 80% of pollution in the Ganga was due to domestic sewage while the rest came from industries. During lockdown, sewage wastes increased due to increase in hand-washing but industrial wastes stopped entering the Ganga. All other human activities near the ghats also stopped. They say that when domestic and industrial wastes mix, it becomes difficult for the river to assimilate pollution. But due to the absence of industrial waste, the river was able to revive itself.

2.2 River Damodar

Just like the river Ganga, another important river Damodar of the Chota Nagpur Plateau region is getting huge pollutants from its well-developed industrial and urban catchment. Minerals and coal-rich Damodar river basin are highly famous for agriculture and industrial growth. Meanwhile, the waste effluents, heavy metals, toxic elements from nearby industries have been discharged into the river and lowering water quality as well as the river ecosystem. Many contemporary pieces of research on the water quality of Damodar have been conducted through various modern methods and techniques (Chakraborty et al., 2020). These relevant studies (physical, chemical or biological assessment) were conducted through popular methods such as water quality index (WQI), pollution load index (PLI), enrichment factor (EF), and aseptic techniques (microbial analysis), descriptive statistics, etc. WQI is commonly applied by researchers to evaluate water quality. It was initially developed by Horton (1965) using 12 common physical, chemical and biological parameters (pH, electrical conductivity, temperature, turbidity, etc.).

The coronavirus pandemic, lockdown, has affected the river hydrology and ecological flow greatly. The increased melting of the ice along with lack of industrial production, lower irrigation and commercial use have also contributed to the change (Mani, 2020). This proves that the rivers can clean themselves and regain their original flow if the amounts of waste drained into them are controlled. Mani argues that the government's flagship programme "Namami Gange" failed to do what nature did in just three weeks (Mani, 2020). According to him, the flaw in the river cleaning projects is that we set out to clean a river system that already works well, just that we keep polluting it with industrial effluents, sewage and plastic. We should have protected the rivers by blocking pollutants from entering them, but what we end up doing is to continue polluting them and cleaning them simultaneously.

Another important reason 'Namami Gange' doesn't work is because of its refusal to understand how the fish and marine population, the river banks, the livelihoods of people living nearby and their socio- economic profile are all linked. It is crucial that we revive the rivers' hydrology without interfering with the multitude of ecosystems they are part of (Mani, 2020).

Chakraborty et al. (2021) in their study discusses the impacts of lockdown on the Damodar river and show how the strict imposition of lockdown proved to be a blessing for the environment (Table 18.1). All the major steel plants in the states of Jharkhand and West Bengal are situated on the banks of the river Damodar. In recent years, the water quality has deteriorated due to untreated industrial effluents and urban sewage.

Water Pollution Index (WPI) of pre- lockdown times, showed that 100% of water samples were "highly polluted". During the lockdown period, the WPI of 90.90% of

Table 18.1 Differences in water quality between pre-lockdown and during lock down for Damodar River

Samples	Before Lockdown		During Lockdown	
	Water Pollution Index	Water Quality	Water Pollution Index	Water Quality
1	1.59	Heavily Polluted	0.57	Good
2	2.02	Heavily Polluted	0.65	Good
3	2.46	Heavily Polluted	0.78	Moderate
4	2.25	Heavily Polluted	0.74	Good
5	1.83	Heavily polluted	0.63	Good

Source Chakraborty et al., 2020

samples was found to have improved to "good quality" and 9.10% of samples are of "moderately polluted". Water in Ganga near Kolkata city was also found to have a much higher level of dissolved oxygen during the lockdown period. Pollution levels had dropped due to no mixing of industrial wastewater, solid waste, heavy metals, etc. during the lockdown period.

Researchers from IIT Kanpur have found in their study that the efforts to reduce wastewater from industrial units have reduced the pollution of heavy metals in the Ganga to a large extent in a short time. They have found that the pollution of the river due to dissolved heavy metals such as cadmium, arsenic, chromium, lead, mercury, iron, nickel, and zinc in the Ganga has been reduced by 50% during the lockdown. If the pollution of the Ganga River decreases, it will benefit five major states- Uttarakhand, Jharkhand, Uttar Pradesh, West Bengal, and Bihar as the country's significant population resides in these states.

2.3 Pitiable Condition of the Rivers During the Second Wave of COVID- 19 in India

The second wave of the COVID- 19 pandemic in India brought to us a very grim picture of these rivers, which were found to be in better health during the pandemic. The same rivers which were getting cleaned in the first wave of the pandemic were loaded with floating dead bodies during the peak of the second wave in India. The increasing number of deaths in the country during the months of April and May in 2021 led to the failure of proper cremation facilities.

River Ganga, which is considered to be the holiest river in India, witnessed floating dead bodies. The images of bodies floating in the river Ganga were doing rounds in the media and were very disturbing in nature. The banks of the river Ganga are considered very auspicious and have high religious value. Popular pilgrimage centres of India such as Varanasi and Haridwar are situated on the banks of the Ganga. Lack of proper cremation facilities on the river banks forced people to drown the dead bodies in the river itself. Local reports claim that more than 100 bodies have been dumped into the river.

The deceased are generally meant to be treated with sensitivity, dignity and respect, but this did not happen in the case of the deceased whose bodies were thrown into the rivers due to the lack of proper cremation facilities in the banks of the rivers. The discovery of dead bodies in Ganga is indeed a tale of denial of dignity in death which also points to the failure of the medical system in the country and apathy of the government towards its people.

3 Negative Impacts of COVID-19 on River Health in India

3.1 Increase in Usage of Face Masks, Gloves and PPE Kits

Since the outbreak of COVID-19, there has been a huge rise in the generation of medical wastes, all over the world. These wastes are a major threat to public health as well as to the environment. Medical wastes are generated for the processes of sample testing, for diagnosis, for treatment of patients, disinfection purposes, etc. (Rume & Islam, 2020; Somani et al., 2020; Zambrano-Monserrate et al., 2020). Waste generated from the hospitals (e.g., needles, syringes, bandages, masks, gloves, used tissue, and discarded medicines etc.) should be managed properly, to reduce further infection and environmental pollution, which is now a matter of concern globally.

To protect themselves from viral infection, people are largely using face masks, hand gloves and other safety equipment. This in turn led to the increase in the amount of healthcare waste. It is reported that, since the outbreak of COVID-19, the production and use of plastic-based PPE kits (Personal Protective Equipment) has increased worldwide (Singh et al., 2020). However, due to a lack of knowledge about infectious waste management, most people dump these (e.g., face mask, hand gloves etc.) in open places and in some cases with household wastes (Rahman et al., 2020). Such haphazard dumping of these trash creates clogging in waterways and leads to worsening of environmental pollution (Singh et al., 2020; Zambrano-Monserrate et al., 2020).

Disposed gloves and masks are also polluting water bodies to a large extent. These things which are meant to be protective in nature are getting transformed into means of pollution as well. Moreover, the damage that is being caused to the environment can last for centuries. Surgical masks have a coating of plastic and gloves are completely made up of plastic. Hence, these things are here to stay for many years.

It is reported that face masks and other plastic-based protective equipment are the potential sources of microplastic fibers in the environment. Polypropylene is generally used to make N-95 masks, and Tyvek is used to make protective suits, gloves, and medical face shields. These chemical compounds can persist for a long time and have the potential to release dioxin and toxic elements into the environment (Singh et al., 2020). Though experts and responsible authorities suggest the proper disposal and segregation of household organic waste and plastic-based protective equipment (hazardous medical waste), people do end up mixing these wastes which further increases the risk of transmission and exposure to the virus (Singh et al., 2020; Somani et al., 2020).

3.2 Improper Disposal of the Medical Wastes

Recently, huge amounts of disinfectants have been applied to roads, commercial, and residential areas to exterminate the SARS-CoV-2 virus. These disinfectants drain into the local sewage which in turn enters into the river bodies. Therefore, there is a need to follow additional measures in wastewater treatment, but this becomes a challenge for developing countries like Bangladesh, where even municipal wastewater is generally drained into nearby aquatic bodies and rivers without treatment. China has already strengthened the disinfection process (increased use of chlorine) to prevent the SARS-CoV-2 virus from spreading through the wastewater. But, the excessive use of chlorine in water could generate harmful by-products as well. (Zambrano-Monserrate et al., 2020).

One of the best ways to treat hospital wastes such as masks, gloves, and syringes is—incineration. A lot of waste products can be turned down into a little amount of ash. Incineration can release harmful gasses and chemicals, but it can be treated if proper technologies are used.

4 Relation Between River Health and Society in India

In the following sections I would describe the benefits of having a healthy river for society and its people. Rivers are essential to human well-being. However, many rivers around the world are at the verge of severe degradation, posing a great threat to ecosystem services. Therefore, it is necessary to take steps in order to preserve the rivers. Proper efficient initiatives to protect the rivers will only be done when we realize the importance of rivers in our society.

River health refers to the overall state or condition of a river. Good river health is often assessed in relation to water quality, environmental flows, connectivity of river habitats, and biodiversity, among other indicators. A healthy river is considered to be distinct from a ‘natural river’. A healthy river could be utilized in a sustainable manner while the natural one is considered to be that which experiences minimal human disturbance, and remains in its natural state. The Ramsar Convention promotes the concept of wise use, recognising that alteration of the river and its ecosystems can facilitate the realization of benefits, but that the level of an alteration should not degrade the system itself. (Ramsar Convention Secretariat, 2010).

Human society is benefited by rivers in several ways. Rivers act as the source of freshwater for domestic consumption as well as for carrying out commercial purposes such as those of farming, fishing, livestock, etc. Water is very important in industries as well. It is a cheap source of transport and also has huge benefits in the sector of tourism, which further has an impact on the nation's economy (Sarkar & Islam, 2021). Riverine ecosystems also play a key function of regulating our environment by supporting biodiversity, transporting sediment and nutrients, diluting pollutants and waste, and regulating floods and droughts. Many of these services are also intrinsically related to factors indicative of river health, such as water quality and ecological status (Sarkar et al., 2021).

Parker and Oates (2016) delineate several social benefits that are derived from the rivers. They are:

- Freshwater fisheries can provide an **important source of income and livelihood** for people in developing countries like India. Rivers also provide water for livestock consumption, important for people belonging to pastoral communities.
- **Healthy freshwater ecosystems play a role in dilution and filtration of pollutants** (agricultural, industrial) and human and animal waste, as well as reducing water-borne or water-related diseases; health benefits are obtained from using clean water for drinking, cooking, bathing and washing clothes, and the reduced risk of vector-borne infections.
- Rivers are also **sources of aesthetic enjoyment** such as for recreational activities e.g., walking, boating, fishing, bird-watching, etc.
- Rivers have deep **religious significance** in many cultures such as in India. Rivers constitute a major component of many rituals related to marriage as well as death and also is a major pilgrim site.
- Rivers also play an important **role in establishing social relations** among people, states, and also nations.
- Water is an **essential component in almost all major industries**. Effective operation of industry requires a sustainable supply of water in the right quantity, of the right quality, at the right place, at the right time, and at the right price.
- Water is important **in manufacturing industries**, where it is used for lubrication, dyeing, cooling and washing.
- **Rivers and water bodies are used to transport people and materials**; water transport can be more cost-effective compared to other forms, particularly for bulk commodities, and can help to expand regional trade.
- Rivers are important for **hydropower generation.**
- River ecosystems (e.g., wetlands) have some **natural capacity to buffer against climate variability and change.**

5 Suggestions to Maintain Good River Health

India's rivers aren't going to remain as clear as they were during the lockdown forever, and will get dirty soon after life gets back to normal and industries start working at their optimum level. It is assumed that all of these environmental consequences are short-term. So, it is indeed the need of the hour to make a proper strategy for long-term benefits, as well as sustainable environmental management. The COVID-19 pandemic has elicited a global response and united countries to fight against the virus. Similarly, to protect this globe, the home of human beings, the united effort of the countries should be imperative (Rume & Islam, 2020).

Regeneration of industrial activities is very crucial to overcoming economic distress and maintenance of public livelihood. Sustainable livelihood is important to be practiced to maintain the health of the total environment.

Mitigation strategies to help in the rejuvenation of river are as follows:

1. Requirement of more rigid regulatory controls over the industries which are letting out wastes into the rivers.
2. Integrated River Basin management should be followed. The geological, geomorphological, hydrological and socio-cultural aspects should be considered to better the health of the river system for domestic and industrial water use (Chakraborty et al, 2020).
3. Most polluting sources should not be allowed to dump effluents/ sewage into rivers, so that we can arrest the rate of decline in the quality and flow.
4. Urban sewage must be treated using wastewater treatment plants.

Some other efficient strategies that can be adopted to curb water pollution in rivers are:

Sustainable industrialization: Industrialization is crucial for economic growth, but it has to be carried out in a sustainable approach. For sustainable industrialization, it is essential to shift to less energy-intensive industries, use cleaner fuels and technologies, and strong energy efficiency policies. Moreover, industries should be built in some specific zones, keeping in mind that waste from one industry can be used as raw materials for the other. After a certain period, industrial zones should have been shut down in a circular way to reduce emissions without hampering the national economy.

Wastewater treatment and reuse: To control the challenges of water pollution of the rivers, both industrial and municipal wastewater should be properly treated before discharge. Moreover, if we practice the reuse of treated wastewater in non-production processes like toilet flushing and road cleaning, it can largely reduce excessive wastage of water.

Waste recycling and reuse: To reduce the burden of waste and environmental pollution, both industrial and municipal wastes should be recycled and reused. Hence, circular economy or circularity systems should be implemented in the production process to minimize the use of raw materials and waste generation. Moreover, hazardous and infectious medical waste should be properly managed by following the guidelines of WHO (WHO, 2020). For this to happen, it is important that the government implements extensive awareness campaigns through different mass media, regarding the methods of proper waste segregation, handling, and disposal.

6 Conclusion

The COVID- 19 pandemic in India has had a deep impact on river health in India. It had both positive as well as negative impacts at different stages of the pandemic. During the lockdown phases, the water quality of the river improved to a great extent after several years, but after things went back to normal and when industrial and other human activities were restarted, the river quality also became poor. Secondly, the second wave of Covid- 19 in India brought us some disturbing pictures of dead bodies floating in the Ganga. This exposed the inefficient working system of the government as well. What we need to question ourselves is why do we need a pandemic to make us realize the importance of nature? It is probably true that 'coronavirus is earth's vaccine and actually we are the virus'. Rivers have their own capacity to maintain their "health", but it becomes extremely difficult when humans continuously keep polluting them. The rate of pollution becomes greater than the rate at which the river can maintain itself.

Moreover, the COVID- 19 has resulted in huge amounts of hospital waste also, which on reaching the rivers pose great threats to aquatic life too. Masks, gloves and PPE kits all have some amount of non- biodegradable substance that increases the level of pollution in the environment. Hence, it is important to take necessary steps to reduce the damage that is being caused to our rivers as they are an essential part of not only our ecosystem but also of our everyday lives, culture, occupation and also religion.

With the help of proper waste water treatment policies and methods such as sustainable industrialization and integrated river basin management, the river health can be maintained in the future. Strict norms should be followed by the industries. More number of real- time monitoring systems such as that of the CPCB should be placed in different regions. And lastly, but most importantly education and awareness must be spread across people so that they realize the importance of healthy rivers.

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A Cross-Sectional Study on the Water Quality and Ecosystem Health of the Jalangi and Bhagirathi River and Their Selected Oxbow-Lakes

Biplab Sarkar and Balai Chandra Das

Abstract Bhagirathi and Jalangi are two distributaries of the river Padma. River Jalangi is tributary to the river Bhagirathi and they meet at Swarupganj, Nadia. Jalangi is a dying river whereas, Bhagirathi is an active river. There are many wetlands in the interfluves of these two rivers. We selected five amongst them and these two rivers and made a cross sectional study of water quality to explore the inter wetlands and inter river trend in water quality and ecological health and to investigate the drivers of ecological stress on water quality. To these ends, we applied tools of different water quality indices like WAWQI, CPI, HPI, OPI, and EI. We confirm that the concentration of dissolved oxygen is critically low (DO = 2.62 gm/l) for the selected wetlands indicating poor water quality. Besides, the values of EI indicate that all the wetlands are eutrophic in nature (EI>1) representing poor ecological health. However, the values of CPI indicate that the water can be used for domestic, irrigation and industrial purposes. Moreover, the low concentration of heavy metals have been observed in the wetland water representing pollution free water based on the values of HPI. Therefore, considering all the parameters mentioned, the water quality of Bhagirathi river is better in comparison to Jalangi river and five wetlands. This is because mainly of the fact that the Bhagirathi river is very active and therefore the pollution dilution capacity is high.

Keywords Weighted arithmetic water quality index · Comprehensive pollution index · Heavy metals pollution · Wetlands · Ecosystem services · Organic pollution · Eutrophication

B. Sarkar
Department of Geography, Aliah University, Kolkata, West Bengal, India

B. C. Das (✉)
Department of Geography, Krishnagar Government College, Nadia, West Bengal, India
e-mail: drbalaidaskgc@gmail.com

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1 Introduction

Provision of freshwater for diversified living beings is one of the important ecosystem services of a river. Many rivers in the world are facing the problem of overextraction of water for satisfying the ever-increasing demand of water resource for socio-economic development (Wen et al., 2021; Willison & Côté, 2009; Zhang et al., 2020). Therefore, maintaining the minimum discharge for sustaining the ecological functions of the river has become a key challenge for river protection and management of river health. Besides, rivers are also facing the problem of water pollution due to various point and mon-point sources of pollution such as discharge of industrial effluents, mixing of sewer from urban areas and agrochemicals from agricultural practices. Thus, availability and quality of river water is a matter of concern in the twenty-first century and emphasizing on environmental flow of a river has become vital for water resource management and habitat provision and sustainable development (Burkina et al., 2018; Giang et al., 2019; Ribeiro-Brasil et al., 2020; Wang et al., 2020).

Diversified approaches are there in the study of aquatic environment and aquatic ecology. The quality of river water for aquatic lives are studied from ecological stress factors where the status of eutrophication, organic pollution, heavy metal contamination is explored from different spatial and temporal framework (Abdel-Satar et al., 2017; Qu et al., 2018; Yarahmadi & Ansari, 2016). Besides, the effect of water pollution on different aquatic species are also studies from species strain factors e.g., biomass, productivity, density and diversity of species (Karaouzas et al., 2017; Smeti et al., 2019; Washington, 1984). Moreover, it has become a vital in the ecological research to study the response of species to water pollution at molecular, biochemical and behavioural levels.

Sophisticated methods and models are available in the study of water quality and ecosystem health. For example, the level of aquatic toxicity measured in terms of the concentration of metals and aquatic toxicity index (ATI) provides useful insights about the quality of environment and potential risks on different species (Wepener et al., 1992). The quality of aquatic environment is also assessed by eutrophication index, organic pollution index, and heavy metal contamination index. Many models are also available for assessing the aquatic habitat quality. For examples, PHABSIM RHYHABSIM, River2D, CASiMiR etc. are important models which provide the information on the threshold flow required for maintaining the habitat quality (Jowett et al., 2008; Kelly et al., 2015; Lee et al., 2010; Mouton et al., 2007). Besides, the health and functional stability of aquatic ecosystem is assessed considering the methods of tropic state index (TSI), species richness index (SRI), Simpson's diversity index (SDI) etc. (Chalar et al., 2010; El-Serehy et al., 2017; Shoup & Wahl, 2009). Therefore, the above-mentioned methods and models can be applied for almost all the rivers in the world which are facing the problems of (a) maintaining the minimum discharge required for sustaining the ecological functions and (b) receiving different kinds of pollutants from different point and non-point sources.

The Jalangi and Bhagirathi-Hooghly are two important rivers in the Indian part of the Bengal delta (Das, 2015; Sarkar & Islam, 2019). Both the rivers are playing an important role in influencing local geomorphology, geo-hydrology, climate, soil, land use and socio-economic spectrum (Sarkar & Islam, 2020). Urban sprawl, emergence of new urban areas because of high population growth, transformation of agricultural land into built up area, emergence of new industry, intensive agricultural practice, construction of road stream crossing are the phenomenon influencing the water quality of rivers of Bengal. As a result, ecological stress is increasing in response to decreasing the water quality of the rivers (Sarkar & Islam, 2020; Sarkar et al., 2020). Therefore, the present study has made an attempt to explore the water quality and ecosystem health of the Jalangi and Bhagirathi River and their selected oxbow-lakes with the following objectives.

i) To explore the inter wetlands and inter river trend in water quality and ecological health
ii) To investigate the drivers of ecological stress on water quality.

2 Database and Methodology

2.1 Study Area

Bhagirathi-Jalangi interfluvial Kalantar tract, within which the C. D. Block Krishnagar-II, is interspersed with numerous wetlands of reverine origin. Some other kind of depressions originated as compulsory associations of delta formation are also found in this area. River Bhagirathi demarcates western boundary of the C. D. Block Krishnagar-II while part of the southern and eastern boundary of the block is demarcated by the river Jalangi. Both these rivers were highly dynamic during the period of delta formation. Bhagirathi in particular is very dynamic at present also. Oscillations of these two rivers opened newer and newer path through avulsions, cut-off of meander necks or in other ways. As a result, numerous derelict river channels are left detached from the parent river and have been converted into wetlands of sluggish stagnant water. As per Project Office on Mapping of Water Bodies, Fisheries Department, Government of West Bengal (2014) there are 600 water bodies in the C.D. Block Krishnagar-II covering total area of 2535.96 acres. Out of these numerous water bodies, there is only one river, river Jalangi, is flowing along the south and south-eastern boundary of the C.D. Block Krishnagar-II. Rest 599 water bodies are either public or private wetlands of natural or of artificial in origin. There are 16 wetlands of natural origin and present study incorporated wetlands of natural origin only. All the wetlands of the C. D. Block Krishnagar- II fall under the category of 'B', (as proposed by West Bengal Wetlands and Water Bodies Conservation Policy' Submitted to Department of Environment Government of West Bengal 2012) because no wetland of this block is forested. In this present study, five largest beels (wetlands) were selected which is exclusively within the boundary of the C. D. Block Krishnagar- II. Gurguriar Khal, also located in this block and much larger than those beels selected in this study, is an old channel rejected by the river Bhagirathi and has been converted into a beel. But it is an inter-block wetland passing through C. D. Block Nakasipara, C. D. Block Krishnagar-II and C. D. Block Nabadwip. That is why, this Gurguria khal is not taken in to this study. Another relict channel of stream, named Gotpara Beel, is located in the northern part of this block is also a major beel in this region. But this beel is also excluded from present study because of its inter-block alignment and passing through the C.D. Block Nakasipara and C. D. Block Krishnagar-II. In this present study, five major beels are selected which are exclusively within this block. They are tabulated in Table 1.

Of these five wetlands (Table 1), Hansadanga Beel, a privately-owned wetland is located in the Grampanchayet Dhubulia-I and interesting thing is that the beel is located within the boundary of a single mouza Banagram. Nawpara beel is located in

Table 1 Five major beels in C. D. Block Krishnagar-II and villages adjacent to them

Sl. No	Name of the beel	Geographical location	Area (Acre)	Perimeter (m)	Class	Adjacent Mouza (s)
1	Hansadanga Beel	Latitude: 23° 26′ 50″ N 23° 27′ 49″ N Longitude: 88° 27′ 42″ E 88° 28′ 35″ E	178.08	9462.19	'B' Natural Private	i.Chaugachha Hansadanga ii.Saheb Nagar iii.Banagram
2	Nawpara Beel	Latitude: 23° 29′ 51″ N 23° 31′ 04″ N Longitude: 88° 28′ 40″ E 88° 29′ 33″ E	240.89	9855.75	'B' Natural Public	i.Noapara ii.Chuakhali iii.Rupdaha iv.Sonatala
3	Satitala Beel	Latitude: 23° 30′ 32″ N 23° 31′ 11″ N Longitude: 88° 23′ 33″ E 88° 24′ 20″ E	43.38	3420.31	'B' Natural Public	i.Bargara ii.Sadhanpara iii.Sujanpur
4	Bara Beel	Latitude: 23° 29′ 30″ N 23° 30′ 38″ N Longitude: 88° 23′ 06″ E 88° 24′ 17″ E	87.46	5180.83	'B' Natural Public	i.Bargara ii.Sadhanpara iii.Sujanpur
5	Rukunpur Beel	Latitude: 23° 30′ 20″ N 23° 31′ 29″ N Longitude: 88° 22′ 44″ E 88° 23′ 20″ E	1.45	301.68	'B' Natural Public	i.Rukunpur

Source Google Earth images and Project Office on Mapping of Water Bodies, Fisheries Department, Government of West Bengal (2014)

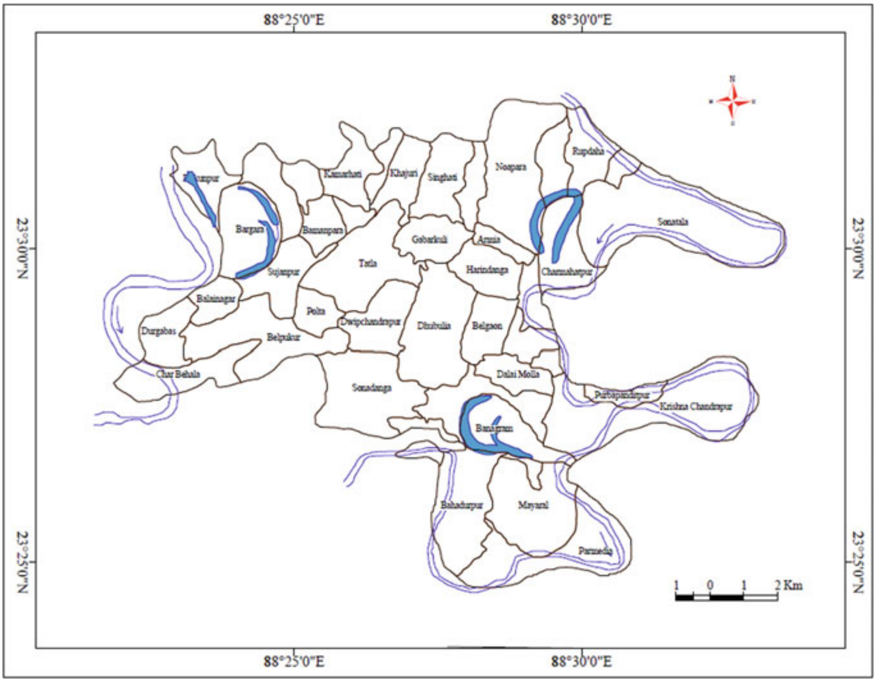

Fig. 1 Location of wetlands (solid blue). Light blue lines along with arrows to the east showing the river Jalangi and to the west, the river Bhagirathi

Grampanchayet Nawpara-I and Nawpara-II. Satitala beel, Bara beel and Rukunpur beel, all these three beels are located in the Grampanchayet Sadhanpara-I. Natural wetlands are much less in number as well as in areas. This is only become possible for a tract of land spotted with marks of numerous scars of paleo-channels by changing natural wetlands in artificial manner. Average share of area of natural wetlands in comparison to artificial wetland in C. D. Block Krishnagar-II is 1:2.14 (Fig. 1).

2.2 Data Sources

As the present investigation aims to investigate ecological stress due to deterioration of water quality of the Jalangi and Bhagirathi Rivers and their selected oxbow-lakes, 4 water samples (1 from the Jalangi, 3 from the Bhagirathi river and 5 from oxbow lakes. Regarding the parameterization many physico-chemical parameters of water have been considered for eutrophication, organic pollution, heavy metal pollution and overall water quality analysis. In particular, dissolved oxygen, chemical oxygen demand, dissolved inorganic nitrogen (NO_3-N and NO_2-N); dissolved inorganic phosphate (PO_4^{3-}) are considered for assessing eutrophication, organic pollution. For heavy metal pollution analysis, iron (Fe), lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), nickle (Ni) and zinc (Zn). Finally, for comprehensive pollution index 10 water quality parameters such as total dissolved solids (mg/l), total suspended solids (mg/l), conductivity (μmhos/cm), dissolved oxygen (mg/l), chemical oxygen demand (mg/l), biological oxygen demand (mg/l) 3 days at 27 °C, nitrate (mg/l) phosphate (mg/l) potassium (mg/l).

2.3 Methods of Data Processing

2.3.1 Water Quality Measurement

General Water Quality assessment Using Weighted Arithmetic Water Quality Index (WAWQI):

For evaluating the water quality of the selected rivers and beels, weighted arithmetic water quality index (WAWQI) has been adopted. The index is popularly used across the world because the parameters considered for this index are significant, reliable and available. The index is presented in Eq. 1. (Brown et al., 1970).

$$WAWQI = \frac{\sum Q_n W_n}{\sum W_n} \tag{1}$$

where, Qn (Eq. 3) and Wn (Eq. 4) are the water quality rating and unit weight of nth water quality parameter respectively.

$$Q_n = \frac{(V_n - V_i)}{(V_s - V_i)} \times 100 \tag{2}$$

$$W_n = \frac{k}{V_s} \tag{3}$$

$$k = \frac{1}{\sum \frac{1}{V_s} = 1, 2 \ldots\ldots\ldots, n} \tag{4}$$

Comprehensive Pollution Index

Comprehensive pollution index is one of the most common approaches used to qualitatively evaluate the water quality. The equation used to calculate the index is as follows.

$$CPI = \frac{1}{n}\sum_{I=1}^{N} p_i = \frac{1}{n}\sum_{I=1}^{N} \frac{c_i}{s_i} (i = 1, 2, \ldots\ldots., n) \tag{5}$$

where, Ci represents value of water quality parameter i; n implies the water quality parameters; and s indicates the standard permissible limit on water quality as recommended by WHO. The ranges of CPI and their uses have been presented in Table 2.

Heavy Mental Pollution of Wetlands

The concentration of heavy metals determines the quality of ecological environment. Heavy metals pollution index is one of the best methods by which water quality of a river and wetland ecosystem can be presented. For the present study, Eq. 5 is used for heavy metals pollution index.

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{6}$$

where Qi

$$Q_i = \sum_{I=1}^{N} \frac{(M_i - I_i)}{(S_i - I_i)} \times 100 \tag{7}$$

where, Qi represents sub-index of the ith parameter; Wi dsenotes unit weightage of the ith parameter; n is the number of parameters; Mi is the monitored value of heavy metal of ith parameter; Ii is the ideal value of ith parameter; Si is the standard value of the ith parameter.

2.3.2 Measuring Ecological Health

Organic Pollution

It is a comprehensive index accounting for multiple effects of BOD, COD, nitrate and phosphate on water quality which is mathematically expressed as follows.

$$OPI = \frac{BOD}{\text{BODs}} + \frac{COD}{COD\text{s}} + \frac{Nitrate}{Nitrate\text{s}} + \frac{Phosphate}{Phosphate\text{s}} \tag{8}$$

(Shakir et al., 2016) where, the numerator are the concentrations of BOD, COD, Nitrate, and phosphate of the samples considered for the present study. Similarly, BODs, CODs, Nitrate_s and $\text{Phosphate}_\text{s}$ are considered as the standard permissible limit. The values of OPI are classified into 6 classes: excellent for OPI < 0; good for 0 < OPI < 1; beginning to be contaminated for1 < OPI < 2; lightly polluted for 2 < OPI < 3; moderately polluted for 3 < OPI < 4) and heavily polluted for OPI > 4.

Table 2 CPI range and water quality

Comprehensive Pollution Index (CPI)	Class/Status	Water Quality and uses
0.0–0.20	Clean	Very good and use as Drinking, Irrigation, and Industrial purpose
0.21–0.4	Sub clean	Good and use as Domestic, Irrigation, and Industrial
0.41–0.8	Qualified	Some pollutants are detected but their concentrations accord with the standard i.e., fair Quality and use
0.81–1.0	Basically Qualified	Concentrations of some pollutants exceed the standard i.e., poor quality and use as Irrigation purpose
1.01–2.0	Polluted	Concentrations of quite a part of pollutants exceed the Standard i.e., very poor quality(polluted) and Restricted use for Irrigation
≥ 2.01	Seriously Polluted	Concentrations of quite a part of pollutants exceed the standard many times i.e., very polluted quality

Eutrophication

Eutrophication is an important indicator water pollution. When water is enriched by nutrients like NO_3^- N and NO_2^- N and PO_4^{3-}, the algae and plants are grew exponentially. This type of growth leads to eutrophication affecting the structure, function, and stability of the ecosystem. The eutrophication index can be measured with the Eq. 8.

$$EI = \frac{COD \times DIN \times DIP}{4500} \times 10^6 \quad (9)$$

where COD, DIN and DIP are the concentration of chemical oxygen demand the dissolved inorganic N (NO_3^- N and NO_2^- N) and dissolved inorganic phosphate (PO_4^{3-}) respectively. The value of EI more than 1 indicates the presence of eutrophication in rivers or wetlands.

2.3.3 Statistical Techniques

Cluster Analysis (CA)

For the present study the hierarchical cluster analysis is applied to classify water sampling sites into meaningful clusters or groups based on the different water quality indices. This technique starts with assembling the most similar sites of pair and forming higher cluster flowing step-by-stem method. In order to get the similarity between two samples Euclidean distance is employed while distance is represented by difference obtained from analytical values from both the samples. The process of forming clusters is continued until all samples come under the umbrella of a single cluster depicted by Dendogram or tree diagram.

ANOVA

For the present investigation, ANOVA has been applied for detecting variations in the water quality indices between the water samples of the rivers and samples from the wetlands. ANOVA may be computed using Eqs. 9–13.

$$F = \frac{MST}{MSE} \tag{10}$$

$$MST = \frac{SST}{p - 1} \tag{11}$$

$$SST = \sum n(x - \overline{x})^2 \tag{12}$$

$$MSE = \frac{SSE}{N - p} \tag{13}$$

$$SSE = \sum (n - 1)S^2 \tag{14}$$

where, F indicates ANOVA coefficient, MST for the mean sum of squares due to treatment, MSE for the mean sum of squares due to error, SST for the sum of squares due to treatment, p for the total number of populations, n for the total number of samples in a population, SSE for the sum of squares due to error, S for the standard deviation of the samples, and N for the total number of observations. If the calculated value of test statistics (ANOVA) is greater than the tabulated value, the null hypothesis is rejected otherwise alternative hypothesis is accepted.

3 Results and Discussion

3.1 Descriptive Statistics of Water Quality Parameters and Status

The statistical summary of the water sample variables (pH, TDS, TSS, TH, chloride, DO, BOD, TA and sulphate) of both the river and wetlands are summarized in Table 3. The average value of pH of all the wetland water samples is recorded as 7.25 which depicts normal surface water system as well as BIS desirable limit. The average value of TDS was found to be 178 mg/l. Besides, the other variables for example 2.62 mg/l for DO, 7.68 mg/l for BOD, 36.6 mg/l for COD 2.92 mg/l for NO_3 were recorded for wetland water samples. Similarly, the average value of pH of both the river water samples is recorded as 7.25. Moreover, the average value of TDS as 178 mg/l. DO as 7.68 BOD as 6.6, COD as 22.92 NO_3 as 2.22 were recorded for river water samples. The values of WAWQI have been categorized into five groups (i) 0–25 as excellent, (ii) 26–60 as good and usable for drinking, irrigation and industrial, (iii) 51–75 as poor and usable for irrigation and industrial, (iv) 76–100 as very poor and usable only for irrigation, and (v) above 100 as unsuitable for all use. The present study has observed that most of the samples of both the Bhagirathi river and the Jalangi river and associated Beels are recorded in 26–60 range indicating suitable for drinking, irrigation and industrial purposes.

3.2 Comprehensive Pollution Index and Heavy Metal Pollution Index

The CPI values of water samples form selected oxbow lakes ranges from 0.11 to 0.245 exhibiting the clean water except the water samples taken from Nawpara Beel. The HPI values of the water samples form selected oxbow lakes has been presented in Table 4. The index value ranges from 96.52 to 103.38 where two oxbow lakes are found above the critical index value 100. Besides, the mean of HPI was found to be 98. 99 with standard deviation 2.82. Thus, the index values confirmed that heavy metal contamination the selected oxbow lakes have little effect on the ecological health.

3.3 Assessing Water Quality for Ecological Health

Few nutrients like dissolved inorganic nitrogen and dissolved inorganic phosphate are triggering factors for organic pollution and eutrophication in water. The organic pollution and eutrophication in water further control the concentrations level of DO, BOD, and COD. Thus, introspecting the status of nutrients accompanied by BOD, COD and DO in both the river and wetland water is essential to measure the existing ecological health status. The average concentrations of DIN, DIP DO, BOD, and COD in the wetlands water samples were recorded as 2.92 ± 0.49, 0.05 ± 0.07, 2.62 ± 13.99, 36.60 ± 2.30 mg/l respectively. Besides, the average concentrations of DIN, DIP DO, BOD, and COD in the river water samples were recorded as 0.83 ± 0.49, 0.07 ± 0.07, 20.81 ± 13.99, 2.49 ± 2.30 mg/l respectively. Moreover, all the values of EI of both the wetland and river water samples were found to exceeding the

Table 3 Descriptive statistics of wetland water quality parameters

Descriptive statistics	pH	TDS mg/l)	TSS (mg/l)	EC(μ/cm)	DO (mg/l)	COD (mg/l)	BOD (mg/l)	Fe (mg/l)	NO3 (mg/l)	PO4 (mg/l)	Na^+ (mg/l)	K^+ (mg/l)
Average	7.52	178.00	32.80	296.30	2.62	36.60	7.68	1.34	2.92	0.05	14.66	3.71
SD	0.26	11.49	32.71	7.55	2.32	15.92	3.24	1.29	1.96	0.01	3.56	2.98
IQR	0.44	17.00	62.50	11.45	3.67	29.00	5.35	2.21	2.35	0.02	6.60	5.87

Table 4 CPI and HMI for five major beels

Beels	CPI	HPI
Satitala Beel	0.110012	103.3833
Nawpara Beel	0.24545	96.52916
Hansadanga Beel	0.117588	100.208
Baro Beel	0.172731	97.40508
Rukunpur Beel	0.172731	97.40508

Table 5 Eutrophication Index of five major beels

Beels	Eutrophication index	Remarks	Range
Satitala Beel	3558.106667	Eutrophication present	EI > 1
Nawpara Beel	531.4088889	Eutrophication present	EI > 2
Hansadanga Beel	1385.92	Eutrophication present	EI > 3
Baro Beel	502.6666667	Eutrophication present	EI > 4
Rukunpur Beel	754	Eutrophication present	EI > 5

critical value 1 indicating eutrophied condition. Again, EI is found highly correlated with DIP ($r = 0.67$) for wetlands and DIN ($r = 0.52$ for river water) (Table 5).

The highest value of OPI is found to be 3.03 for Satitala Beel indicating moderately polluted wetland water. Most of the samples have confirmed that the wetlands water is beginning to be contaminated type. The correlation study reveals that OIP is highly correlated with COD and BOD for both the wetlands and river water samples (COD: $r = 0.92$, BOD: $r = 0.98$ for wetlands; COD: $r = 0.84$, BOD: $r = 0.95$ for river) (Table 6).

Table 6 OPI values of five major beels

Beels	OPI	Remarks	OPI Range
Satitala Beel	3.0326	Moderately polluted	3 < OPI < 4
Nawpara Beel	1.1206	Begaining to be contaminated	1 < OPI < 2
Hansadanga Beel	1.3392	Begaining to be contaminated	1 < OPI < 2
Baro Beel	1.173	Begaining to be contaminated	1 < OPI < 2
Rukunpur Beel	1.377	Begaining to be contaminated	1 < OPI < 2

3.4 Comparative Assessment of River and Oxbow-Lake Water Quality

All the five beels and the river Jalangi show lentic nature of habitat. Lack of flow and consequent organic and inorganic traits are portrayed in all most all the water quality indices. Eutrophication level as well as BOD are quite high in wetlands and in the river Jalangi. On the other hand, with low BOD < 1.0 and almost zero eutrophication, river Bhagirathi portraying itself as a lotic habitat of fast flowing water, a river. Although Jalangi is a river, yet its water quality portrays qualities as if a stagnant waterbody. This is because of the fact that, the river no more flows except few days a year. As the offtake of the river Jalangi from the river Padma remains detached year-round, so there is almost nil or very negligible flow through the river and showing lentic nature.

4 Conclusions

We explored organic and inorganic traits of water of the river Bhagirathi and the river Jalangi and five oxbow lakes in between these two rivers and assessed their water-quality. Although pH of all the water bodies, be it lentic or lotic, portrayed neutral nature (7.5), yet variability in water quality of wetlands and the river Bhagirathi in terms of heavy metals pollution index, comprehensive pollution index, eutrophication index, and organic pollution index is quite high.

Lack of robust data on wide temporal scale is the prime drawbacks we felt. For best understanding the water quality in terms of aqua-cultural traits, regular monitoring is compulsory. However, this baseline study may be beneficial for future researchers in the domains of wetland studies and environmental flow assessment of rivers.

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Contrasting Diffusive Methane Emission from Two Closely Situated Aquaculture Ponds of Varying Salinity Situated in a Wetland of Eastern India

Sania Shaher, Abhra Chanda, Sugata Hazra, Sandip Giri, Isha Das, Sourav Samanta, and Sourav Das

Abstract Inland aquaculture practice is becoming popular throughout the world to suffice the increasing protein demand of the growing population. Aquaculture ponds in general emit methane (CH_4) towards the atmosphere. However, available data are scarce from India, where the number of aquaculture plots is growing at a fast pace. We measured the partial pressure of CH_4 in surface water [pCH_4(w)], the atmosphere-pond CH_4 fluxes, and several relevant biogeochemical parameters in sewage–fed freshwater (FWP) and oligohaline (OHP) aquaculture ponds situated in an eastern Indian wetland. We hypothesized that pCH_4(w) and the atmosphere-pond CH_4 effluxes would significantly vary between FWP and OHP as salinity plays a crucial role in regulating the methanogens in any water column. Measurements were carried out in both FWP and OHP throughout an annual cycle. FWP and OHP emitted CH_4 at the rate of 22.4 ± 16.2 mg m^{-2} h^{-1} and 13.4 ± 13.6 mg m^{-2} h^{-1}, respectively. Apart from low salinity, turbidity was higher in FWP, which in turn led to reduced photosynthetic activities and lower dissolved oxygen levels compared to OHP. pH was also substantially lower in FWP compared to OHP. More anaerobic and low pH conditions in FWP compared to OHP favored methanogenic activities and methane oxidation was discouraged, which led to higher atmosphere-pond CH_4 fluxes from FWP compared to OHP. However, both FWP and OHP exhibited annual mean CH_4 effluxes much higher than the efflux rates observed in most of the Chinese aquaculture ponds.

Keywords Methane emission · GHG · Aquaculture · Sewage–fed · Freshwater · Brackish water · Wetland · East Kolkata Wetland · Sundarban Biosphere Reserve

S. Shaher · A. Chanda (✉) · S. Hazra · S. Giri · I. Das · S. Samanta · S. Das
School of Oceanographic Studies, Jadavpur University, Kolkata 700032, West Bengal, India
e-mail: abhrachanda.sos.rs@jadavpuruniversity.in

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1 Introduction

Aquaculture ponds have become an essential land-use class and encompass a substantial part of the surface water ecosystems of the Earth (Yang et al., 2018a). Since the 1970s, aquaculture ponds have come up as an alternative to capture fisheries and it has been serving well to meet the ever-increasing demand for aquatic foods like fish, shrimp, crabs, etc. (Hu et al., 2012). Distributed over a wide range of tropical to temperate regions, the freshwater and brackish water aquaculture ponds comprise an area of about 1,10,832 km^2 throughout the world (Verdegem & Bosma, 2009). However, like many other inland lentic ecosystems (e.g. lakes, ponds, reservoirs), aquaculture ponds have been also found to emit a substantial quantity of carbon dioxide, methane, and nitrous oxides (Boyd et al., 2010; Chen et al., 2016; Yang et al., 2015a). Among the several greenhouse gases, methane (CH_4) emission has perhaps received the highest attention (Bastviken et al., 2011; Hu et al., 2014, 2016). The aquaculture ponds receive a substantial amount of organic load which when remains unutilized acts as a substrate for the microbes to act upon and under anaerobic conditions, the methanogens produce a substantial amount of CH_4 from it (Yang et al., 2019). According to the estimates made at the beginning of the present decade, inland aquatic bodies are capable of emitting 650 Tg C $year^{-1}$ in the form of methane (Bastviken et al., 2011). However, it is believed that these magnitudes include considerable uncertainty as the CH_4 emissions from shallow aquaculture ponds are mostly not considered while drawing these estimates (Long et al., 2016; Yang et al., 2018a). Moreover, field observations of CH_4 emission are still very few and mostly concentrated in Chinese pisciculture plots (Chen et al., 2016; Long et al., 2016; Yang et al., 2015a, 2018b, 2019).

CH_4 transport from the water column of any aquatic ecosystem towards the atmosphere mainly takes place through either diffusion (Chen et al., 2016) or ebullition (Dutta et al., 2013). A wide range of biotic and abiotic factors are known to regulate the production of CH_4 by the methanogens and its consumption by methanotrophs which in turn govern the partial pressure of CH_4 in surface water [$pCH_4(w)$] and hence the atmosphere-pond CH_4 flux (Yang et al., 2019). Earlier pieces of research have highlighted that water temperature plays a critical role in governing the CH_4 biogeochemistry (Knox et al., 2016; Olsson et al., 2015; Palma-Silva et al., 2013). Factors like pH (Hu et al., 2017), dissolved oxygen (DO) (Liu et al., 2015), primary productivity (Xiao et al., 2017), water table (Yang et al., 2013) and substrate availability (Venkiteswaran et al., 2013) also regulates the water column CH_4 production. In addition to these factors, one of the most important and decisive factors that substantially alters the $pCH_4(w)$ is the salinity of the water (Hu et al., 2017; Vizza et al., 2017; Welti et al., 2017), based on which aquaculture ponds are differentiated into freshwater and brackish water categories. An increase in salinity is often found to reduce $pCH_4(w)$ and hence lead to lower atmosphere-pond CH_4 fluxes (Yang et al., 2018b). Earlier studies exhibited that higher salinity leads to ion stress to methanogens (Chambers et al., 2013; Neubauer et al., 2013). It provides alternative electron acceptors like sulfate ion to the water medium, which in turn suppresses the methanogens from producing CH_4 in the water column (Laanbroek, 2010; Sun et al., 2013). So far, very few attempts have been made to analyze the difference in $pCH_4(w)$ dynamics in aquaculture ponds of varying salinity (Yang et al., 2018a, 2019) and most of these studies were carried out in highly saline mariculture ponds. Moreover, almost all of the studies where $pCH_4(w)$ dynamics of aquaculture ponds are characterized are carried out in such aquaculture ponds where daily fish feeds are provided. Comparisons between sewage-fed freshwater aquaculture ponds and oligohaline aquaculture ponds are not at all available at the present date.

Keeping in view this background, the present research work was carried out to expand the knowledge by quantifying atmosphere-pond CH_4 fluxes from sewage fed freshwater as well as an oligohaline aquaculture pond in the eastern part of India, located in East Kolkata Wetlands (EKW), and Minakhan block, within the Sundarban Biosphere Reserve (SBR), respectively (West Bengal, India). It is worth mentioning that aquaculture practice is steadily increasing in India and they encompass a substantial area (7,900 km^2) of India's total areal extent (Adhikari et al., 2012). However, endeavors of quantifying the atmosphere-pond CH_4 fluxes from such water bodies are very few (Adhikari et al., 2012; Pathak et al., 2013). This is why; this data set generated from this study is expected to contribute to the global database of CH_4 fluxes from aquaculture ponds. Atmosphere-pond CH_4 fluxes have been found to exhibit potential variations in different seasons (Heyer & Berger, 2000). Thus we have carried out sampling all-round the year covering three seasons [monsoon season (June, July, August, and September), pre-monsoon season (February, March, April, and May), and post-monsoon season (October, November, December, and January)] for this piece of research. We hypothesized that $pCH_4(w)$ dynamics and hence atmosphere-pond CH_4 flux would significantly vary between freshwater and an oligohaline aquaculture pond situated close and experience the same climate conditions due to different salinity. Following this hypothesis, the main aims of this research were to (i) characterize and compare the $pCH_4(w)$ and atmosphere-pond CH_4 fluxes from freshwater as well as an oligohaline aquaculture pond throughout an annual cycle, (ii) examine seasonal variations of CH_4 fluxes from the two aquaculture ponds and (iii) characterize the relationship between $pCH_4(w)$ and the associated biogeochemical factors, with special emphasis on salinity.

2 Methodology

2.1 Study Sites

The EKW (Fig. 1) lies on the east of the Kolkata metropolis. Being tagged as a 'wetland of international importance', EKW found its place in the list of Ramsar Sites in 2002. EKW is known to be the 'kidney of the city of Kolkata' because of its unique natural purification system (Kundu et al., 2008). This wetland complex stands tall as the largest conglomeration of human-built pisciculture ponds in the world.

EKW receives the wastewater load from the adjacent city of Kolkata and treats the water mass through activities like pisciculture, agriculture, and solid waste farms. In this way, the bulk sewage water load of Kolkata is naturally treated. The sewage canal flows into the Bidyadhari River that ends in the Bay of Bengal through the Sundarban mangrove ecosystem. According to the estimates of Aich et al. (2012), EKW has almost 250 functional aquaculture ponds that encompass 12 km^2. This system altogether produces substantial fish and vegetables that engage close to 0.5 million people and acts as the primary food source to the residents of the metropolis (Chaudhuri et al., 2012). EKW's performance has continued in this fashion since the late eighteenth century and it has been acting as an economic, ecosystem-resilient, and effective system of both aquatic and solid waste management (Kundu et al., 2008). These ponds are usually very shallow (1 to 1.5 m depth). The fishermen maintain a flat bottom in these ponds. These ponds vary in size from 10,000 m^2 to 100,000 m^2. The infrastructural characteristics of these ponds are portrayed in detail by Ghosh and Furedy (1984) and Ghosh (2005). The concept behind this natural engineering is discussed by Chaudhuri et al. (2007) and Chaudhuri et al. (2008). All the ponds within this system are mostly freshwater as a mixture of groundwater and sewage water is utilized for pisciculture in this setup.

The OHP which was sampled in this study is situated in the Minakhan community development Block situated almost 25 km to the east of EKW near the bank of Bidhyadhari River. This block is a part of the SBR, known to shelter the world's largest continuous stretch of mangrove forest. Local people of this region mainly practiced agriculture since the 1970s (Naskar, 1985), however, after the construction of dikes and embankments by the Department of Irrigation, Govt. of West Bengal people started switching for aquaculture with the help of the oligohaline water flowing through the Bidyadhari River (Bunting et al., 2017). Coupled rice–shrimp farming is quite popular in Minakhan. In the present date, the number of pisciculture ponds has observed a drastic increase in the Minakahn Block (Mondal & Bandyopadhyay, 2015).

2.2 Sampling Strategy

Samples were collected once a month covering the entire annual cycle from March 2018 to February 2019. Sampling was conducted in two aquaculture ponds; one situated within the EKW (freshwater pond) and the other in Minakhan Block (oligohaline pond) [hereafter referred to as FWP (22.514744 N, 88.482124 E) (depth: 1.2 m; area: ~ 45,000 m^2) and OHP (22.50693 N, 88.75452 E) (depth: 3 m; area: 54,000 m^2) respectively]. Samples were collected at every 2 h intervals over a complete diel cycle. The ambient temperature, wind velocity, and atmospheric pressure were measured by deploying a portable weather station. The water surface physicochemical parameters were monitored in-situ using typical probes. For other parameters like CH_4 concentration in water and air, chlorophyll–*a* (chl–*a*), and biochemical

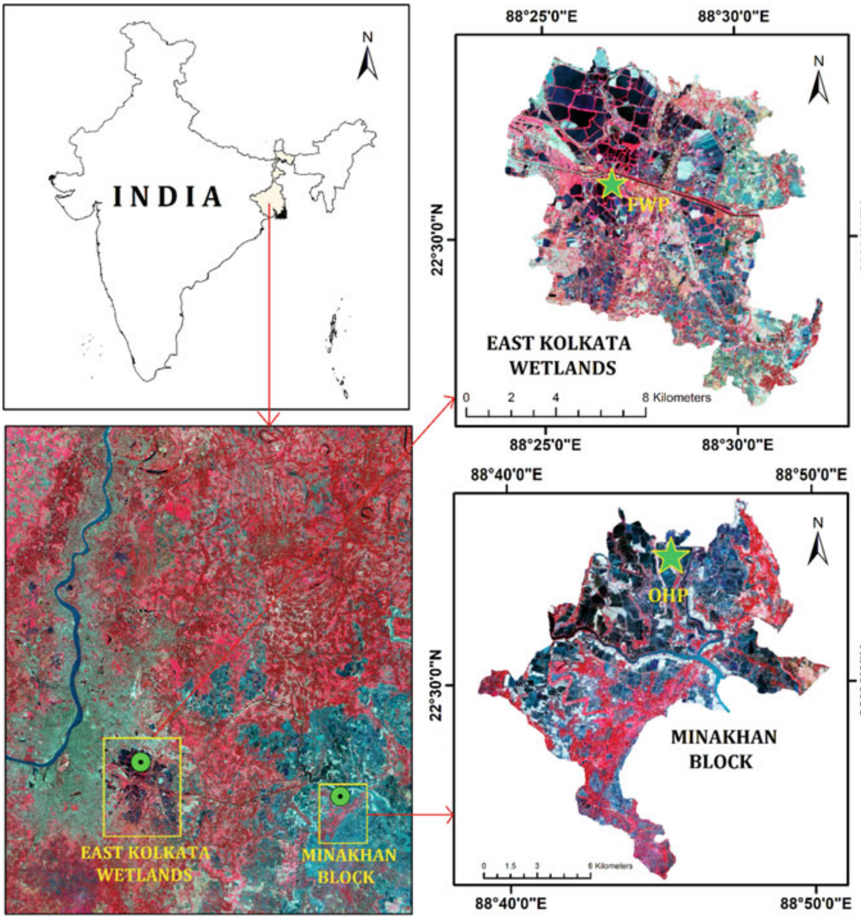

Fig. 1 The location map portraying the freshwater aquaculture pond (FWP) situated in the EKW and the oligohaline aquaculture pond (OHP) located in the Minakhan Block, West Bengal, India

oxygen demand (BOD), samples were retrieved and relocated to the laboratory after taking necessary measures of preservation.

2.3 Pisciculture in FWP and OHP

Oreochromis nilotica (Tilapia) and *Penaeus monodon* (Tiger prawn) was cultured in FWP and OHP respectively. Unlike other aquaculture ponds, no external fish feed is used in these ponds. In the EKW ponds, the organic detritus of the sewage are utilized by the fish as their food throughout the year. However, during the monsoon season, the sewage load sometimes becomes overdiluted and can not provide sufficient food to the fish. Bunting et al. (2010) mentioned that under such occasional circumstances, external fish feed is deployed by the fisher community. Quantifying the total quantity of feed or the feed conversion ratio is an almost impossible endeavor in EKW ponds, as the quality and quantity of sewage vary significantly over a short-term temporal scale (Chanda et al., 2019). Ponds of the Minakhan area utilize the oligohaline water Bidhyadhari River channelized through lock gates to maintain the salinity levels. The fisher community of this region practices variable stocking density and periodically harvest fish at new moon and full moon phases of the lunar cycle (Alagarswamy, 1995; De Roy, 2012).

2.4 Biogeochemical Analysis

2.4.1 Ancillary Environmental Measurements

Atmospheric temperature and wind velocity were recorded by a field-operable weather station (WS–2350, La Crosse Technology, USA). Electrical conductivity (EC) (precision: 1 μS/cm) and water surface temperature (precision: 0.1 ºC) were recorded by a digital EC meter (Thermo Scientific, Eutech, Germany). Dissolved oxygen (DO) (accuracy: ± 1%; precision: 0.01 mg l^{-1}) was recorded using a FiveGo portable F4 Dissolved Oxygen meter, Mettler Toledo. The DO readings were cross-checked by performing Winkler's titration. pH was monitored by an Orion PerpHecT ROSS Combination pH Micro Electrode fitted to a micro–pH data reader (Thermo Scientific, USA) (analytical resolution – 0.001; precision – 0.009). NBS scale technical buffer solutions were used to calibrate the glass-calomel electrodes. Nephelometric turbidity was measured with Eutech TN–100 turbidity meter. Determination of underwater photosynthetically active radiation (UWPAR) was carried out using LI–192SA, LiCor, USA (precision 0.1 μ mol m^{-2} s^{-1}) and a data reader (Li–250A, LiCor, USA). Quantification of chl–*a* was carried out using a spectrophotometer (precision 0.01 mg m^{-3}). The community respiration (CR) and gross primary productivity (GPP) in both the ponds were monitored by the standard light-bottle-dark-bottle incubation method. A 24-h incubation was followed to monitor the alterations in DO concentrations. BOD was estimated by incubating water samples from each pond at 27 °C for 3 days. Chl–*a*, BOD, CR, and GPP were quantified according to the protocols of APHA (2005).

2.4.2 Measuring CH_4 Concentrations in Water and Air

Surface water from FWP and OHP was directly filled in 40 ml glass ampoules equipped with a latex septum. No headspace was left during the sampling. Supersaturated $HgCl_2$ solution (100 μl) was pushed through the septum to cease all microbial activities till further analysis. Before analysis, half of the sample was injected out of the vial and 99.99% pure nitrogen gas was used to purge the remaining half to equilibrate the sample. The samples were equilibrated for 2 h. A Hamilton syringe was used to collect the headspace gas (5 ml). The collected gas was flown through a gas chromatograph (GC) (Systronics GC–8205) to estimate CH4 concentrations. The uncertainty in estimation was ± 2.9%. The carrier gas was pure nitrogen and the retention time for CH_4 was 37s. Moisture removal was done from the system by enhancing the injector temperature to 105 °C. The GC was regularly calibrated by reference standard CH_4 gas of known concentrations. A battery-operated pump was attached to a glass sampling bulb to draw in air samples from above the pond water interface. The glass bulbs were carefully evacuated and washed with distilled water before sampling. While bringing the air samples to the laboratory, parafilm coverings were used to seal the knobs and outlets. These samples were analyzed in GC using the same method discussed above.

2.4.3 Air–water CH_4 Flux Estimation

pCH_4(w) and pCH_4(a) were transformed to concentrations of CH4 in surface water (CH_4wc) and air (CH_4ac) as per the Eqs. (1) and (2) (Morel, 1983) and (3) (Lide, 2007).

$$CH_4wc = K_H \times pCH_4(w) \tag{1}$$

$$CH_4ac = K_H \times pCH_4(a) \tag{2}$$

$$\begin{aligned} \ln K_H = &-115.6477 + 155.5756/(T_K/100) + 65.2553 \\ &\times \ln(T_K/100) - 6.1698 \times (T_K/100) \end{aligned} \tag{3}$$

where K_H stands for the gas partition coefficient of CH_4 in water at sampling temperature, expressed in mole l^{-1} atm^{-1}, and T_K refers to the temperature (Kelvin).

The CH_4 flux is estimated as per Eq. (4) (MacIntyre et al., 1995).

$$CH_4Flux\left(mg\ m^{-2}h^{-1}\right) = k_x(CH_4wc - CH_4ac) \tag{4}$$

where k_x denotes the mass transfer coefficient (cm h^{-1}) and it is computed according to Eq. (5) (Wanninkhof, 1992)

$$k_x = k_{600} \times (S_c/600)^{-x} \tag{5}$$

where S_c is the Schmidt number for CH_4. It depends on water temperature as per Eq. (6). k_{600} is computed from the wind velocity (U_{10}), as per Cole and Caraco (1998) (Eq. 7) and 'x' = 0.66 for wind speed $\leq$ 3 m s^{-1} and 'x' = 0.5 for wind speed > 3 m s^{-1}.

$$S_c = 1897.8 - 114.28 \times T + 3.290 \times T^2 - 0.039061 \times T^3 \quad (6)$$

$$k_{600} = 2.07 + \left(0.215 \times U_{10}^{1.7}\right) \quad (7)$$

2.4.4 Statistical Computations

We carried out a one-way analysis of variance (ANOVA) to test whether the seasonality exhibited by all the parameters in each of the ponds is statistically significant or not. Independent samples Student's t-test was applied to examine the difference in the average of all the parameters between FWP and OHP. Pearson correlation coefficients were computed to study the relationship between $pCH_4(w)$ and the measured physicochemical parameters. We used the SPSS version 16.0 (SPSS, Inc., USA) to carry out these analyses. 95% confidence level ($p < 0.05$) was set as the threshold in this study to determine the statistical significance.

3 Results

3.1 Variability of Physicochemical Parameters

Seasonal mean pH values were higher in OHP compared to FWP in all the seasons [pre–monsoon: 8.189 ± 0.096 (FWP) and 8.291 ± 0.108 (OHP); monsoon: 8.030 ± 0.066 (FWP) and 8.071 ± 0.068 (OHP); post–monsoon: 8.187 ± 0.089 (FWP) and 8.273 ± 0.122 (OHP)] (Table 1). The difference in seasonal pH between OHP and FWP were significant in all the seasons (pre–monsoon: $t = -4.9$, $p < 0.001$; monsoon: $t = -3.0$, $p = 0.003$; post–monsoon: $t = -3.9$, $p < 0.001$). The seasonal variability in pH within FWP ($F = 55.7$, $p < 0.001$) and OHP ($F = 69.3$, $p < 0.001$) were also statistically significant (Fig. 2a).

The EC values were also significantly different in OHP and FWP in all the seasons (see Table 1) with almost 5 to 7 times higher values in OHP compared to FWP. EC varied in FWP from 434 $\mu S\ cm^{-1}$ to 1403 $\mu S\ cm^{-1}$, whereas, in OHP it varied from 3018 $\mu S\ cm^{-1}$to 6267$\mu S\ cm^{-1}$. The seasonal variability in EC was statistically significant in both FWP ($F = 46.1$, $p < 0.001$) and OHP ($F = 30.8$, $p < 0.001$) with considerably lower values during monsoon season compared to the other two seasons (Fig. 2b).

The seasonal mean water temperature was found highest during the monsoonal months, followed by the pre-monsoonal months and the lowest was observed during the post-monsoonal months. The seasonal variability in water temperature was statistically significant in both FWP ($F = 86.8$, $p < 0.001$) and OHP ($F = 82.5$, $p < 0.001$). However, water temperature did not exhibnit any statistical difference between FWP

Table 1 Mean ± standard deviation of all the parameters observed in the FWP and the OHP during the three seasons

Parameters	Pre-monsoon		Monsoon		Post-monsoon	
	FWP	OHP	FWP	OHP	FWP	OHP
pH	8.189 ± 0.096 (7.998 – 8.375)	8.291 ± 0.108 (8.088 – 8.504)	8.030 ± 0.066 (7.904 – 8.181)	8.071 ± 0.068 (7.977 – 8.214)	8.187 ± 0.089 (8.023 – 8.370)	8.273 ± 0.122 (8.063 – 8.482)
Conductivity (µS cm^{-1})	1043 ± 212 (706 – 1403)	5393 ± 536 (4706 – 6267)	814 ± 253 (434 – 1205)	4351 ± 1173 (3018 – 6101)	667 ± 60 (555 – 782)	4219 ± 519 (3393 – 4873)
Water temperature (°C)	30.7 ± 4.1 (23.1 – 37.9)	30.7 ± 4.2 (22.8 – 37.5)	34.8 ± 1.5 (32.1 – 38.0)	34.9 ± 1.6 (32.3 – 41.3)	25.6 ± 4.0 (19.0 – 32.2)	25.6 ± 4.1 (17.9 – 32.4)
DO (mg l^{-1})	8.3 ± 1.4 (6.1 – 11.2)	9.4 ± 1.5 (6.7 – 12.8)	8.0 ± 1.3 (5.9 – 10.5)	8.0 ± 1.3 (5.6 – 10.5)	9.1 ± 1.5 (6.3 – 12.1)	9.8 ± 1.4 (6.8 – 12.4)
UWPAR (µmol m^{-2} s^{-1})	6.5 ± 2.9 (0.9 – 12.1)	7.4 ± 3.5 (1.3 – 15.5)	7.0 ± 2.9 (2.1 – 11.5)	9.0 ± 4.0 (2.3 – 16.4)	2.8 ± 1.7 (0.4 – 6.6)	3.8 ± 1.6 (1.2 – 7.1)
BOD (mg l^{-1})	12.8 ± 0.9 (11.4 – 14.3)	8.3 ± 0.6 (7.1 – 9.2)	12.4 ± 1.5 (10.3 – 14.7)	7.9 ± 0.7 (6.9 – 9.1)	10.4 ± 0.5 (9.4 – 11.2)	7.4 ± 0.5 (6.5 – 8.1)
Chl-*a* (mg m^{-3})	40 ± 4 (32 – 46)	29 ± 3 (24 – 35)	34 ± 6 (24 – 42)	30 ± 5 (24 – 38)	35 ± 4 (28 – 41)	27 ± 4 (20 – 34)
Turbidity (NTU)	42.8 ± 3.0 (37.9 – 47.5)	31.4 ± 2.9 (27.6 – 37.2)	38.2 ± 5.2 (30.5 – 46.9)	28.9 ± 3.5 (23.5 – 34.7)	37.9 ± 3.4 (32.6 – 43.8)	31.2 ± 2.8 (26.5 – 35.4)
GPP (gO_2 m^{-2} d^{-1})	5.6 ± 0.5 (4.9 – 6.5)	5.0 ± 0.3 (4.3 – 5.4)	5.5 ± 0.5 (4.5 – 6.2)	5.1 ± 0.2 (4.6 – 5.5)	5.6 ± 0.3 (5.2 – 6.4)	5.7 ± 0.2 (5.4 – 5.9)
CR (gO_2 m^{-2} d^{-1})	22.2 ± 3.4 (17.9 – 27.4)	16.1 ± 1.1 (14.2 – 17.5)	28.3 ± 1.5 (25.9 – 30.5)	17.3 ± 0.7 (16.3 – 18.5)	23.6 ± 2.2 (20.5 – 27.5)	14.7 ± 1.3 (12.9 – 16.4)
pCH_4(w) (µatm)	8.53 ± 2.36 (4.75 – 14.38)	5.57 ± 1.33 (3.46 – 9.15)	8.83 ± 2.98 (5.18 – 14.50)	6.04 ± 2.99 (2.02 – 13.59)	6.97 ± 1.84 (3.80 – 12.46)	4.59 ± 2.30 (1.32 – 10.69)

(continued)

Table 1 (continued)

Parameters	Pre-monsoon		Monsoon		Post-monsoon	
	FWP	OHP	FWP	OHP	FWP	OHP
pCH_4(a) (μatm)	1.866 ± 0.007 (1.854 – 1.881)	1.861 ± 0.009 (1.843 – 1.880)	1.872 ± 0.007 (1.858 – 1.887)	1.867 ± 0.007 (1.855 – 1.888)	1.863 ± 0.006 (1.850 – 1.875)	1.860 ± 0.006 (1.849 – 1.871)
K_{600}	4.29 ± 0.35 (3.79 – 4.60)		4.76 ± 0.36 (4.24 – 5.06)		3.86 ± 0.41 (3.44 – 4.34)	
CH_4 Flux (mg m^{-2} h^{-1})	23.1 ± 14.7 (5.3 – 72.2)	12.9 ± 8.0 (2.9 – 40.0)	32.4 ± 17.7 (12.3 – 78.9)	20.7 ± 18.8 (0.7 – 97.6)	11.6 ± 6.8 (2.8 – 35.1)	6.4 ± 6.7 (-0.9 – 29.7)

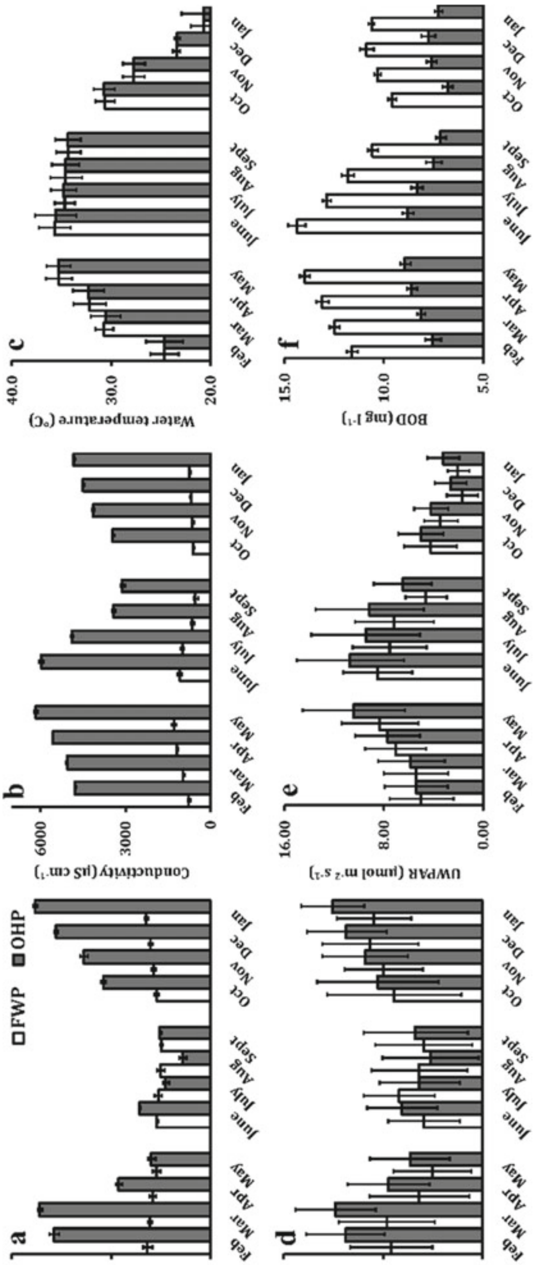

Fig. 2 The monthly observations of daily mean **a** pH, **b** electrical conductivity, **c** water temperature, **d** DO, **e** UWPAR, and **f** BOD observed in FWP and OHP throughout the year. The error bars indicate the standard deviation from the average value

and OHP in any of the seasons (pre–monsoon: t = −0.02, p = 0.981; monsoon: t = −0.14, p = 0.883; post–monsoon: t = −0.02, p = 0.986) (Fig. 2c).

The seasonal mean DO concentration was significantly higher in OHP (pre–monsoon: 8.3 ± 1.4 mg l^{-1}; monsoon: 8.0 ± 1.3 mg l^{-1}; post–monsoon: 9.1 ± 1.5 mg l^{-1}) compared to FWP (pre–monsoon: 9.4 ± 1.5 mg l^{-1}; monsoon: 8.0 ± 1.3 mg l^{-1}; post–monsoon: 9.8 ± 1.4 mg l^{-1}) during pre-monsoonal months (t = −3.8, p < 0.001) and post-monsoonal months (t = −2.57, p = 0.011), however, no significant difference (t = −0.05, p = 0.957) was observed during the monsoonal months. The seasonal difference in DO was statistically significant for both FWP (F = 7.8, p = 0.001) and OHP (F = 22.6, p < 0.001) (Fig. 2d).

Like pH and EC, UWPAR exhibited higher magnitudes in OHP compared to FWP in all the three seasons, however, the difference was not statistically significant in any of the three seasons (pre–monsoon: t = −0.99, p = 0.326; monsoon: t = −2.0, p = 0.052; post–monsoon: t = −1.9, p = 0.062). In monsoon and post–monsoon seasons the p–value was marginally higher than 0.05. However, the seasonal difference in UWPAR within FWP (F = 18.2, p < 0.001) and OHP (F = 16.4, p < 0.001) was statistically significant (Fig. 2e).

BOD in FWP was significantly higher than OHP in all the three seasons (pre–monsoon: t = 13.8, p < 0.001; monsoon: t = 9.3, p < 0.001; post–monsoon: t = 14.8, p < 0.001). Over the annual cycle, BOD ranged between 6.5 mg $l^{-1}$and 9.2 mg l^{-1} in OHP, whereas, it varied between 9.4 mg $l^{-1}$and 14.7 mg l^{-1} in FWP. The seasonal difference in BOD was also statistically significant within FWP (F = 18.2, p < 0.001) and OHP (F = 7.3, p = 0.002) (Fig. 2f).

3.2 *Variability of Primary Productivity-Related Parameters*

The chl–*a* concentration was higher in FWP compared to OHP in all the seasons, however, the difference was significant during pre–monsoon season (t = 7.4, p < 0.001) and post–monsoon season (t = 4.5, p < 0.001). During monsoon season the p–value was marginally not significant (t = 1.9, p = 0.059). The inter–seasonal variation in chl–*a* was statistically significant in case of FWP (F = 5.1, p = 0.012), however, in OHP there was no significant variation over the annual cycle (F = 1.8, p = 0.172) (Fig. 3a).

There was significant difference in turbidity between FWP and OHP in all the three seasons (pre–monsoon: t = 9.5, p < 0.001; monsoon: t = 5.1, p < 0.001; post–monsoon: t = 5.2, p < 0.001), with higher values in FWP compared to OHP. The seasonal mean difference in turbidity varied from ~ 6 NTU to ~ 11 NTU. The seasonal variability of turbidity was significant in FWP (F = 5.8, p = 0.007), however, like chl–a, it was not significant in OHP (F = 2.4, p = 0.110) (Fig. 3b).

The difference in GPP between FWP and OHP was statistically significant in pre–monsoon season (t = 3.6, p = 0.001) and monsoon season (t = 2.4, p = 0.024), however, during post–monsoon season the difference was not significant (t = −0.32, p = 0.747). Though the difference in GPP was significant in two seasons, in terms of

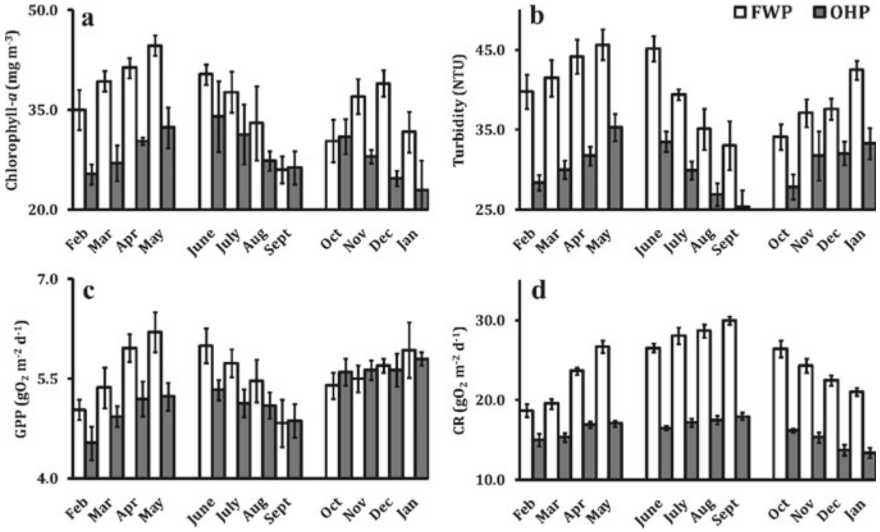

Fig. 3 The monthly variability of the daily mean **a** chl–*a*, **b** turbidity, **c** GPP, and **d** CR observed in FWP and OHP throughout the year. The error bars indicate the standard deviation from the average value

magnitude, the mean difference ranged from 0.4 gO_2 m^{-2} d^{-1} to 0.6 gO_2 m^{-2} d^{-1}. In contrast to chl–a, the inter–seasonal variation in GPP was not significant in FWP ($F = 0.31$, $p = 0.733$), however, it was statistically significant in case of OHP ($F = 22.6$, $p < 0.001$) (Fig. 3c).

Unlike GPP, CR was significantly higher in FWP compared to OHP in all the three seasons (pre–monsoon: $t = 5.8$, $p < 0.001$; monsoon: $t = 23.6$, $p < 0.001$; post–monsoon: $t = 12.1$, $p < 0.001$). The magnitude of difference varied from 6gO_2 m^{-2} d^{-1} to 11gO_2 m^{-2} d^{-1}, which was much higher than the difference in GPP between FWP and OHP. At the same time, the seasonal variation within FWP ($F = 20.1$, $p < 0.001$) and OHP ($F = 19.2$, $p < 0.001$) was also statistically significant (Fig. 3d).

3.3 Variability in $pCH_4(a)$, $pCH_4(w)$ and Air–Water CH_4 Flux

$pCH_4(a)$ varied over a very short range of 1.843 ppmv to 1.888 ppmv, however, it was marginally higher near FWP compared to OHP in all the three seasons (pre–monsoon: $t = 3.3$, $p = 0.002$; monsoon: $t = 3.7$, $p < 0.001$; post–monsoon: $t = 3.1$, $p < 0.001$). $pCH_4(a)$ also exhibited significant seasonal variation near FWP ($F = 21.5$, $p < 0.001$) as well as OHP ($F = 15.2$, $p < 0.001$) (Fig. 4a).

Seasonal mean $pCH_4(w)$ followed the trend monsoon > pre–monsoon > post–monsoon in both FWP and OHP, with significantly higher values in FWP compared to

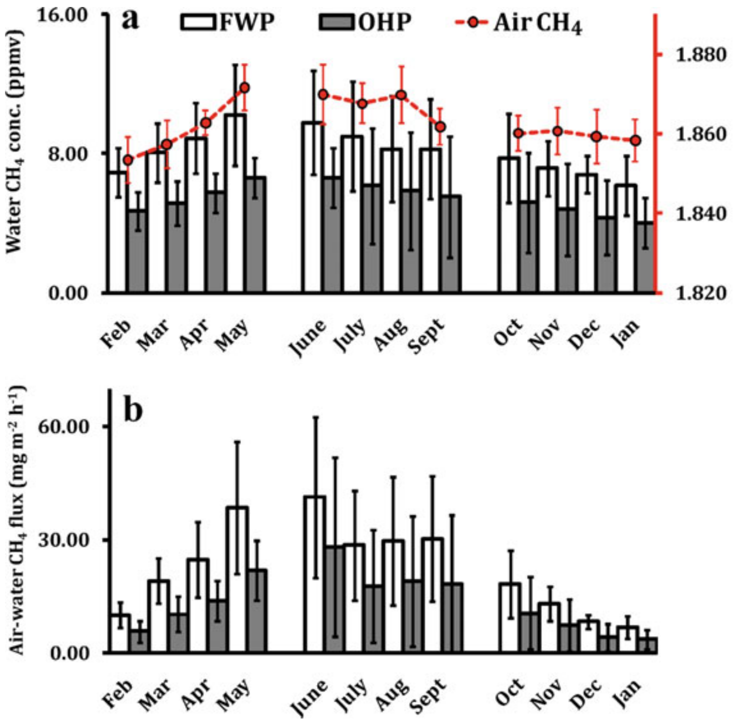

Fig. 4 The monthly variation of the daily mean (a) air CH_4 concentration [pCH_4(a)] and water CH_4 concentration [pCH_4(w)] along with (b) air–water CH_4 fluxes observed in FWP and OHP throughout the year. The error bars indicate the standard deviation from the average value

OHP (pre–monsoon: $t = 7.5$, $p < 0.001$; monsoon: $t = 4.6$, $p < 0.001$; post–monsoon: $t = 5.6$, $p < 0.001$). The seasonal difference in mean pCH_4(w) was statistically significant in both FWP ($F = 8.1$, $p < 0.001$) and OHP ($F = 4.9$, $p = 0.009$) (Fig. 4a).

Both FWP (22.4 ± 16.2 mg m^{-2} h^{-1}) and OHP (13.4 ± 13.6 mg m^{-2} h^{-1}) acted as source of CH_4 towards atmosphere throughout the year, with significantly higher values of CH_4 efflux from FWP compared to OHP in all the seasons (pre–monsoon: $t = 4.2$, $p < 0.001$; monsoon: $t = 3.1$, $p = 0.002$; post–monsoon: $t = 3.7$, $p < 0.001$). Mirroring the trend of seasonal mean pCH_4(w), air–water CH_4 flux also followed the same trend monsoon > pre–monsoon > post–monsoon in both FWP and OHP. The inter–seasonal difference in air–water CH_4 flux was statistically significant in both FWP ($F = 27.3$, $p < 0.001$) and OHP ($F = 15.9$, $p < 0.001$) (Fig. 4b).

3.4 Relationship Between $pCH_4(w)$ and Biogeochemical Variables

pH exhibited significant negative relationship with $pCH_4(w)$ in both FWP ($r = -0.62$, $p = 0.031$) and OHP ($r = -0.68$, $p = 0.015$) (Fig. 5a). EC showed significant positive relationship with $pCH_4(w)$ in FWP ($r = 0.72$, $p = 0.008$), however, in OHP the relationship was not significant ($r = 0.38$, $p = 0.220$) (Fig. 5b). Water temperature exhibited very strong positive relationship with $pCH_4(w)$ in both FWP ($r = 0.91$, $p < 0.001$) and OHP ($r = 0.94$, $p < 0.001$) (Fig. 5c). The relationship between DO and $pCH_4(w)$ was significantly negative in both FWP ($r = -0.86$, $p < 0.001$) and OHP ($r = -0.83$, $p = 0.001$) (Fig. 5d). Like water temperature, BOD also showed significant positive relationship with $pCH_4(w)$ in both FWP ($r = 0.81$, $p = 0.001$) and OHP ($r = 0.65$, $p = 0.021$) (Fig. 5e). Chl–a exhibited significant positive relationship with $pCH_4(w)$ in OHP ($r = 0.86$, $p < 0.001$), however, the relationship was not significant in case of FWP ($r = 0.50$, $p = 0.098$) (Fig. 5f). Turbidity and GPP did not exhibit any significant relationship with $pCH_4(w)$ (Fig. 5g,h). CR showed significant positive relationship with $pCH_4(w)$ in OHP ($r = 0.83$, $p = 0.001$), but in FWP it was marginally beyond the significance limit ($r = 0.56$, $p = 0.057$) (Fig. 5i).

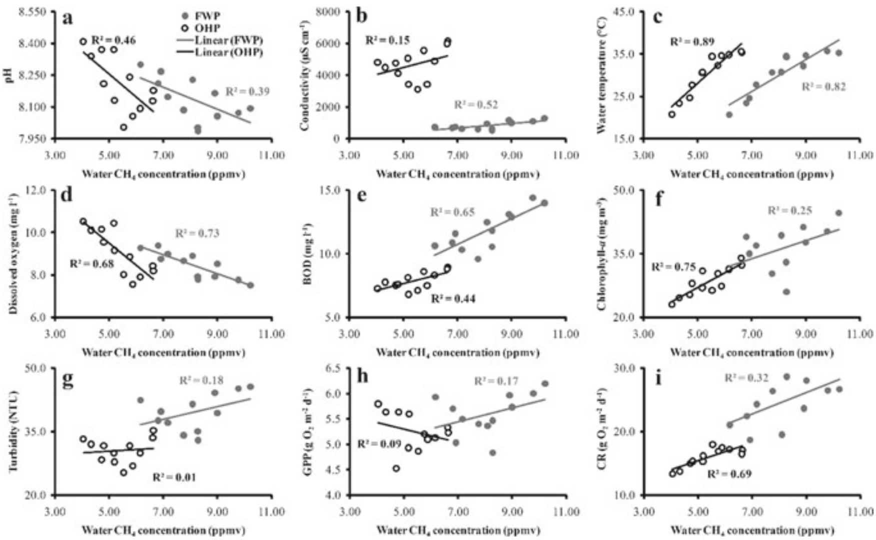

Fig. 5 The scatter plots displaying the relationship between monthly mean water CH_4 concentration [$pCH_4(w)$] and monthly mean **a** pH, **b** electrical conductivity, **c** water temperature, **d** DO, **e** BOD, **f** chl–*a*, **g** turbidity, **h** GPP, and **i** CR. Linear trend lines along with the goodness of fit (R^2) are shown separately for FWP and OHP

3.5 *Diurnal Variation in $pCH_4(w)$ and Atmosphere-Pond CH_4 Flux*

During all the seasons the $pCH_4(w)$ and hence the atmosphere-pond CH_4 efflux exhibited a steady increase from dawn till noon and the peak was observed during 1400 h to 1600 h (Fig. 6). During night time both the $pCH_4(w)$ and the atmosphere-pond CH_4 efflux was much lower compared to the day time.

4 Discussion

Analyzing the results it can be observed that OHP had significantly lower $pCH_4(w)$ and atmosphere-pond CH_4 fluxes compared to FWP all-around the year. In terms of physicochemical variables, the difference in salinity was the major reason behind choosing these two ponds and comparing their dissolved CH_4 dynamics. EC values in OHP were substantially higher than FWP throughout the year and this could be the most crucial factor which led to lower $pCH_4(w)$ in OHP due to reduced methanogenesis; as also observed in earlier studies like Poffenbarger et al. (2011) and Welti et al. (2017). Thus we could accept our hypothesis that a difference in salinity (or EC) leads to a difference in $pCH_4(w)$ and atmosphere-pond CH_4 fluxes between OHP and FWP. However, unlike previous studies like Cotovicz et al. (2016)

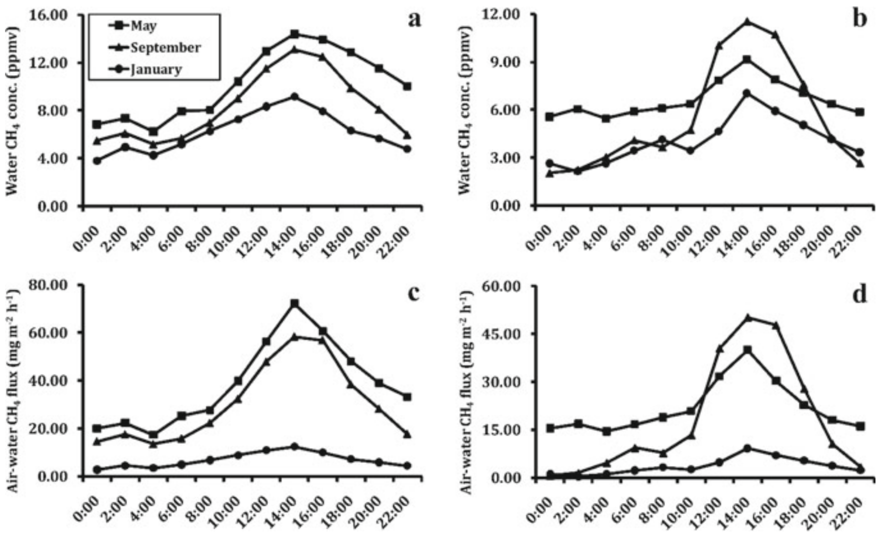

Fig. 6 The diurnal variability of water CH_4 concentration [$pCH_4(w)$] in **a** FWP and **b** OHP and the diurnal variability of atmosphere-pond CH_4 flux in **c** FWP and **d** OHP in May (pre-monsoon season), September (monsoon season) and January (post-monsoon season)

and Yang et al., (2018a, 2019), no significant negative relationship was observed between EC and $pCH_4(w)$ in neither FWP nor OHP. This shows that there are some other factors as well which are regulating the $pCH_4(w)$ in these two ponds apart from EC.

Water temperature has been regarded as one of the crucial factors which govern both methanogenesis (Inglett et al., 2012; Yang et al., 2015b) and methane oxidation (Lofton et al., 2014; Osudar et al., 2015). In the present study, a strong positive association between water temperature and $pCH_4(w)$ was portrayed in both the ponds, and no significant difference was observed in water temperature as well between the two ponds. Hence it can be affirmed in both the ponds increase in water temperature aided methanogenesis by enhancing organic matter degradation and hence providing suitable labile substrates from which CH_4 is produced by microbial activity. Similar observations were made by Xiang et al. (2015) in coastal marshes and Yang et al. (2019) in aquaculture ponds. The difference in $pCH_4(w)$ magnitudes between FWP and OHP despite having the same water temperature further shows that methane oxidation is not prompted by the effect of temperature fluctuation, rather the intrinsic difference in water column substrates led to the difference in $pCH_4(w)$ between FWP and OHP as also observed by Roland et al. (2017).

Earlier studies emphasized that the growth and thriving of the methanogens are quite dependent on the pH of the aquatic column, and they prefer to grow at lower pH close to ~ 7.7 (Chang & Yang, 2003). The pH all over the annual cycle was significantly lower in FWP compared to OHP, which could have facilitated better growth of methanogens in FWP compared to OHP. This reason could be further ascertained as both the ponds exhibited significant negative relation between pH and $pCH_4(w)$, which showed that with decreasing pH, methanogens flourished and led to enhancement of $pCH_4(w)$. Datta et al. (2009) also recorded a similar negative association between pH and $pCH_4(w)$ while working in a rain-fed fish farming pond situated in Eastern India. Yang et al. (2018b) also observed a similar relationship in aquaculture ponds of China and attributed the reduced activity of methanogens behind such observations.

The present study also showed that OHP had significantly higher DO levels compared to FWP. This could be attributed to the lower turbidity and higher UWPAR in OHP which in turn facilitated a higher degree of autotrophic activities and hence higher production of DO compared to that in FWP. Several studies have observed that *Oreochromis nilotica* which is cultured in FWP is a fast-moving bottom feeder (Adeyemi et al., 2009; Jihulya, 2014; Njiru et al., 2004) and the strong fish movement in the sediment–water interface often causes enhanced turbidity (Chapman & Fernando, 1994; Frei & Becker, 2005). *Penaeus monodon,* on the other hand, being cultured in OHP is also known to be a bottom feeder but shrimps and prawns are usually more sluggish than fish species, hence the bottom churning due to their movement is expected to be quite less. This differential photosynthesis-induced difference in DO content between the two ponds could play a crucial role in having different $pCH_4(w)$ magnitudes between FWP and OHP. Kettunen et al. (1999) and Yang et al. (2013) reported that reduced DO levels promote methane production by enhancing anaerobic decomposition rates and at the same time lower DO levels reduce methane oxidation.

BOD serves as a proxy of biodegradable organic matter in any aquatic column and the present study observed significantly higher BOD in FWP compared to OHP. FWP utilizes sewage water to carry out fishing practice and since BOD concentration in city sewage remains very high, FWP reflected the higher levels of BOD (Sarkar et al., 2017). On the contrary, OHP utilizes the brackish water of the adjacent Bidhyadhari River, which though receives the sewage water of the Kolkata metropolis but the BOD levels are quite reduced when the sewage effluent reaches Bidhyadhari River after passing through EKW (Ghosh, 2018). Higher BOD in any aquatic ecosystem indicates the presence of the labile biodegradable substance and under reduced DO and lower pH levels and leads to a higher rate of methane emission [as also observed by Yang (1998) while working in the rivers and lakes of Taiwan].

The effect of lower DO and higher BOD was also reflected on the CR of the two selected ponds. Though both FWP and OHP showed CR magnitudes greater than the magnitudes of GPP, CR in FWP was significantly higher than OHP, which further indicated that the degree of net heterotrophy was substantially higher in FWP. Previous studies have clearly shown that there is a strong relationship between net heterotrophic conditions and supersaturation of CH_4, especially in small ponds like that of the chosen aquaculture ponds (Holgerson, 2015). It should be also mentioned in this regard, that chl–*a* concentrations were also substantially higher in FWP compared to OHP. Chl–*a* magnitude in any lentic ecosystem acts as a proxy of trophic status and provides an idea about the primary productivity in shallow lentic ecosystems (Liu et al., 2017; Yang et al., 2015a). Higher chl–*a* magnitudes indicate higher algal production rates which in turn consequences the creation of autochthonous organic substrates (Palma-Silva et al., 2013). Chl–*a* and GPP portrayed a positive (significant) relation with the pCH_4(w) clearly emphasizing that the autochthonous production of organic substrates facilitated methanogenesis (Flury et al., 2010; Furlanetto et al., 2012) and hence facilitated higher methane emission.

In terms of the annual mean magnitude of atmosphere-pond CH_4 efflux, the methane emission observed in this piece of research (FWP: 22.4 ± 16.2 mg m^{-2} h^{-1} and OHP: 13.4 ± 13.6 mg m^{-2} h^{-1}) was found higher than many of the recent measurements. Datta et al. (2009) observed a mean CH_4 emission of 2.5 mg m^{-2} h^{-1} from the refuge rain-fed ponds of Cuttack, India. In Chinese aquaculture ponds, most of the recent estimates exhibited lower magnitudes than those observed in the present study. Wu et al. (2018) observed a mean CH_4 emission of only 0.5 mg m^{-2} h^{-1}in the experimental farm of Nanjing Agricultural University, China. Yang et al (2018b) observed a mean CH_4 emission of 1.1 ± 0.9 mg m^{-2} h^{-1} and 10.5 ± 4.9 mg m^{-2} $h^{-1}$from the undrained and drained ponds of Shanyutan Wetlands, China. Yang et al. (2015a) recorded mean CH_4 efflux of 1.6 ± 0.5 mg m^{-2} h^{-1} from mixed polyculture ponds of China, whereas, from shrimp they observed a mean CH_4 emission rate of 19.9 ± 4.3 mg m^{-2} h^{-1} (which was higher than that observed in the OHP of the present study). However, very few studies like Yang et al. (2017) observed substantially higher effluxes (123 ± 48 mg m^{-2} h^{-1}) than the present estimates while working in the shrimp ponds near Min River Estuary, China. Thus in totality, it can be inferred that atmosphere-pond CH_4 fluxes from the aquaculture ponds of EKW and Minakhan Block were found higher than the recent observations being made throughout the world, especially in China.

4.1 Uncertainties and Scope for Future Studies

The present study implemented the bulk formula method and thus the estimation of atmosphere-pond CH_4 flux was carried out from the difference of CH_4 concentration between pond and atmosphere. This is why we could measure only the diffusive flux in this study. In the future, the chamber method should be deployed to characterize the CH_4 ebullition rates from this region. More aquaculture ponds of this region should be sampled based on different species being cultured, different depths, and so forth to draw a holistic CH_4 budget of this crucial region. In the present study, sampling was conducted in all the months of a calendar year. However, different stages of aquaculture should be distinctly studied as they usually exhibit different signatures of fluxes in several annual studies (Liu et al., 2016; Wu et al., 2018). In addition to these, the dissolved organic carbon should be measured in the future and the methane dynamics in the sediment–water interface should be also studied.

5 Conclusion

Analyzing all the results and outcomes of the present study, it can be concluded that partial pressure of CH_4 [$pCH_4(w)$] and hence atmosphere-pond CH_4 fluxes were much higher in the freshwater aquaculture ponds (FWP) of East Kolkata Wetlands compared to the oligohaline aquaculture ponds (OHP) of Minakhan Block, both being situated under the same climatic regime in eastern India. Higher salinity was found to inhibit methanogens which resulted in lower $pCH_4(w)$ in the OHP compared to FWP. The difference in fishing practice in the two ponds was also found to regulate the turbidity and hence the presence of photosynthetically active radiation in the two ponds. The higher turbidity in FWP led to lower dissolved oxygen levels and enhanced community respiration which in turn facilitated anaerobic conditions and thus the methanogen activity was much more in FWP compared to OHP. Aquaculture practice is becoming popular day by day in India, however, efforts of characterizing the methane fluxes from these ecosystems stand very few in the present date. The annual study revealed that the mean CH_4 emission observed in these sites of India was much higher than most of the recent estimates being carried out in the Chinese aquaculture ponds. Thus this study is expected to provide an impetus to carry out similar measurements in other aquaculture ponds of India to meet the present need of the hour and fill the data gap.

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Soil Loss Estimation Using Rainfall Erosivity and Soil Erodibility of RUSLE Model in the Jayanti River Basin (Jharkhand)

Md Safi and Dipankar Oraw

Abstract Jayanti river basin is selected as the study area for soil erosion estimation. Main objective of the study is the applicability of rainfall erosivity and soil erodibility to estimate soil loss and identify most intense zone of soil erosion. Primarily two factors i.e. rainfall erosivity and soil erodibility of RUSLE Model is used in GIS environment. For soil erosion estimation, daily, monthly or yearly average rainfall gives good rainfall erosivity value. If the other factors of RUSLE model such as slope-length, vegetation cover and land protection practices remain constant higher the R factor represents more vulnerable zone of soil erosion. The R value of Jayanti river basin represents different soil erosion intensity zone. On the basis of R value south-western side of the study area are more prone to soil erosion than other area. Soil erodibility is the susceptibility to erosion. Most of the northern part of the study area represents higher K value and more susceptible to soil erosion.

Keywords Rainfall erosivity · Soil erodibility · RUSLE model · Soil management

1 Introduction

Now a day's soil erosion is a global problem. Each and every year a huge amount of soil is eroded from the upper part of the soil. Like most countries in (sub) tropical and semi-arid climates, soil erosion by water (Overland and channelized) is a primary agent of land degradation in India too (Bhattacharyya et al., 2015, 2016; Lal, 2001). About 68.4% of the nation's degraded tracts experience accelerated soil erosion at rates greater than 10 t ha^{-1} yr^{-1} (NAAS, 2010). Natural causes as well as human activities make soil erosion more intensive and severe. One estimate put the loss of top soil by water action at 1200 m tones every year in India which costs Rs. 12,000 crores annually (Vohra, 1985). There are lots of models such as Universal

M. Safi (✉)
Department of Geography, Asansol Girls' College, Asansol 713304, West Bengal, India
e-mail: md.safi09@gmail.com

D. Oraw
Department of Geography, Triveni Devi Bhalotia College, Raniganj 713347, West Bengal, India

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Soil Loss Equation, (Wischmeier & Smith, 1965, 1978) Soil and Water Assessment Tool (Arnold & Fohrer, 2005), European Soil Erosion Model (Morgan et al., 1998) and Water Erosion Prediction Project (Flanagan et al., 2007) have been developed to estimate the soil erosion throughout the world. Revised Universal Soil Loss Equation is one of the widely used model which is propounded by K.G. Renard. Geographical Information System (GIS) enable users to analyze and manipulate the spatial data easily and it also helps users to identify the spatial locations vulnerable to soil erosion (Kamuju, 2016). The two factors rainfall erosivity (R) and soil erodibility (K) is being used in the study area in GIS environment.

The Jayanti river basin is selected as the study area because of Jayanti and its tributaries received a huge amount of rainfall in monsoon period and increasing human interference make the basin more vulnerable to soil erosion.

The main objectives of the study are to find out the R-value and K-value of the study area which reflects different soil erosion intensity zone. Identifying such soil erosion intensity zone is very necessary for better management of soil erosion of the study area.

2 Study Area

The study area Jayanti river basin is located in Jharkhand district and extends from N 24°5′54″ to N 24°17′21″ and E 86°23′03″ to E 86°46′59″.The total area of the study area approximately 544 SQ.KM. The Slope of the area is from west to south-east. Jayanti river is a tributary of Ajay river and joined with Ajay river near Siktia of Jharkhand. The two streams Jayanti Nala and Lahaswadaha form the Jayanti River. The source of the Jayanti Nala is Dundo Mouza (N 24° 15′10″ and E 86°24′11″) and elevation is 322 m. The source of the Lahaswadaha stream is Chagarkatta (N 24° 15′46″ and E 86°24′46″) and elevation is 327 m. The whole basin situated under Chotonagpur plateau. The average annual rainfall is almost 1100 mm of the study area and receives most of the monsoonal rain from June to September (Figs. 1, 2, 3 and 4).

3 Materials

For application of R and K factor to identify soil erosion intensity zone, training area is selected from google earth and also validated with continuous field survey. To calculate R-factor and K-factor as well as successful running of model, downloading of digital elevation model (DEM), rainfall data, soil data, making of thematic maps is necessary. DEM was prepared in ERDAS imagine and the thematic map was prepared in the ArcGIS environment.

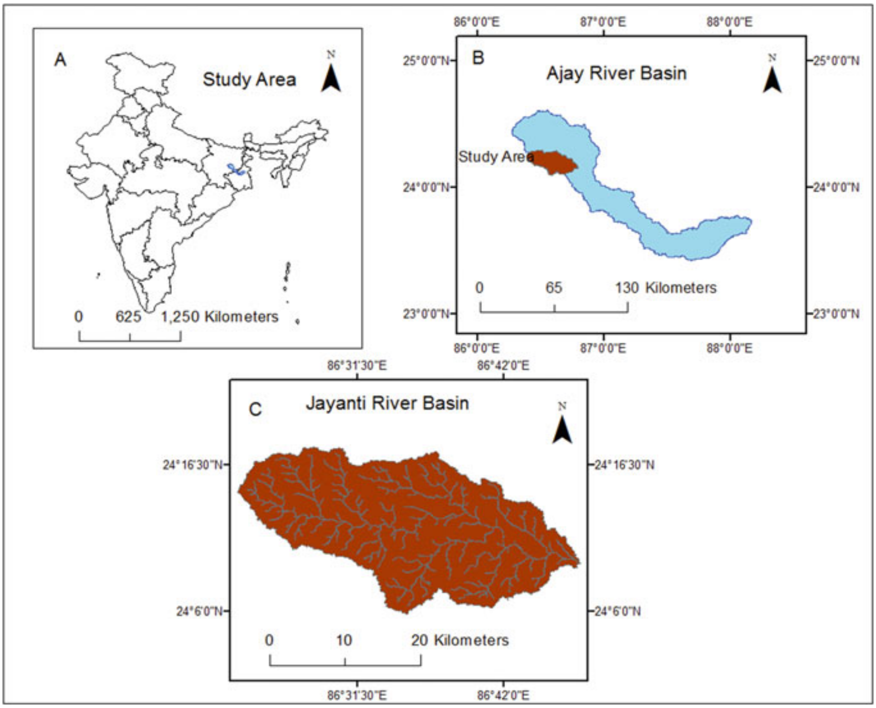

Fig. 1 Location of the study area

3.1 Dem

SRTM 30 m resolution DEM was downloaded from NASA Earth explorer.

3.2 Climatic Data

Climatic data was downloaded from NASA POWER of two rain gauge station Madhupur and Gandey. For preparation of R-factor map ten years average rainfall is calculated in raster calculator in spatial analyst tool.

3.3 Soil Data

Soil data is collected from Food and Agricultural Organization (FAO). There are two textural classes of soil that is sandy clay loam and loam.

Fig. 2 **a** Soil collection, **b** and **c** Soil erosion site, **d** Source of Jayanti River

3.4 RUSLE

In RUSLE model the R-factor and K-factor are most important factors. Rainfall erosivity is the external factor and soil erodibility is the internal factor. The equation for RUSLE model-

$$A = R*K*L*S*C*P$$

Here,

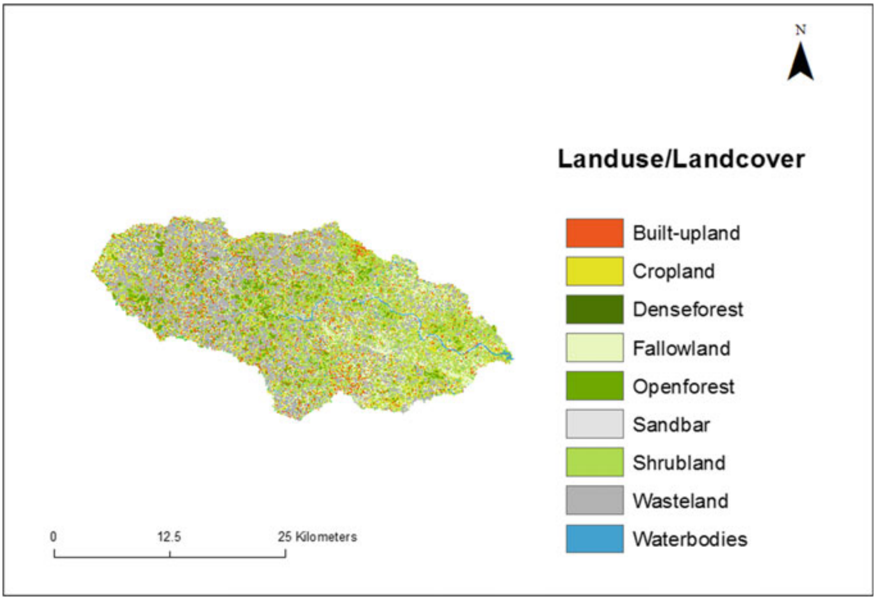

Fig. 3 Landuse/Landcovr map of the study area

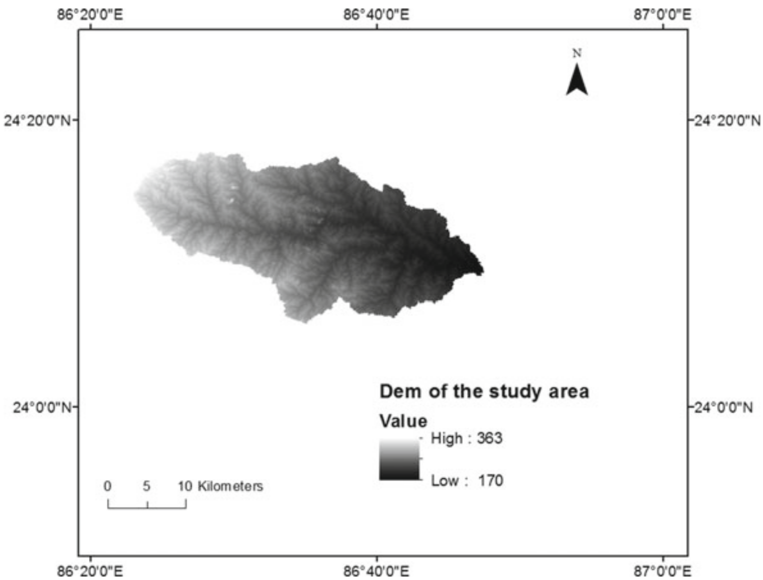

Fig. 4 Dem of the study area

A = Annual average soil loss in tons/ha/yr.
R = Rainfall-runoff erosivity factor
K = Soil erodibility factor
L = Slope length factor
S = Slope steepness factor
C = Cover management factor
P = Support practice factor

Rainfall erosivity

The value of EI for a given rainstorm equals the product of total storm energy (E) times the maximum 30-min intensity (I_{30}) (Renard, 1997). Most of the time the storm energy data rarely available, that's why monthly or annual average data are used for R-factor calculation. Here we used the ten years rainfall data. To calculate R-factor the given formula is being used for Jharkhand.

R = 81.5 + 0.375*MAP (Babu et al., 2004)

where,
R = Rainfall erosivity
MAP = Mean annual precipitation

Soil erodibility

Soil erodibility is the internal characteristic of a soil mainly soil structure, texture, permeability capacity, organic matter etc. It can be said that erodibility is the reflection to the external forces. The following formula (Renard et al.) for calculating K-factor is being used.

$$K = \left(2.1 \times 10^{-4}(12 - OM)M^{1.14} + 3.25(s - 2) + 2.5(p - 3)\right)/100$$

M = (%silt + %sand)*(100—%clay)
S = Structure code
P = Permeability code

4 Results and Discussion

There are two rain gauge stations in the study area. One Madhupur station located under the study area and another station Gandey located just outside of the study area. In India most of the rainfall occurred during June to September as it is monsoonal rainfall. These four months are prime time for soil erosion. The ten years average rainfall of the two stations after being putted in the formula and it shows the range of R-factor value from 4856.66 MJ mm ha^{-1} h^{-1} yr^{-1} to 5053.845 MJ mm ha^{-1} h^{-1} yr^{-1}. It can be said that If the other factors mainly slope length and steepness, vegetation cover, conservation practices remain constant higher the value of R factor greater the soil erosion intensity. According to calculated R-value North-Western side of the study area represents higher R value than the other area and also may represents more prone to soil erosion. In Fig. 5B the white patches represents more R value and

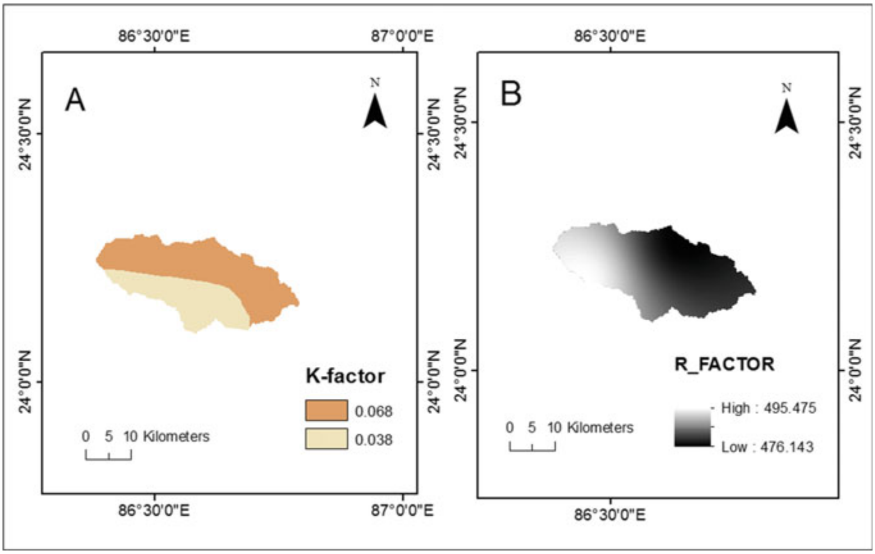

Fig. 5 **a** Soil erodibility map, **b** Rainfall erosivity map

more prone to erosion and black patches represents low R value and less susceptible to erosion.

After calculating the formula the highest K value is 0.068 and the lowest K value is 0.038. There are two types of soil namely Eutric Nitosols and Chromic Cambisols in the study area. The textural class of Eutric Nitosols is sandy clay loam and Chromic Cambisols is loam. The percentage of sand, silt, clay and organic matter of Eutric Nitosols is 68.4, 10.5, 21.2, 0.6 and Chromic Cambisols is 40.1, 21.5, 38.4, and 1.44 respectively. In generally the presence of silt content in soil is very important for determination of K factor as the silt reduces the amount of permeability and increases surface runoff which ultimately leads more soil erosion. Such a way different structure and organic content controls the permeability as well as soil formation which are responsible for the variation of K-factor. If other factors (i.e. rainfall erosivity, slope length and steepness, vegetation cover and land conservation factors) remain constant same thing can be said for calculating K-factor i.e. greater the value of K-factor more prone to soil erosion and lower the value of K lesser the probability of soil erosion. There are two textural classes of soil in the study area, sandy clay loam and loam (Fig. 5A). The deep brown color represents sandy clay loam and on the basis of K-factor it represents more susceptible to erosion as it shows higher K-value. The light color represents loam soil and less susceptible to erosion as it represents low K-value.

Higher elevation, higher intensity of rainfall in just two or three months, higher slope and rocky surface make more surface flow, speedy and unobstructed surface flow because of deforestation and increasing human construction all these factors leads to more intense soil erosion in the study area.

5 Conclusion

We assess the applicability of R and K factor on soil erosion estimation with GIS environment. The whole region of Jayanti river basin is a plateau fringe. The range of R-factor value vary from 4856.66 MJ mm ha^{-1} h^{-1} yr^{-1} to 5053.84 MJ mm ha^{-1} h^{-1} yr^{-1} and the K factor range from 0.038 to 0.068. After field investigation it is very clear that most of the study area is not only influenced by R and K factor but human construction, land use pattern, deforestation also modified the soil erosion. Undulating slope and deforestation makes R and K factors more intense. Not only the R and K factor of RUSLE model but also the application of other factors such as vegetation cover, slope-length, and land conservation practices are very necessary for estimation of soil erosion of Jayanti river basin. The collective application of RUSLE model, intensive field survey will reflect the actual zone of soil erosion which will ultimately help for better soil erosion management.

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Geo-Spatial Assessment of Irrigation-Induced Groundwater Depletion and Groundwater Prospect in an Alluvial River Basin of West Bengal

Soumya Kundu and Sandipan Ghosh

Abstract The present chapter tries to emphasize on the groundwater-stress condition of an alluvial river basin (Khari River) which is escalated by the anthropogenic extraction of water resource in the Purba Bardhaman district of West Bengal. With the rapid development of irrigation technology, high crop yield and water consumed rice varieties, and high cropping intensity (>250%), the farmers of the basin have been faced to go for deeper and deeper underground aquifers (>180 m bgl) to extract water for summer rice (Boro) cultivation. Due to intensive exploitation of groundwater (annual drafting of 103,667.61 ham groundwater) five semi-critical blocks (viz., Mangolkote, Bhatar, Manteswar, Purbasthali II and Memari II) of the basin have experienced significant pre-monsoon fall (0.871–1.322 m yr^{-1}) and post-monsoon fall (0.445 to 2.267 m yr^{-1}) of groundwater level. The study shows that in the semi-critical blocks about 738.6 to 4130.8 hect land should be covered under irrigated water on each day of pre-monsoon summer months (for Boro rice cultivation). The required deep tube well pump discharge (operating maximum 10 h per day) can escalate up to 37,281 to 178,141 m^3 hr^{-1} to moisture those lands during Boro harvesting. The geo-spatial analysis reveals that the monsoon recharge rate of –3.72 to + 2.38 m yr^{-1} is observed between August 2019 and 2020 in the basin area. The groundwater potential zone map (using Analytical Hierarchal Process) shows four principal categories of groundwater prospect in the basin, viz., poor (0.08%), moderate (5.78%), good (68.96%) and very good (25.18%). The active floodplain zone of eastern part (Katwa I and II, Purbasthali I and II) and the active channel part of Khari have very high potential for groundwater resource (1984,416 m^3 per year). It is finally stated that through proper water management system or utilisation (flood water as resource), the 1174 km^2 area of land (covering Mangolkote, Bhatar, Manteswar, Bardhaman I and II and Katwa I blocks) can source of massive groundwater recharge (611,000 to 640,000 ham) during the monsoon rainfall.

Keywords Groundwater recharge · Stage of groundwater development · Analytical hierarchal process · Groundwater potential zone · Boro rice · Khari river basin

S. Kundu · S. Ghosh (✉)
Department of Geography, Chandrapur College, Purba Bardhaman, West Bengal, India
e-mail: sandipanghosh19@gmail.com

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1 Introduction

Groundwater resource of India is under increasing risk from escalating over-development, over-extraction and pollution, due to increasing population pressure, increasing standard of living, growing span of irrigated area, industrialization and a lack of proper management to match the demands and consumption patterns with the natural resource base (Romani, 2006; Villholth & Sharma, 2006). Globally average water stress is 11%, and India is among the 31 countries experiencing water stress in the range of 25–70% (DEMO, 2021). With 18% of world's population and only 4% of world's water resources, India is already a water-stressed nation and per capita annual water availability (i.e., 1720.29 m^3) is declining rapidly (ERI, 2021). The Ganges Basin (drainage area of 1,089,370 km^2) is one of the most populated river basins in the world with a population density of 550 persons km^{-2} and groundwater availability of 135.3 bcm (billion m^3) (Rajmohan & Prathapar, 2013). The grave satiation is that in the basin the demand of water in all sectors (irrigation, domestic, industrial, power and others) can reach up to 1093 bcm in 2025 and 1447 bcm in 2050 (DEMO, 2021). The vagaries of monsoon rainfall, dried-up of rivers and inadequacy of water holding and preservation, the projected deficit of water in near future are highlighted in many articles to indicate stress on groundwater under a fast-growing population pressure of India (Bhanja et al., 2017; Brahma, 2021; Konar & Dey, 2015; MacDonald et al., 2016; Mukherjee, 2009; Ray & Shekhar, 2009; Ray et al., 2008; Sahoo et al., 2021).

The sudden boom in groundwater development (for high yield *Boro* rice cultivation and food crop replacement by cash crop) has triggered the secular and seasonal groundwater level declines, wells running dry and well failures, rising energy use and pumping costs, weakening drought protection, growing salinity in coastal areas and health hazards due to arsenic, fluoride etc., and these impacts are seriously threating the long-term sustainability of the use of the resource (CGWB, 2021a; Mukherjee, 2009). Satellite-based estimates (2002–2016) indicate rapid depletion in eastern and northern zones of India at a rate of -1.16 ± 0.35 and -1.40 ± 0.14 cm yr^{-1} (-14.02 ± 1.37 and -14.49 ± 4.36 km^3 yr^{-1}) respectively. Out of 6607 number of assessed administrative units (Blocks/Taluks/Mandals/Districts etc.), 1071 units are over exploited, 217 units are critical and 697 are semi-critical groundwater stressed situation (MWR, 2017). In India all total 48,673 C.D. blocks are marked as over exploited blocks, and about 233,240 over-exploited blocks are found in the region of Quaternary - Tertiary alluvium (Dhiman, 2012). The pressure on groundwater resource was evident from the fact that the number of groundwater abstraction structures (shallow and deep tube wells) have increased to about 21 million in last two decades with an estimated annual groundwater withdrawal of about 221 bcm (Dhiman, 2012).

In West Bengal the irrigated area under surface water sources as percentage of gross cropped area (GCA) has declined from 42.63 to 34.38%, and irrigated area under groundwater as percentage of GCA has increased from 0 to 2.27% in between 1995–1996 to 2010–2011 (Konar & Dey, 2015). In 2000, the total water requirement of the State stood at 10.85×10^4 million m^3 showing a deficit of 38%, and it raised up to 48% in 2011 (CGWB, 2021a; Ray et al., 2008). The water scarcity is reflected in a much more severe way where the annual per capita water availability comes down drastically from 1528 m^3 in 1971 to 844 m^3 in 2000 (Ray et al., 2008). West Bengal has the second highest number of villagers (78 lakh population, out of 411 lakh population) who do not have access to safe drinking water in India, second only to Rajasthan (Hindustan Times, 2017). Over the period 1993–2021, the number of dark blocks (groundwater development is less than 65%) increased from 1 to 76 (increased rate 2.67 per year within 28 years), though the State gets sufficient monsoon rainfall (1234–4316 mm annually), including good network of drainage and vast reserve of aquifers (up to 300 m below ground level) (CGWB, 2021b). By comparing, the water level data for April mean (1997–2006) with depth of water level (DWL) data of April, 2007, the entire state of West Bengal showed the rise (43.17%) and fall (58.11%) in water level (Ray & Shekhar, 2009). In Purba and Paschim Bardhaman districts at present 11 C.D. Blocks are recognized as semi-critical water stress condition, covering 2643.04 km^2 of areal coverage, and 51% of wells experience a sharp decline of water-level of range 0–2 m bgl (maximum 4 m bgl) in pre-monsoon months. Few important articles (Bandyopadhyay et al., 2014; Das & Pal, 2020; Das et al., 2021; Halder et al., 2020; Pal et al., 2020; Sar et al., 2015; Sikdar et al., 2019) were already published to portray the water stress situation and groundwater potentiality mapping in the districts of West Bengal, but there is a need to unearth the emerging issues, factors and spatio-temporal pattern of groundwater depletion and groundwater potentiality in a hydrologic basin-scale approach. Therefore, in this book chapter we are tried to analyse the key dimensions of human-induced water stress condition in the alluvial parts of the western Bengal Basin, covering the Khari River Basin of Purba Bardhaman district (a rice dominated region).

2 Study Area

The Khari River Basin (a western sixth order sub-basin of Bhagirathi-Hooghly River system) is encompassed by latitude 23° 09′ 56.59′′ N–23° 38′ 53.41′′ N and longitude 87° 29′ 38.53′′ E – 88° 20′ 07.48′′ E, covering entire Purba Bardhaman district of West Bengal (Fig. 1). Geographically, the estimated basin area is near about 2210 km^2 which is approximately 40.8% of district area (5416 km^2), and sixteen blocks (viz., Ausgram I and II, Galsi I and II, Bhatar, Bardhaman I and II, Memari I and II, Kalna I, Katwa I and II, Pubasthali I and II, Mangolkote and Mansteswar) are included in the basin hydrological area. According to 2011 census the total population of the district was 48,35,532, and in the sixteen blocks the population density (Fig. 2c) varied from 634 persons km^{-2} (Bhatar) to 1394 persons km^{-2} (Katwa I and Purbasthali I). In the basin the estimated areal coverage (2020) of agriculture and settlement is 1174 km^2 and 382 km^2 respectively (Fig. 2d). Irrigated agricultural field and Boro rice cultivation are depicted in selected field photographs (Fig. 3). The climate is sub-tropical and warm-humid (72% of annual rainfall occurred in between June–September) with short winter season, having average temperature of 28°–32° C (Shah & Chatterjee, 2021). At summer the maximum temperature can rise up to 42° C at western part, and at winter the mean temperature varies from 16°C–20°C. The current mean normal rainfall (1951–2000) of the basin varies from 1234 to 1458 mm, experiencing heavier rainfall during occasional thunderstorms and tropical cyclones (Fig. 2b).

The elevation is decreased from the western lateritic upland (81 m from mean sea level) to the eastern Bhagirathi floodplain (8 m from mean sea level), maintaining average eastern basin slope of 0.843 m km^{-1}. The basin is appeared largely as Pleistocene—Holocene interfluve of three major rivers, and it is bounded by three distinct floodplain units—(1) Ajay floodplain at north, (2) Bhagirath-Hooghly floodplain at east, and (3) Damodar fan-delta plain at south. The sub-surface lithology of this region is sub-divided into five categories (Fig. 2a)—(1) Lalgrah laterite and gravel formation (Early—Late Pleistocene), (2) Sijua Formation (Late Pleistocene to Early Holocene), (3) Panskura Formation (Early to Late Holocene), (4) Bhagirathi-Hooghly Formation (Late Holocene to Recent), and (5) Present day deposits (Recent) (Ghosh & Guchhait, 2017). The basin comprises three different morpho-stratigraphic units—(1) the Lateritic Upland / Plain (Early—Late Pleistocene), (2) the Older Alluvial Plain/Kusumgram Plain (Pleistocene—Holocene), and (3) the Younger Delta Plain/Valley Cuts of Khari Floodplain (Holocene—Recent) (Acharyaa & Shah, 2007; Ghosh & Guchhait, 2017; Shah & Chatterjee, 2021). In the downstream part of Khari,

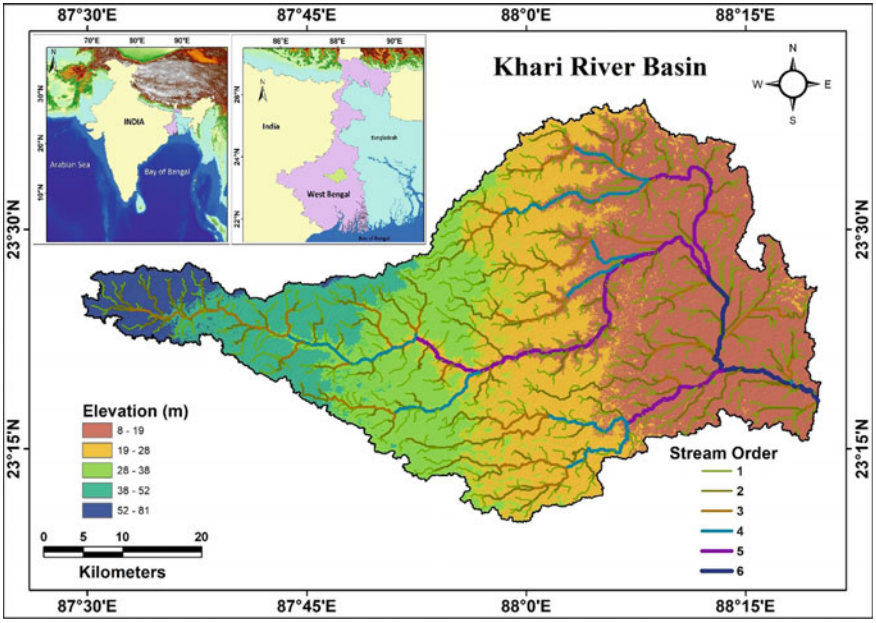

Fig. 1 Location map of Khari River Basin (Purba Bardhaman, West Bengal)

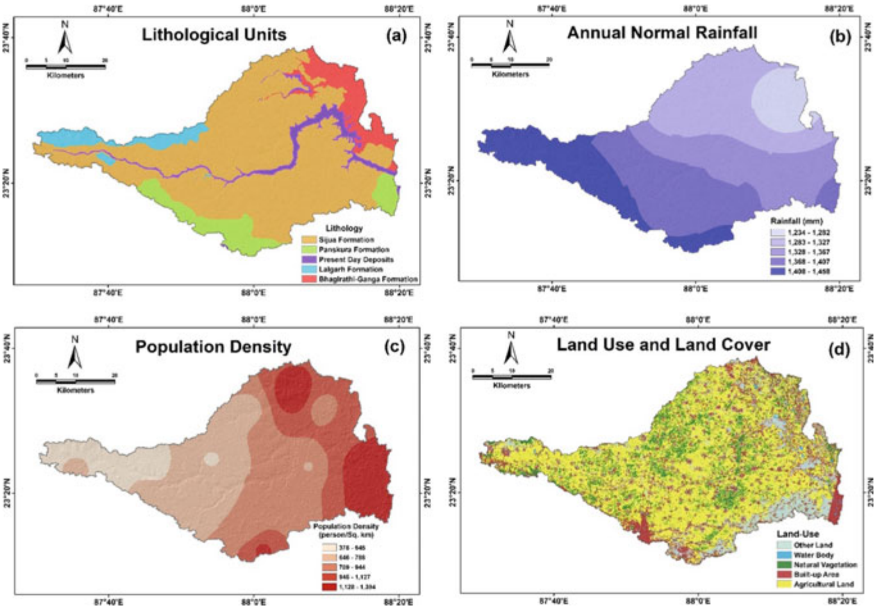

Fig. 2 **a** Lithological sub-divisions of the Khari River Basin; **b** spatial distribution of annual normal rainfall (1951–2000); **c** increasing population density (2011) from west to east, and **d** regional association of various land use and land cover (2020)

the Older Alluvial Plain deposits are truncated, incised and superposed by the lower-level terraces of Younger Delta Plain, which in turn is incised by the present channel (Acharyaa & Shah, 2010). Fairly thick and regionally extensive confined—unconfined aquifers down to 300 m occur in the upper mature deltaic plain and paradeltaic flood surface (lithofacies of sand, slit and clay with caliche concretion, and lithofacies of clay alternating with sand and silt), having moderate yield prospects (50–150 m^3 hr^{-1}) (Figs. 2 and 3).

3 Materials and Methods

In this study the geo-hydrological analysis incorporates administrative unit (i.e., C.D. Blocks or District) and alongside the river basin is exclusively considered as a spatial scale of study (a hydrological unit) because the groundwater system functions ideally as open system along a drainage basin.

Fig. 3 Snapshots of field visit: **a** stretch of Khari River at Nadanghat during April, 2021; **b** Anthropogenic intervention (Narja Bridge and Paper industry) on river valley at Narja, Bhatar (April, 2021); **c** active electrified deep tube well to irrigate Boro rice field at Manteswar during March, 2022; **d** Boro rice cultivation in topographically low-level water concentrated land at Kurmun during March, 2022; **e** Boro rice cultivation in active flood-prone area (water prospect region) at Maldanga during March, 2022; and **f** Boro rice cultivation on the left bank floodplain of Khari at Maldanga during March, 2022

3.1 Data Set Preparation

The basin map of Khari River was prepared from the data repository of HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivating at multiple scale) which was a mapping product that provides hydrographic information (Lehner & Grill, 2013) for regional and global-scale applications in a consistent format (www.hydrosheds.org/page/hydrobasins). The block map of Purba Barddhaman district was collected from the official website (www.purbabardhaman.nic.in/map-of-district/), and it was reprojected in UTM WGS-84 reference system using ArcGIS 10.4 software. The surface geology, lineaments, drainage and other geomorphic information and thematic maps were retrieved from the web portal of Geological Survey of India (www.bhukosh.gsi.gov.in). Monthly and annual rainfall data were retrieved from the CHRS (Center for Hydrometeorology and Remote Sensing) data portal (www.chrs.eng.uci.edu) which provided gridded precipitation data of resolution $0.04° \times 0.04°$ (4×4 km) from March, 2003 to Present. The rainfall data belongs to PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) CCS (Cloud Classification System) algorithm which relates to variable threshold cloud segmentation (Nguyen et al., 2019). Alongside, another $0.25° \times 0.25°$ resolution gridded rainfall data was collected from the official website of Indian Meteorological Department (www.imdpune.gov.in). The land use and land cover (LULC) information were collected from the web portal of ESRI 2020 Land Cover Downloader -(https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2) where the analysis was done using the Sentinal- 10 m resolution imagery (2017–2021). Again, the digital LULC classification was done in Erdas Image 2014 software using Landsat OLI TM imagery of 30 m resolution. The SRTM (Shuttle Radar Topographic Mission) digital elevation data of 30 m resolution was collected from the web portal of Earth Explorer (www.earthexplorer.usgs.gov). The dataset of surface water occurrence (SWO) was gathered from the web portal (www.global-surface-water.appspot.com/download) of the Joint Research Centre's Global Surface Water Dataset (1984–2020) which was prepared to analyse the seasonal occurrence of inundated areas and permanent waterbodies using the Landsat TM, ETM + and OLI sensors (Pekel et al., 2016). National level hydrological modelling framework (National Remote Sensing Centre, Hyderabad) provides the database of evapotranspiration, surface runoff, soil moisture on a daily basin of 5.5 km grid resolution in India (www.bhuvan.nrsc.gov.in/nhp). The irrigation statistics of West Bengal (2014–2017) were collocated from the official irrigation census report of River Development and Ganga Rejuvenation Minor Irrigation Wings, Government of India (http://wbwridd.gov.in/swid/). District wise crop yield rate and production (2010–2011 to 2014–2015) was collected from the Bureau of Applied Economics and Statistics (BAES; Government of West Bengal) (BAES, 2015, 2016).

3.2 Thematic Mapping of Periodic Groundwater Level

To understand the spatio-temporal variations in the existing hydrogeological regime of West Bengal, a network (numbers—1500) of Ground Water Monitoring Wells (GWMW) had been set up by the Central Ground Water Board (CGWB). In the basin seventeen GWMW sites were spatially distributed, and periodic (i.e., April, August, November and January) ground water level measurements were taken up four times in a year by CGWB. The groundwater data set of 2019–2020 and 2020–21 were derived from the Ground Water Year Book of West Bengal and Andaman & Nicobar Islands (CGWB). To develop the maps of periodic trend in water table per GWMW sites for the period 2019–2020 and 2020–2021, the database was merged and combined with the basin geodatabase. The inverse distance weightage (IDW) method was used to create spatial pattern of water table fluctuation in ArcGIS 10.4 software. To get pre-monsoon to post-monsoon deviation of groundwater table, the geospatial tool analysed the water table departure (fall or rise in table) of January database from the April database for two periods. Alongside, to get information on extent and characteristics of principal and major aquifer systems, the atlas, 'Aquifer Systems of West Bengal' (CGWB, 2014, 2016) was used. The supportive database (block wise groundwater resource data, groundwater exploration, water level behaviour, groundwater resource estimation etc.) of groundwater was taken from the web portal (www.indiawris.gov.in/wris/#/home) of India Water Resource Information System (WRIS).

3.3 Quantitative Hydrogeological Techniques

Groundwater resource estimation methodology (MWR, 2017) was taken from the report of the Ground Water Resource Estimation Committee (Ministry of Water Resources, Government of India). To estimate groundwater recharge from rainfall the following formula (rainfall infiltration factor method) had been applied here:

$$R_{RF} = R_{FIF}.A.\left(R - a\right)/1000 \quad (1)$$

where, R_{RF} is rainfall recharge (ham), A is area (hectare), R_{FIF} is rainfall infiltration factor, R is rainfall (mm) and a is minimum threshold value above which rainfall induced groundwater recharge (mm). In the river basin CHRS gridded rainfall data of resolution 0.04° × 0.04° (4 × 4 km, i.e., 16 km^2 cell size) was used to get recharge estimation, and the IDW method is applied to get spatial pattern of it. The stage of groundwater development can be estimated using the formula:

$$GWD_L = \left(D_Y/IR_U\right).100 \quad (2)$$

where, GWD_L is level of groundwater development, D_Y is net yearly draft, and IR_U is utilizable resource for irrigation.

In the absence of field-scale data to estimate recharge, simpler methods, such as the water-table fluctuation (WTF) technique, are more widely used to estimate monsoon recharge (R_g; Healy & Cook, 2002; Bhanja et al., 2019). R_g may be defined as:

$$R_g = h \,.\, S_y \tag{3}$$

where, h represents seasonal changes in groundwater levels and S_y is the specific yield. In this study, to estimate amount of monsoon recharge (m yr^{-1}) the hydrological analysis concentrates on CGWB data of August, 2019 and 2020.

Basin runoff of each monsoon month (June to September) is estimated using the SCS (Soil Conservation Service) Curve Number (CN) method which is based on the assumption of proportionally between retention and runoff. The mathematical relation for runoff is given by (Chow et al., 1988):

$$Q = (P - I_a)^2 / (P - I_a + S) \tag{4}$$

where, Q is the actual runoff (mm), P is the precipitation (mm), I_a is the initial abstraction which includes interception, surface storage and infiltration into soil and S is the potential retention. The following relationships between initial abstraction and potential maximum retention have been developed for the soils of India (Zade et al., 2005):

$$Q = (P - 0.3\,S)^2 / (P + 0.7S) \tag{5}$$

where, S is determined by CN, through the following relation (Zade et al., 2005):

$$S = 25400\,/\,CN - 254 \tag{6}$$

Each cell of 16 km^2 (CHRS data resolution 0.04° × 0.04°) was assumed as a unique hydrological unit of runoff analysis. LULC map, prepared from Landsat 8 imagery, was reclassified in 16 km^2 cell unit to get CNs in the basin.

To locate the concentration region of basin runoff water the Topographic Wetness Index (TWI) was introduced here, and the results were verified the database of SWO. In a DEM the index is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction (Beven & Kirkby, 1979). The formula of estimating TWI was given by Sørensen et al. (2006) and Kopecky et al. (2021):

$$\text{TWI} = \ln\,(a / \tan\beta) \tag{7}$$

where, a is upslope contributing area and β is slope in radians.

3.4 AHP-Based Groundwater Potential Mapping

Geospatial technology has precise capability and flexibility to estimate the groundwater potential zones incorporating various topographic, geologic and hydrological database with the help of machine-learning algorithm and multi-criteria decision-making method. Analytical Hierarchical Process (AHP) is the popular multi-criteria decision-making method developed by Saaty (Saaty) that is frequently used to identify Groundwater Potential Zones (Das & Pal, 2020; Das et al., 2021; Halder et al., 2020; Pal et al., 2020; Sar et al., 2015; Sikdar et al., 2019), thus in the present study it was applied. Multiple factors which are associated with occurrence of groundwater were used to find groundwater potential zone. Those factors were set weights based on according to Saaty's scale ranging from 1 to 9 to their level of relative importance on groundwater recharge and previous existing study on the same topic and field experience. The selected factors were compared with each other using pair - wise comparison matrix. The sub-categories of factors were derived by using the Jenks natural breaks classification method in ArcGIS software. The sub-categories of each factor were giving rank on a scale of 0–9, based on their relative influence on the development of groundwater.

A numerical weight is given to the each influencing factors and ranks were set to every sub-category of various factors (thematic layer) connected with the recharge based on their relative importance. After that, the groundwater potential map can be generated by overlapping weighted layers with the help of weighted overlay method under spatial analyst tool in ArcGIS 10.8 using following Equation:

$$GPZ = \sum_{n=1}^{N} (W_n * R_m) \tag{8}$$

where GPZ denote as groundwater potential zone, n and m are the factors and sub-categories, N is the total number of factors, W_n represent the weight of each factor and R_m represent the rank of the sub-categories of each factor.

The final GPZ map was classified into 4 classes viz. low, moderate, high and very high zones based on their groundwater potentiality and validated using the tube-well and bore well data collected from the published reports of Central Ground Water Board (CGWB, 2019–2020 and 2020–2021) of the Burdwan district. Methodology adopted in the present study, summarised in the flow chart (Fig. 4).

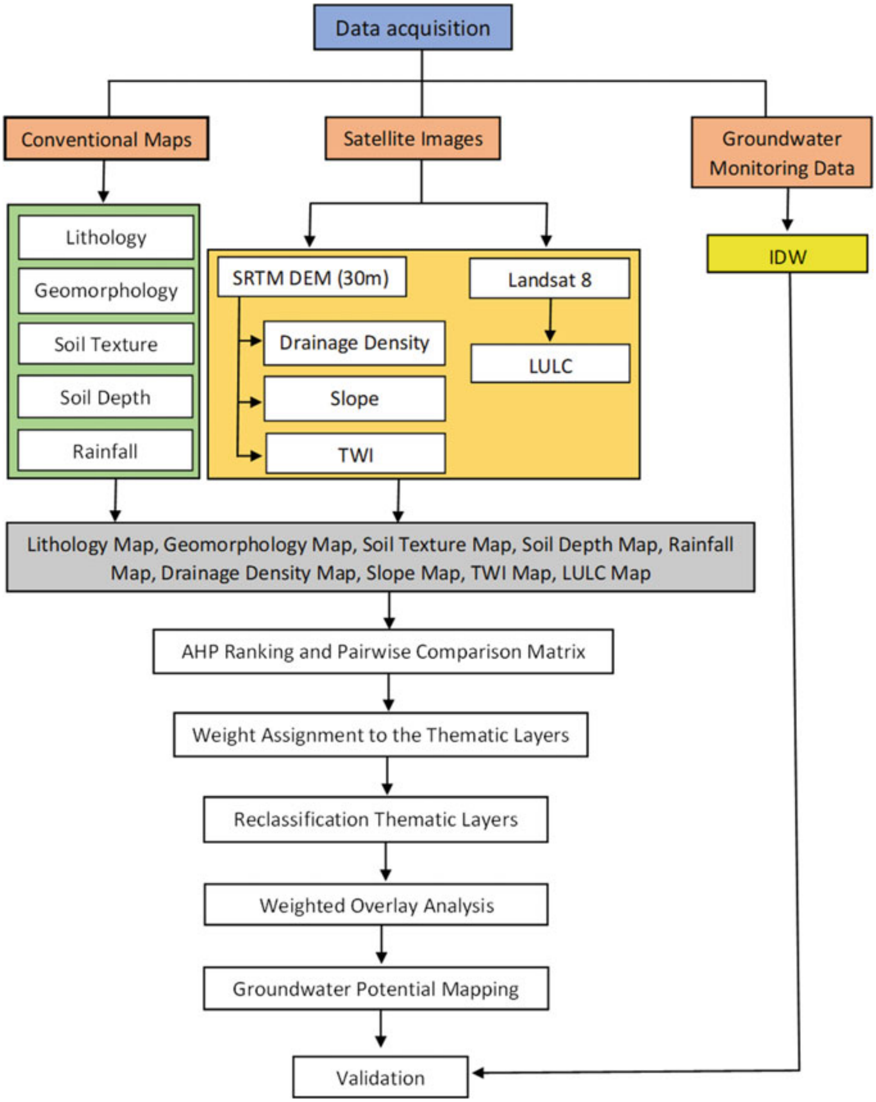

Fig. 4 Workflow chart of analytical hierarchical process for groundwater potential zone estimation

4 Results

4.1 Status of Groundwater Resource

In southern part of West Bengal the principal aquifer systems (i.e., semi-confined to confined aquifers) of Quaternary alluvium and laterite have spatial extent of 57,983 km^2 and 14,280 km^2 respectively, making 88.01% of total aquifer distribution. The mean thickness of aquifers varies from 50 to 700 m, and the trapped zone ranges in between 40 and 400 m bgl, having 5–10 m of DWL (Depth to Water Level). In the basin annual extractable groundwater resource is near about 236,877 ham, having 43.76% stage of groundwater development (GWD_L, Eq. 2). The gross annual groundwater uses in irrigation and domestic / industrial purposes are 94,059 ham and 9,067 ham respectively (Table 1). The projected demand for domestic and industrial uses up to 2025 will be 12,187 ham. Five semi-critical blocks (e.g., Purbasthali II, Manteswar, Memari II, Mangolkote and Bhatar) are located along the Khari Basin of Purba Bardhaman district, and GWD_L of these blocks varies from 40.56 to 87.53% (Table 2). In Bhatar block, three trapped zones of multiple aquifer system are identified—(1) 28–58 mbgl, (2) 105.50–123.50 m bgl, and (3) 181–295 m bgl respectively, having transmissibility of 1700 m^2 day^{-1}. In Manteswar block, up to a depth of 125 m bgl multiple aquifer system of 31.81–1700 m^2 day^{-1} transmissibility is recognized. In these five water-stressed blocks net groundwater availability ranges in between 10,374 and 17,407 ham.

In the Khari River Basin, principally two distinct groups of aquifers (extracted for groundwater irrigation) comprise coarse sand and gravels with or without intervening clay lens (up to 34 m thick). In this monsoon dominated agricultural plain the phreatic zone, or the zone of saturation, is identified as a part of primary aquifer, named 'O' group, developed locally within 25–40 m bgl of younger alluvium in the floodplains of Katwa I, Katwa II and Ketugram II. Total thickness of Aquifer 'I' group ranges

Table 1 Dynamic groundwater resources of Purba Bardhaman

Sl. No	Parameters		Values (ham)
1	Groundwater Recharge (ham)	*Monsoon Season*	170,643.19
			13,283.39
		Non-Monsoon Season	42,504.98
			35,214.86
		Total Annual Groundwater Recharge	261,646.42
2	Total Natural Discharge (ham)		24,768.66
3	Annual Extractable Groundwater Resource (ham)		236,877.76
4	Current Groundwater Extraction (ham)	*Irrigation*	94,059.6
		Industrial	1526.33
		Domestic	8081.69
		Total	103,667.61
5	Annual Groundwater Allocation for Domestic Use as on 2025 (ham)		15,762.29
6	Net Groundwater Availability for Future Use (ham)		127,055.87
7	Stage of Groundwater Extraction (%)		43.76

Source CGWB (2021b)

Table 2 Seasonal variation of groundwater level (2013–14 to 2020–21) at CGWB sites of the Basin (Purba Bardhaman)

CGWB Site		Malamba	Maldanga	Bolgona	Koichor
C.D. Block		Manteswar	Manteswar	Bhatar	Mangolkote
Depth of Well (m)		55	40	61	45.7
Seasonal Depth to Water Level (m)	April, 2013	18.56	15.72	18.6	20.1
	April, 2020	24.66	24.75	27.86	26.45
	Rise (+) / Fall (−)	−6.1	−9.03	−9.26	−6.35
	August, 2013	8.4	12.21	14.05	15.36
	August, 2020	24.6	24.6	27.8	20.77
	Rise (+) / Fall (−)	−16.2	−12.39	−13.75	−5.41
	November, 2013	9.26	14.02	14.2	20.16
	November, 2020	25.13	22.19	26.64	23.28
	Rise (+) / Fall (−)	−15.87	−8.17	−12.44	−3.12
	January, 2014	9.7	14.6	15.04	20.36
	January, 2021	15.26	23.78	13	24.18
	Rise (+) / Fall (−)	−5.56	−9.18	2.04	−3.82
Declining Rate of DWL (m/year)	Pre-monsoon trend	0.871	1.29	1.322	0.907
	Monsoon trend	2.314	1.77	1.964	0.772
	Post-monsoon Trend	2.267	1.167	1.777	0.445

Source CGWB (2014, 2021b)

within 20.5–125 m in Bardhaman I, Bardhaman II and Katwa II, with a depth of 145 m bgl in older alluvium (Brahma, 2021; CGWB, 2016). DTW of Aquifer 'I' in pre-monsoon was estimated as 30–35 m bgl, and it increased up to 18–25 m bgl during 2006–2016 (Brahma, 2021). The yield or discharge (*D*) of this aquifer group ranged with 8–128 m^3 hr^{-1}, and maximum transmissivity (*T*) of 1700 m^2 day^{-1} was encountered in the blocks (CGWB, 2014).

Aquifer 'II' group was encountered beneath aquifer 'I' in the blocks of Katwa I, Bhatar, Manteswar and Memari II. Its groundwater potentiality is less and thickness of this aquifer (occurred as semi-confined to confined condition in fine to medium sands) ranges within 17–51 m, having depth range of 80.5–240 m bgl (Brahma, 2021; CGWB, 2016). It was found that 'I' and 'II' aquifer groups were merged to form a single aquifer, having collective thickness of up to 135 m, D ranged in between 10–122.40 m^3 hr^{-1} and *T* greater than 1000 m^2 day^{-1} (Brahma, 2021). DTW of Aquifer 'II' in pre-monsoon was estimated as 10–30 m bgl, and it increased up to 18–25 m bgl during 2006–2016 (Brahma, 2021; CGWB, 2016).

The inhabitants of semi-critical blocks already exploited the groundwater resource of Aquifer 'I' to a large extent for irrigation draft, resulting in water level depletion. In 2006 the groundwater drafting (for irrigation purpose) of semi-critical blocks varied from 4,068 to 8,787 ham in respect of number of pumps and cropping intensity. Heavy duty tube wells extracted water at a rate of greater than 150 m^3 hr^{-1}. As a whole, in Purba Bardhaman district total monsoon recharge from rainfall is near about 170,643 ham and from other sources the recharge amount is 13,283 ham (CGWB, 2021a). Total extractable groundwater resource is 236,877 ham (CGWB, 2021a, b). At demand side, the groundwater uses for domestic, industrial and agriculture are 8,081 ham, 1,520 ham and 94,059 ham respectively (CGWB, 2021b). Finally, after gigantic uses of groundwater resources in 2020 Purba Bardhaman district exhibit six semi-critical water-stressed blocks (2643.04 km^2), having 36.39% of total recharge area of West Bengal (CGWB, 2021a, b)

4.2 Trend in Groundwater Depletion

It is essential to unearth the seasonal or periodic fluctuation of DWL in the selected CGWB stations of the basin. Total analysis is divided quarterly, i.e., April, August, November and January to cover the pre-monsoon, monsoon and post-monsoon trend of DWL for the period of 2019–2020 and 2020–2021. The peak summer or pre-monsoon trend (i.e., time of Boro rice cultivation) of DWL (April, 2019 and April, 2020) is depicted in Fig. 5, and the map represents a high depth of DWL (16.130–28.219 m bgl) in the middle part of the basin, incorporating the blocks of Mongolkote, Bhatar, Manteswar, Katwa I and Memari II. A similar picture is observed in the monsoon period (August, 2019 and 2020), with very little recovery of DWL (16.120–28.219 m bgl) through rainfall recharge in those blocks. Interestingly, in post-monsoon period (November and January) no significant deviation of DWL is recognized in the basin, exhibiting similar high depth DWL (15.210–27.279 m bgl) at middle part. Pre—to post-monsoon DWL (April–November) deviation of period 2019–2020 shows a positive trend or rise (0.22–13.79 m) in DWL in the maximum part of the basin, covering mainly Galsi I, Ausgram I and II, but in the period of 2020–2021 the positive trend (2.03–17.12 m) is observed in the middle part of the basin, covering Ausgram II, Galsi II, Bardhaman I and II, Bhatar, and parts of Mongolkote. Alongside, Katwa I and II, Purbasthali I and II blocks show a negative trend of DWL (0 to −1.67 m) in both periods, reflecting decreasing DWL at post-monsoon from pre-monsoon season.

The high depth DWL zone of concentration is found in the semi-critical blocks of Purba Bardhaman, signifying a continuous loss of groundwater depth in aquifer 'I' zone. Principally, three semi-critical blocks, i.e., Mongolkote, Bhatar and Manteswar, exhibit regionally deep DWL in all seasons, ranging from 20.917 to 28.219 m bgl. The pre- and post-monsoon DWL of session 2019–2020 and 2020–2021 shows a depth range of 20.710–26.630 m bgl in those blocks, signifying less monsoonal recharge or storage of shallow aquifer 'I', high irrigation drafting and high gradient discharge towards south-eastern blocks. It is very alarming findings that the pre-monsoon deviation of DWL, from April 2019 to April 2020 (Fig. 6a), shows negative trend, i.e., fall or loss of water level in the middle and eastern part of the basin, covering all semi-critical blocks. Specifically, Galsi II, Bardhaman I, Bhatar, Manteswar, Mongolkote and Purbasthali II blocks exhibits up to—9.67 m fall in

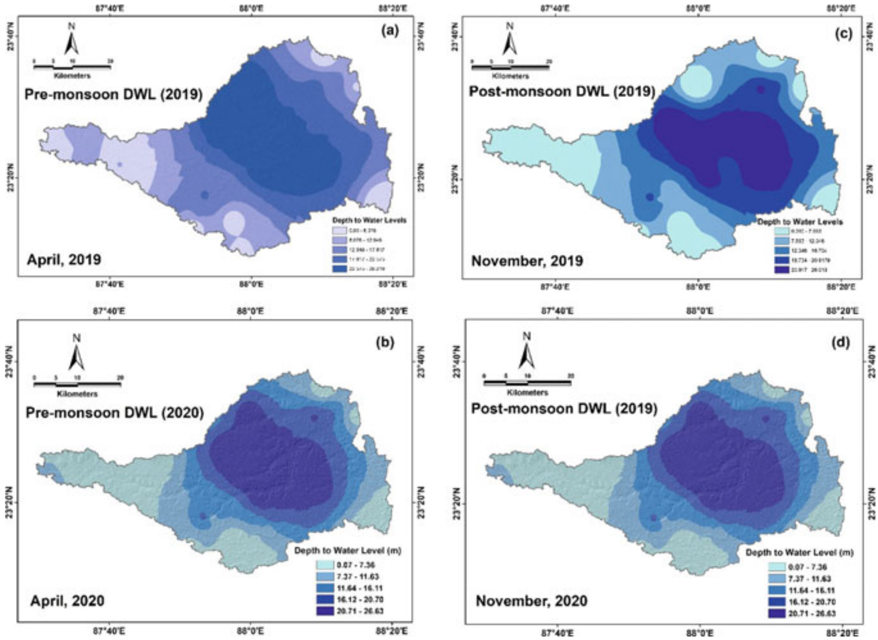

Fig. 5 Pre-monsoon and post-monsoon spatial variation of DWL (depth to water level) in the Khari River Basin (Purba Bardhaman)

DWL in the pre-monsoon months (2019–2020), and Ausgram I and II blocks shows rise in DWL, up to range of 1.0–14.62 m. The post-monsoon deviation of DWL, from November 2019 to November 2020 (Fig. 6b), reflects again a massive fall in DWL, up to—23.27 m, in Mongolkote and Bhatar (semi-critical blocks). This fact imitates the prevailing groundwater drought condition in the alluvial aquifer rich and agriculturally-dominated floodplains. Continuous high depth DWL and fall of water level of middle basin proves the reason behind the semi-critical water-stress stage of the region, and it can be attributed to high irrigational drafting of groundwater since 1990s due to boom in electrified deep tube wells. In Purba Bardhaman, average declining trend (1997–2006) of DWL to the tune of 0.01 to 1.00 m yr^{-1} was observed in the 64% of monitoring wells. From the database of CGWB (2013–2021) it is found that four CGWB well sites of the basin show a sharp declining trend of groundwater level in all seasons (Fig. 6)—(1) pre-monsoon fall rate of 0.871 to 1.322 m yr^{-1}, (2) monsoon fall rate of 0.772 to 2.314 m yr^{-1}, and (3) post-monsoon fall rate of 0.445 to 2.267 m yr^{-1} (Table 2).

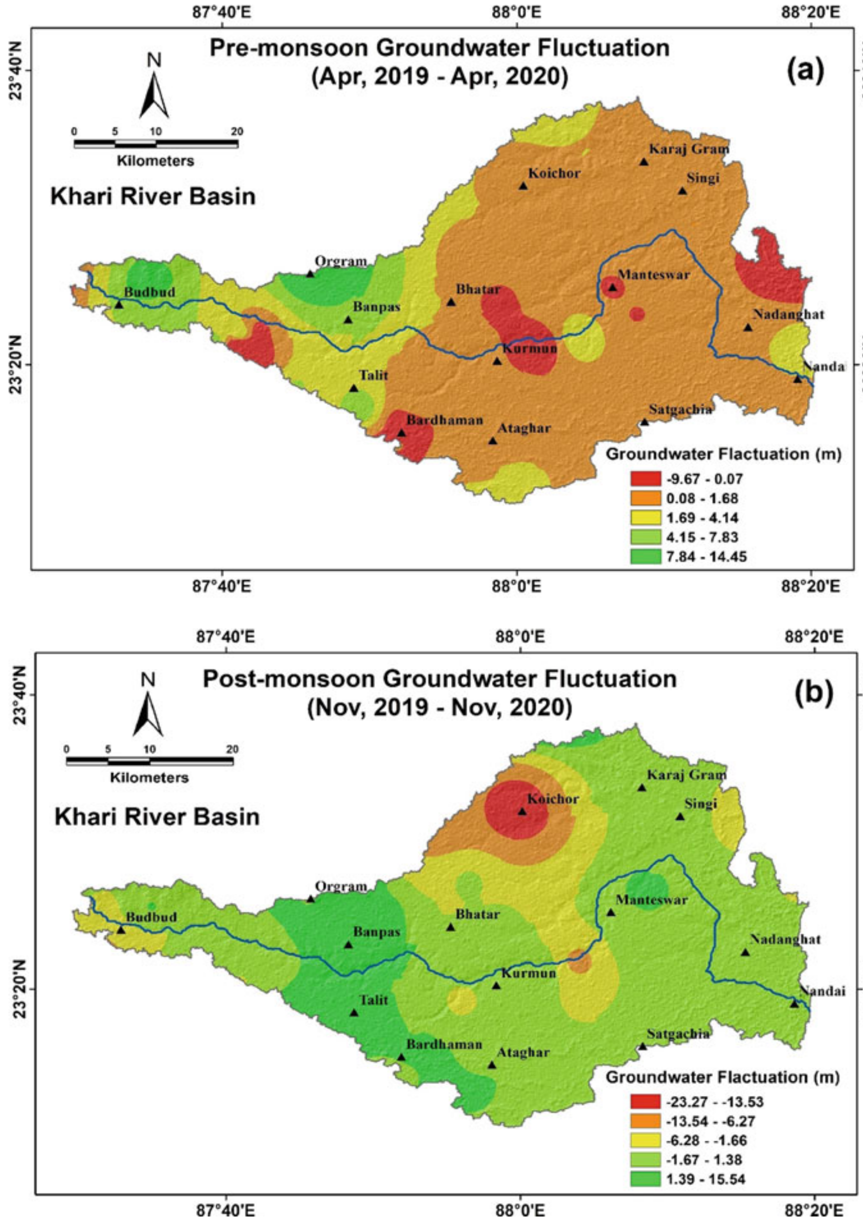

Fig. 6 Spatial changes and fluctuation (rise or fall) of groundwater level in **a** pre-monsoon (April, 2019–April, 2020) period, and **b** post-monsoon (November, 2019–November, 2020) period

4.3 Role of Irrigated Agriculture

A disproportionate stress is building up on the groundwater resources of the Gangetic West Bengal or western parts of the Bengal Basin, because this region comprises agriculturally dominated and densely populated districts, viz*.,* Purba Bardhaman, Birbhum, Nadia, Hooghly, Howrah eta., hosting more than 50% of total population (Mukherjee, 2009). The introduction of high-yielding dry season rice (Boro) accelerated the demand for irrigation since 1970s. As a consequence, several million wells (ranging from low yielding hand pumped to heavy duty motor driven pumps) were installed in order to meet irrigation, drinking and industrial water demands (Mukherjee et al., 2007). Operation of deep tube wells have grown rapidly from 0.1 million in 1978 to 0.5 million in 2000–2001, 1.45 million in 2006–2007 and more than 2.6 million in 2013–2014, creating intensive pressure on groundwater resource (MWR, 2017). In West Bengal, all total 4,22,739 irrigation structures (i.e., shallow, medium and deep tube wells) were operating in 2013–14, and about 3,71,353 heavy-duty (1500 m^3 hr^{-1}) pumps were operated by electricity and diesel (MWR, 2017). In 2013–2014 the number of deep tube wells (60–180 m bgl) and shallow tube wells (10–50 m bgl) are 923 and 408 respectively, operating for irrigation purpose in Purba and Paschim Bardhaman. Due to non-availability of adequate water, less discharge of water, mechanical breakdown and lack of maintenance, 4357 pumps are not functioned, and due to groundwater depletion already 562 pumps were permanently damaged in West Bengal (MWR, 2017). Now, in the Khari Basin all total 847 deep tube wells are functioned for irrigation, and the blocks of Kalna I and Galsi II have maximum number (> 100) of wells (Fig. 7a).

Summer rice cultivation (Boro) was intensively practiced by the farmers since 1970s with the introduction of high yielding rice varieties like TN1, IR8, Jaya, Ratna and later IR50, IR64 and IR36, IET 4094 and IET4786 in irrigated system (Goswami and Saha, 2011). For rice cultivation of West Bengal groundwater is becoming an increasingly popular resource because of the relative ease and flexibility with which it can be tapped (Mehta, 2006). Water demand for irrigation sector was 688 bcm in 2010 and it can rise up to 1072 bcm in 2050 in India, promoting more water depletion. It is found that area under Boro rice irrigation ranged from 189,433 to 150,267 hect in between 2010 and 2015, and green yield rate varied from 5195.58 to 5475.57 kg $hect^{-1}$ in the Purba and Paschim Bardhaman (Table 3). The estimated production of Boro rice varied from 585,863 to 490,532 tonnes in 2010–2015. In 2014–2015 Purba and Paschim Bardhaman districts produced all total 1,896,032 tonnes of rice, having share of 1,361,138 tonnes Boro production. The rapid increase of summer rice area to the tune of 5–10% annually over the last decade is only possible with indiscriminate groundwater pumping mostly from unconfined aquifer, close to earth surface (10–35 m bgl) through private shallow tube wells (Goswami and Saha, 2011). In West Bengal 6.0 lakh ha summer rice was grown under shallow and deep tube wells commands, i.e., 40% of total Boro rice area (15 lakh hect). Groundwater fed summer area was maximum in Purba and Paschim Medinipur (1.08 lakh hect) followed by Purba and Paschim Bardhaman (0.99 lakh hect).

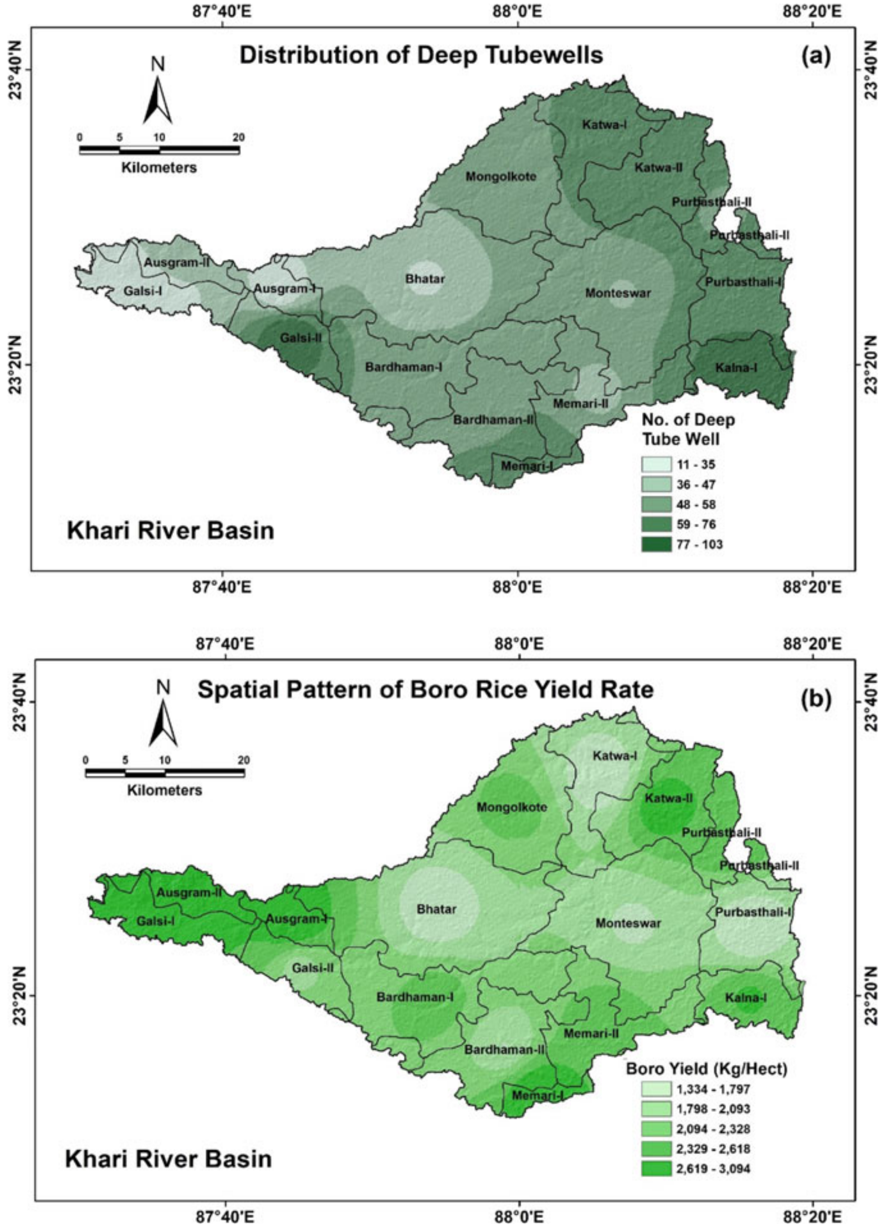

Fig. 7 **a** Spatial pattern of functioned deep tube wells (60–180 m bgl), and **b** variation of Boro rice yield rate (1334–3094 kg $hect^{-1}$) in the basin

Table 3 Summary of Boro rice yield rate and production (2010–2011 to 2014–2015)

Parameters	2010–2011		2011–2012		2012–2013		2013–2014		2014–2015	
	Purba & Paschim Bardhaman	West Bengal	Purba & Paschim Bardhaman	West Bengal	Purba & Paschim Bardhaman	West Bengal	Purba & Paschim Bardhaman	West Bengal	Purba & Paschim Bardhaman	West Bengal
Area under Boro rice ('000 hect)	189.443	1369.892	169.333	1221.076	163.328	1228.263	176.219	1286.995	150.267	1290.02
Estimated dry yield rate of Boro (kg/hect)	3092.55	3289.93	2812.99	3173.51	3627.64	3309.59	3793.05	3370.75	3264.4	3373.4
Estimated green yield rate of Boro (kg/hect)	5195.58	5536.42	4728.98	5342.44	6173.18	5632.28	6395.23	5700.48	5475.57	5704.96
Estimated Production ('000 tonnes)	585.863	4506.484	476.332	3875.1	592.495	4065.052	668.407	4338.142	490.532	4351.753
Driage Ratio	0.8937	0.8906	0.8898	0.8901	0.8812	0.8814	0.8893	0.887	0.8935	0.887

Source BAES (2015, 2016)

Table 4 Block-wise distribution of Boro rice cultivation area, production, yield rate, number of deep tube wells, per day irrigation area and pump discharge

Sl No	Block	Area (km^2)	Population Density	Boro Rice Cultivation Area (hect)	Production (Metric Tonne)	Yield (Kg/Hect)	No. of Deep Tube Well	Area to be covered on each day irrigation for Boro (hect)[a]	The pump discharge required for Boro (m^3/hr)[b]
1	Galsi—I	257.37	729	753	2.059	2735	11	150.6	6495
2	Galsi—II	219.09	672	7158	14.109	1971	103	1431.6	61,738
3	Ausgram—I	222.34	537	2919	9.013	3088	19	583.8	25,177
4	Ausgram—II	360.45	419	1373	2.987	2176	73	325.7	20,078
5	Bhatar	415.01	634	14,216	19.332	1360	32	2843.2	122,613
6	Bardhaman—I	250.41	862	5689	10.568	1858	55	1137.8	49,068
7	Bardhaman—II	189.57	807	6179	11.062	1790	53	1235.8	53,294
8	Memari—I	186.91	1169	1016	3.145	3095	77	203.2	8763
9	Memari—II	186.84	804	3163	8.022	2536	43	632.6	27,281
10	Kalna—I	169.08	1224	4172	11.193	2683	102	834.4	35,984
11	Manteswar	305.19	778	20,654	34.667	1678	46	4130.8	178,141
12	Purbasthali—I	148.44	1394	4790	6.389	1334	62	958	41,314
13	Purbasthali—II	192.47	1103	3693	90.597	2599	56	738.6	31,853
14	Katwa—I	148.44	1394	4790	6.389	1334	62	958	41,314
15	Katwa—II	163.2	838	4659	13.781	2958	75	931.8	40,184
16	Mangolkote	365.44	720	9950	24.909	2503	51	1990	85,819

Note Highlighted rows are the important database of semi-critical blocks
Source BAES (2017); [a] & [b] Data calculated from the web portal of WBADMIP (https://www.wbadmip.org/watreq)

The production database of the district showed that since 2010–2011 the intensity of Boro rice cultivation (1221,076 to 1369,892 hect), green yield rate (5342 to 5705 kg hect^{-1}) and gross production (4065,052 to 4506,484 tonnes) was notable high in West Bengal (Fig. 7b). In between 2010–2011 and 2014–15 the area under Boro varied from 150,267 to 189,443 hect in Purba and Paschim Bardhaman. In the districts the production reached up to 490,532 to 668,407 tonnes and estimated green yield rate of Boro ranged between 5,195.58 to 6,395.23 kg hect^{-1} (2010–2015) which was measured as maximum in West Bengal. Fifteen blocks, covering the Khari Basin, exhibited Boro rice yield rate range of 1,334 kg hect^{-1} (Katwa I) to 3,095 kg hect^{-1} (Memari II) in 2016–2017, and in those blocks the population density (2011) varied from 537 to 1394 persons km^{-2}, reflecting the human pressure on intensive Boro rice cultivation with irrigated water. Five semi-critical blocks (viz., Bhatar, Manteswar, Mongolkote, Memari II and Purbasthali II) of the basin showed that the arable land under Boro was maximum and it reached up to 14,246 to 20,654 hect in Bhatar and Manteswar, having 19 to 103 functioned tube wells (total operating tube well number—847).

WBADMIP (Department of Water Resources Investigation and Development) crop water requirement calculator estimated the area to be covered on each day irrigation for Boro rice and required pump discharge for irrigation (permissible pump working hour 10 h day^{-1}) for the fifteen blocks. The final results show that in semi-critical blocks 738.6 to 4130.8 hect land should be covered under irrigated water on each day of pre-monsoon summer months. The required pump discharge can escalate up to 37,281 to 178,141 m^3 hr^{-1} to moisture those lands during Boro rice harvesting. It is essential to mentioned that the operating pump discharge (10 h day^{-1}) for Boro cultivation in the blocks of Bhatar, Manteswar and Mongolkote is estimated as 122,613, 178,141 and 85,919 m^3 hr^{-1} respectively, highest groundwater abstraction in the Basin or Purba Bardhaman district. For that reason, all-round the year DWL of these blocks goes very deep in comparison to surrounding blocks, ranged between 11–28 m bgl. In Purba Bardhaman the average DWL decreased from 9.37 m to 9.60 m bgl (negative trend of–6.167 cm yr^{-1}) in between 2015–2020.

4.4 Analysing Groundwater Recharge Potential

As a part of management strategy, it is prerequisite to analyse the potential zones of groundwater resource using GIS-based topographic and hydrological parameters (Table 5). Mapping of groundwater potential zones is essential for planning the location of new abstraction wells (as well as for increasing groundwater storage in existed aquifers) to meet the increasing demand for water in an agriculturally dominated region. Variable factor weights and individual factor weights for each thematic layer (viz., lithology, geomorphology, soil texture, soil depth, land use land cover, drainage density, slope, rainfall, topographic wetness index) have been assigned to delineate groundwater potential zones using the AHP method. Lithology or morpho-stratigraphic unit is the most important parameter to delineate potential zone because the permeability of the sedimentary unit directly influences infiltration and recharge into aquifers. In the basin the Sijua Formation (Late Pleistocene—Early Holocene) covers maximum portion, having thick 6–9 m clayey horizon (low groundwater potential), sub-surface sandy horizon, sub-angular quartz fragments, altered feldspar and caliche concretion. Alluvial plain of Late Quaternary is a recognized geomorphic unit in the basin, except western Pediment-Pediplain complex of laterite formation and eastern floodplain of recent deposits (high groundwater potential). Seven major land use—land cover classes are determined—(1) permanent water bodies (39.58 km^2), (2) vegetation (351.13 km^2), (3) grassland (4.91 km^2), (4) flooded vegetation (1.26 km^2), (5) cropland (1174.19 km^2), (6) shrubs and fallow land (254.54 km^2) and (7) settlement and built-up area (383.23 km^2).

In the basin mainly fine loamy—coarse loamy and fine—coarse loamy soils show high recharge potential. Alongside, very low slope (0°–1.10°) and low slope (1.11–1.84°) terrain cover maximum part of the basin, having relatively high potential for groundwater. It is observed that drainage density is increased along the main river and its tributaries, and its value ranges between 3.46 and 5.83 km km^{-2}, but the region experiences low groundwater prospect due to high runoff. Beside topographic wetness index range of 5.90–23.29 provides very high potential for groundwater due to concentration of runoff water in the basin. After GIS-based analysis of each parameter score a groundwater potential zone is developed for the Khari Basin, covering maximum part of Purba Bardhaman district (Fig. 8). The potential zone map (using Eq. 8) shows four principal categories of groundwater prospect, viz., poor (1.82 km^2), moderate (127.74 km^2), good (1524.0 km^2) and very good (556.44 km^2). The region of laterite formation (Ausgram II and part of Bhatar) show very poor – moderate groundwater prospects whereas the active floodplain zone of eastern part (Katwa I and II, Purbasthali I and II) is relatively very high potential for groundwater. Also, the active floodplain zone of Khari River exhibits a high potential zone of groundwater. In spite of that the DWL is gradually declined in the pre-monsoon water stressed condition, and five blocks have experienced semi-critical stage of groundwater development.

Using Eq. 3, the monsoon recharge (R_g), between August 2019 and 2020, is estimated in a range of –3.72 to + 2.38 m yr^{-1} in the basin area. The map (Fig. 9a) shows that the parts of Mangolkote, Bhatar, Manteswar and Memari II (semi-critical blocks) experience negative trend (loss) of groundwater recharge, ranging between—0.27–3.72 m yr^{-1}, but rest of region experiences increasing trend (gain) of recharge at a rate of 0.20 to 2.38 m yr^{-1} (maximum recharge in blocks of Ausgram I, Galsi II and Bardhaman I). Now, apart from the AHP-based groundwater potential zone analysis, the CGWB-based rainfall recharge estimation is done here using parameters of rainfall infiltration factor (10–20% of normal annual rainfall in high clay content soil), annual normal rainfall (based on 18 years record), minimum rainfall threshold value (above which rainfall induces groundwater recharge; 10% of normal rainfall) and area for computation of recharge. Recharge had been estimated to range from 0.3 to 5.5 mm day^{-1}, and an average 1.6 mm day^{-1} annually for the Bengal Basin (Mukherjee, 2009). SWID (State Water Investigation Directorate) suggested that recharge would be $\leq \sim 223$ mm yr^{-1} in West Bengal (15% of mean annual rainfall).

Table 5 Pairwise comparisons matrix for AHP and Priority used in groundwater potential zone mapping

Factors	Lithology	Geomorphology	Soil Texture	Soil Depth	LULC	Drainage Density	Slope	Rainfall	TWI	Priority
Lithology	1.00	2.00	3.00	3.00	4.00	5.00	6.00	7.00	8.00	0.28
Geomorphology	0.5	1.00	2.00	2.00	3.00	4.00	5.00	6.00	7.00	0.19
Soil Texture	0.33	0.5	1.00	2.00	3.00	4.00	5.00	6.00	6.00	0.16
Soil Depth	0.33	0.5	0.5	1.00	3.00	4.00	4.00	5.00	6.00	0.13
LULC	0.25	0.33	0.33	0.33	1.00	2.00	3.00	4.00	5.00	0.07
Drainage Density	0.2	0.25	0.25	0.25	0.5	1.00	2.00	3.00	4.00	0.05
Slope	0.17	0.2	0.2	0.25	0.33	0.5	1.00	2.00	3.00	0.03
Rainfall	0.14	0.17	0.17	0.2	0.25	0.33	0.5	1.00	2.00	0.02
TWI	0.13	0.14	0.17	0.17	0.2	0.25	0.33	0.5	1.00	0.01

TWI—Topographic Wetness Index; LULC—Land Use Land Cover

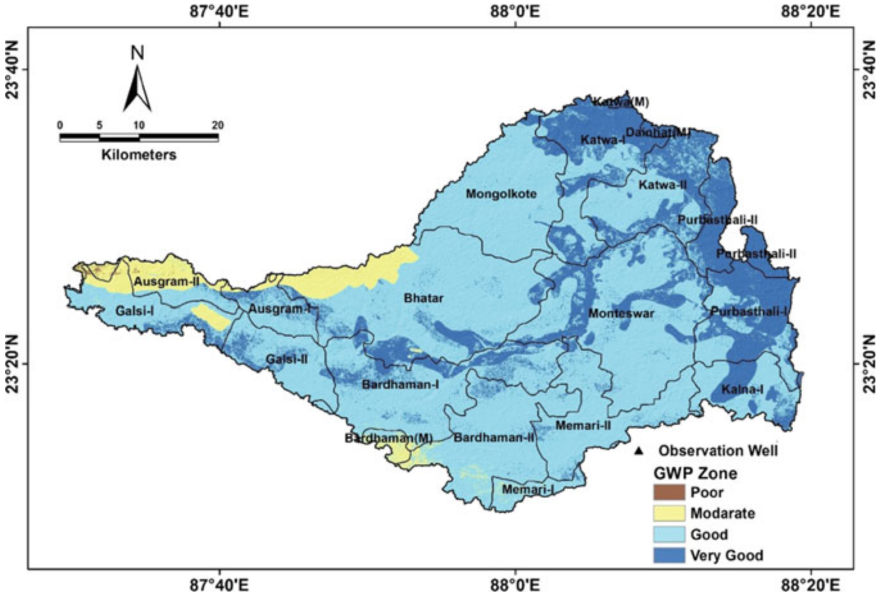

Fig. 8 AHP-based zonation of groundwater resource potential in the Khari River Basin (Purba Bardhaman)

Mukherjee et al. (2007) calculated the mean annual potential recharge for the lower Ganges Basin of West Bengal as 587 mm yr^{-1} or 1.61 mm day^{-1} (range: 384–767 mm yr^{-1}), which is 39% of the mean annual rainfall.

The map of groundwater recharge potential from rainfall (Fig. 9b) can provide some insights on the micro-climatic zone of high groundwater prospect based on the normal rainfall pattern (1591–1823 mm). Through proper water management system or utilisation, the 1174 km^2 area of arable land can source of massive groundwater recharge in the monsoon rainfall. The map shows that the central part of the basin (covering Mangolkote, Bhatar, Manteswar, Bardhaman I and II and Katwa I blocks) has very good potential for groundwater recharge with a range of 611,000 to 640,000 ham. Alongside, Katwa II, Purbasthali II, Ausgram I and II and Galsi II blocks show relatively low potential (<601,000 ham) due to less amount of rainfall (<1600 mm). The estimated total recharge for the lower Ganges Basin is between 9.4×10^9 and 1.3×10^{10} m^3 each year (Mukherjee, 2009). It is found that increasing number of rainy days can give opportunity for more infiltration and recharge into underlying aquifers. For example, normal rainy days of a year for Bardhaman, Katwa and Mangolkote are 65.3 days, 66.8 days and 59.1 days respectively. Another finding is that the high prospect of groundwater recharge zone belongs to semi-critical blocks. It means a sharp gap between demand (high abstraction) and supply (rise in water level) promoting increasing level of groundwater depletion in those blocks.

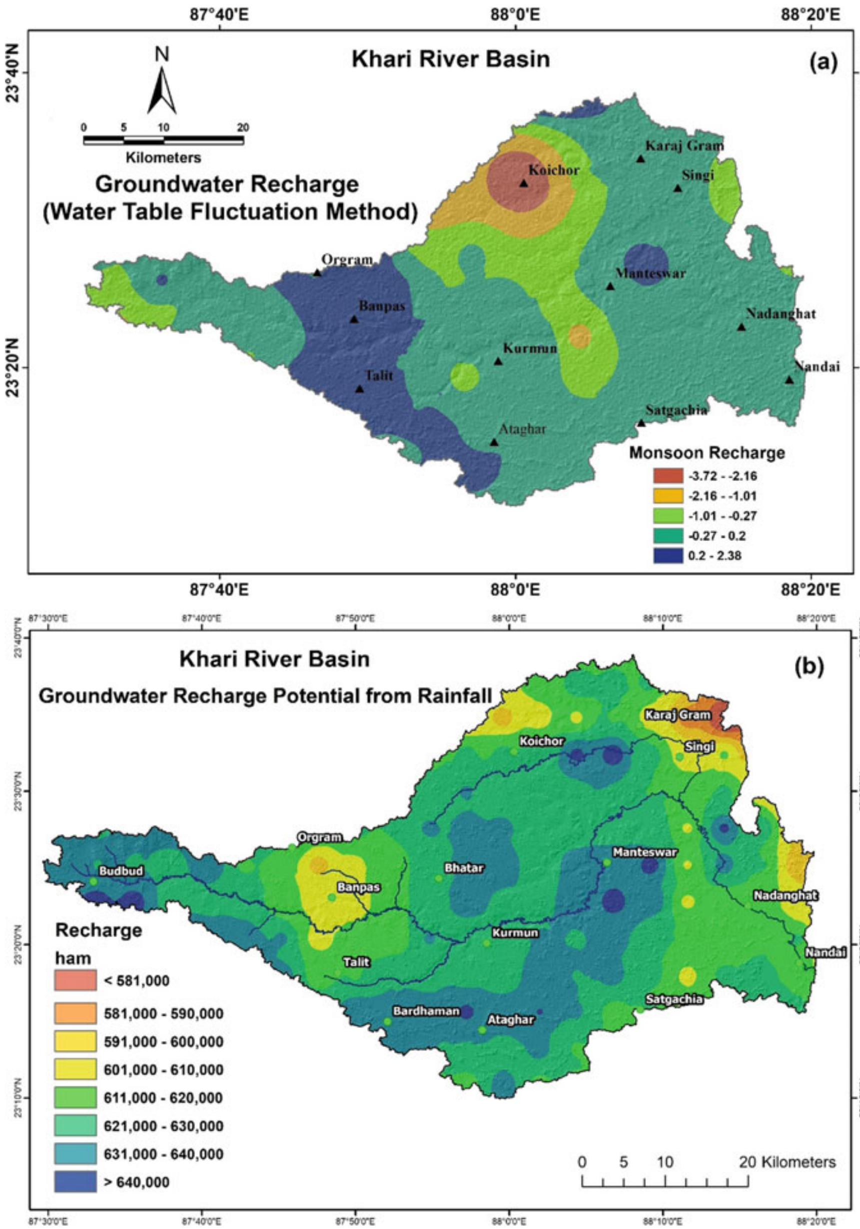

Fig. 9 **a** Spatial pattern of groundwater recharge from water table fluctuation method (August, 2019–August, 2020), and **b** potential groundwater recharge zones (>581,000 ham) from normal rainfall (2000–2020) in the basin

5 Discussion

Average cropping intensity as computed by the ratio of gross-cropped area to net cropped area has increased from 160% in 1994–1995 to 174% in 2000–2001. This rise in cropping intensity in the Lower Ganges Basin (mainly in Purba Bardhaman, Birbhum, Murshidabad and Nadia) is fuelled by intensive rice cultivation. The significant shift of cultivated area away from monsoon rice towards summer rice (Boro) accounting for about 305% total rise over the period 1980–1981 to 2000–2001. Crop water requitement or intensity is the highest (minimum 30,000 m^3 ha^{-1}) for summer rice which makes the situation more critical in preserving the groundwater resource in this region. Though the study area (renowned as 'rice bowl of India') receives abundant annual rainfall (1500 mm–1800 mm), but the region moves towards groundwater drought condition as the number of semi-critical blocks increases from 1 to 76 within 27 years (increase rate 2–3 per year). With the rapid development of tube well irrigation since 1980s coupled with chemical fertilization and higher profit margin pushed up the Boro rice cultivation areas of West Bengal to 1.6 million ha in 2004 from 0.26 million ha in 1989–1990. Intensive abstraction of groundwater (25,177–122,613 m^3 hr^{-1}) for irrigation are the prime factor for groundwater depletion (2–4 m in between 2019–2020 and 2020–2021) in the semi-critical blocks of the Khari Basin. According to Dangar et al. (2021) groundwater pumping for irrigation remains the primary driver of groundwater depletion, which can further affect food and water security in Indian states under climate change. A new finding is that low rate of rural electrification has forced majority of farmers to depend on diesel for groundwater pumping and the steep increase in diesel prices over the last few years has resulted in economic scarcity of groundwater (Mukherji, 2007).

Owing to tremendous pressure on irrigation sector in terms of water demand in future, timely assessment of crop water requirement for designing optimal cropping pattern is the need of the hour. In general, water requirement of popular crops is estimated as: (1) Rice: 900–1300 mm, (2) Sugarcane: 1800–2400 mm, (3) Potato: 400–600 mm, and (4) Wheat: 300–400 mm. Rice as grown in India is a water-guzzler, because farmers use on an average 15,000 L to produce one kg of paddy, depending on groundwater. Though water technologies at the Indian Agricultural Research Institute (IARI) in New Delhi said no more than 600 L is needed if proper water management techniques were followed. In Purba Bardhaman district first cropping system, i.e., Rice—Potato—Summer Rice, is very popular, and total crop water requirement with alternate cropping system (rice and potato) is near about 48,670 ham. Agricultural scientist feels that this is the right to introduce the strategy of smart water management system, i.e., 'more crop with less water'. A large amount of water is lost in seepage, deep percolation and flood water in the alluvial plains of Purba Bardhaman. Loss from deep percolation is estimated as 50% in heavy textured clay soils and about 85% in light textured loamy sands and laterite soils. Studies in eastern India show effective soil compaction and puddling can reduce percolation losses by 20% and also reduce the risk of crop failure during droughts.

Farmers widely believe that water should be stored on paddy fields to prevent weed growth, but studies in West Bengal and Odisha show that standing water of more than 10 cm height leads to heavy leaching of soil nutrients and percolation losses. In all seasons, a 2–5 cm water depth and intermittent irrigation saves 10–50% of water without adversely affecting yield. If irrigation is terminated 14–17 days before harvest, the grain would ripen uniformly and a considerable amount of water would be saved without lowering yield levels. Proper crop rotation can also reduce water consumption and result in higher yield. The key to sustainability of water resource development is only in shifting the focus from water resource development to water resource management that effectively encompasses both supply and demand side management issues (Roy et al., 2008). Educating people/farmers with scientific information on regional hydrological stress and mechanisms of water depletion and contamination is of paramount importance in successful supply-side management. In this monsoon dominated region, in situ rainwater harvesting and recharging is likely to be very effective as an enormous quantity of rainwater that becomes runoff to the rivers and sea. The groundwater recharge potential from rainfall varies from 581,000 to 643.000 ham, and the recharge amount will be facilitated using the ponds and tanks in the semi-critical blocks. So, maintenance and re-digging of such ponds and tanks can contribute significantly to the recharging of dried aquifers.

SCS-CN (Eq. 5 and 6) based runoff study (weighted curve number—77.06 for the Khari Basin) reveals that the basin yields potential monsoon runoff of 344–622 mm in the period 2000–2010 and 177–613 mm in the period 2010–2020 respectively. This amount of water is lost annually through the channels. Now, it is essential to think about managing the runoff water through trapping techniques along the main channels (use of bunds or check dams) or recharging directly into the aquifers. The analysis shows high runoff potential in Bhatar, Ausgram I and II, Galsi II, Mangolkote and Manteswar blocks where the depth of groundwater level is very high (greater than 11 m) than surroundings. The runoff water has chance of concentration in the zones of high TWI (5.98–23.29; using Eq. 7) where the semi-critical blocks (mainly Bhatar, Katwa I, Purbasthali II and Manteswar) is annually flooded due to overflow of the Khari River (Fig. 10a). Now it is the time to rethink the flood water as resource for the groundwater-stressed region. This region was flooded for maximum 10 to 12 days in heavy monsoon month. If this flood water (area of 118.12 km^2 or 11,812 hect) can recharge the aquifers directly through main channels and palaeochannels, the level of groundwater will rise gradually in future. Groundwater recharge from an active floodplain is mainly function of areal extent of floods, return period of flood, type of sub-soil strata and silt charge in the river water. Therefore, the potential water resource in the flood prone area (Fig. 10b and 10c) is estimated as nearly 1984,416 m^3 per year which can be added as groundwater repository.

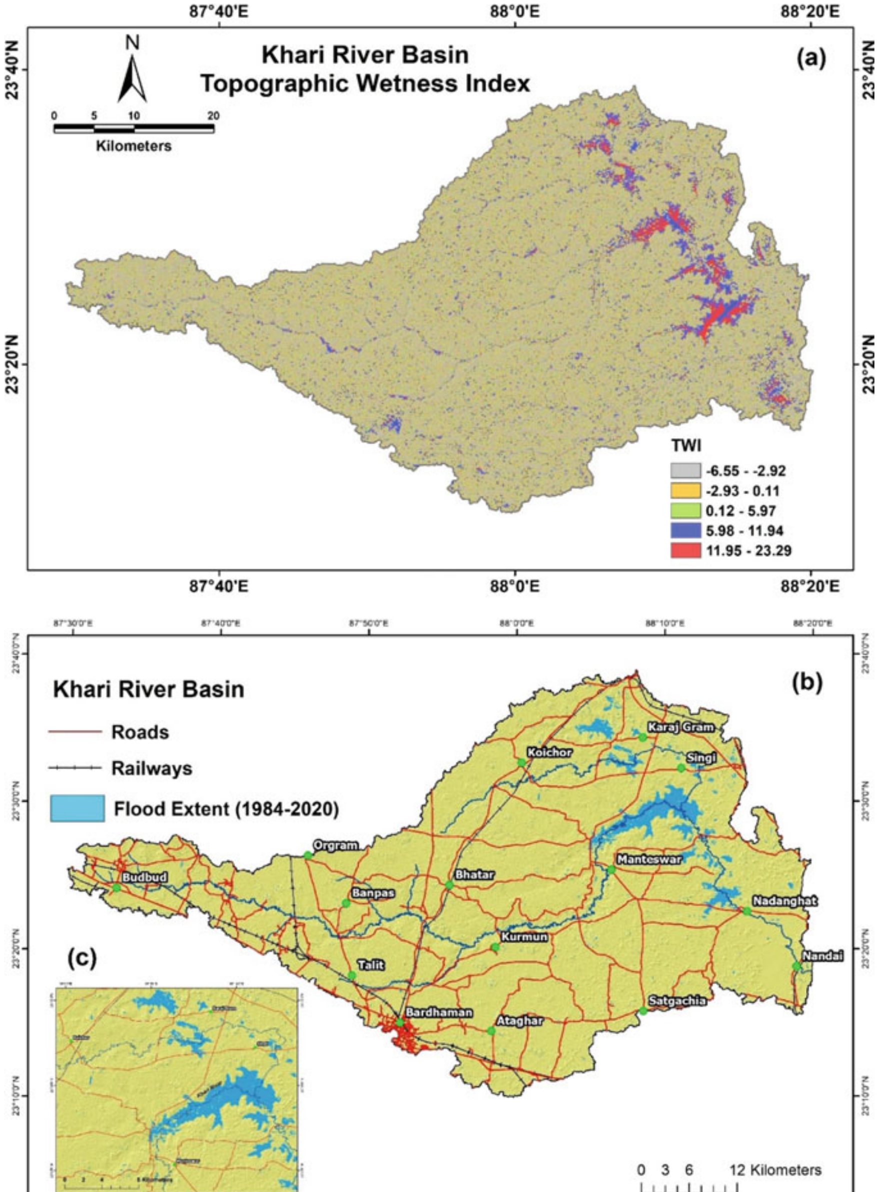

Fig. 10 **a** Topographic wetness index map showing the spatial pattern of maximum water concentration region (TWI > 5.98), **b** annual extent of flood water (resembling with high TWI region) in the basin, and **c** key prospect region introducing flood water as resource and groundwater repository

6 Conclusion

The analysis suggests an alarming fact that being a part of multiple aquifer rich Quaternary Lower Ganges Basin, the intake depth of groundwater is beyond 70 m bgl in the southern part of West Bengal due to high population demand, irrigation abstraction and intensity of Boro rice cultivation. The dwindling groundwater resource is also faced As (arsenic sulphides) and Fe contamination in the eastern part of the basin because the shallow aquifers (up to range to 20–60 m bgl) are already dried and exposed to aeration and oxidization (make As in water soluble). Field observation reveals the dominancy of Boro cultivation (62% of total rice production; 19 to 90 metric tonnes) in connection with significant growth of shallow and deep tube well (number in 2016–2017—1588) irrigation system in the district. In the district the use of surface water irrigation is declining (100–92.68% in between 1995–1996 and 2010–2011) and groundwater irrigation is increasing (0–7.32% in between 1995–1996 and 2010–2011) in crop production. The result is the declination of DWL to a significant depth (fall of 3.5 cm yr^{-1}) in Mangolkote, Bhatar, Manteswar, Memari II and Purbasthali II which are the CGWB-recommended semi-critical blocks of West Bengal. Now, sustaining the massive welfare gains that groundwater has created in West Bengal without running the resource base is key water challenge facing the semi-critical blocks today. To achieve drought projection and drought resilience there is a need to stop over-exploitation of groundwater for irrigation. The geo-spatial analysis emphasizes on the sustainable use of water resources (optimum water requirement in Boro rice cultivation) and recharge opportunity in the good to very good groundwater potential zones. The rejuvenation of paleochannels (present day deposits) and flood water utilisation can enhance the storage capacity of groundwater in the basin. Therefore, there is a need of alternative plan to manage supply side of water resources through natural and artificial recharge techniques in the Khari River Basin of Purba Bardhaman.

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Application of Geospatial Techniques to Demarcate Groundwater Availability Zone in Bangladesh

M. M. Shah Porun Rana, Mallik Akram Hossain, and Md. Enamul Huq

Abstract Overexploitation of ground water has imposed immense pressure on the groundwater resources in Bangladesh. To mitigate this water shortage problem, demarcation of ground water availability is one of the main concern for the country. So, delineation of ground water availability by making groundwater potential zonation map of Bangladesh is one of the major objectives of this paper. Analytical hierarchy process (AHP) in association with geographical information system (GIS) & remote sensing have been utilized in this study. Twelve spatial layers such as elevation, slope, physiography, soil types, soil texture, soil porosity, topographic wetness index (TWI), modified normalized difference water index (MNDWI), curvature, rainfall, drainage density, land use land cover (LULC) have been integrated with overlay analysis in ArcGIS 10.5 software to develop ground water availability zone map for the year of 2020. The resulting groundwater availability zone map have been categorized into five classes for example, poor, low, moderate, high, and excellent. The findings of this research show that 21.09% land of Bangladesh comprise of "high-excellent" ground water availability zone while the "moderate" ground water potential zone include 58.33% followed by low to poor 20.58%. The study also reveals that north-western part of Bangladesh (Dinajpur, Rangpur, Thakurgaon, Nilphamari, Joypurhat, Naogaon, Chapainawabganj, Rajshahi, Kurigram), hilly region (Rangamati, Khagrachari, Bandarban), Gazipur & Dhaka contribute "Low-poor" groundwater potential zone, while coastal part of the country contributes excellent groundwater availability zone. The outcome of this study will be helpful to identify suitable locations to extract and preserve ground water for further use.

M. M. S. P. Rana · M. A. Hossain (✉)
Department of Geography and Environment, Faculty of Life and Earth Science, Jagannath University, Dhaka, Bangladesh
e-mail: mallik.a@geography.jnu.ac.bd

M. M. S. P. Rana
e-mail: shahparanranageo38@gmail.com

Md. E. Huq
College of Environmental Science, Hohai University, Nanjing, China
e-mail: enamul_huq@whu.edu.cn

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1 Introduction

By groundwater potential, we understand probability of groundwater availability in an area (Jha et al., 2010). Groundwater, an indispensable natural resource which is stored beneath the ground area is the vital part of crustal plate (Arulbalaji et al., 2019). It acts as sustaining natural resource providing the regular water demands of local inhabitants, raw materials in industrial activities, and also supports agricultural expansion of a country (Biswas et al., 2020). In developing countries both sustainable economic growth and fresh water supply are highly dependent on groundwater (Bhunia et al., 2012). Groundwater plays crucial role in agro-economy, hydrology, biodiversity, and ecosystem. Estimation confirms that groundwater provides approximately one third of fresh water globally while 27%, 38%, 42% of the total groundwater is utilized for industrial, household and agriculture purposes respectively (Taylor et al., 2013). Unfortunately, it is fact that the level of groundwater is severely affected by natural and anthropogenic factors. Though Bangladesh is a riverine country with 310 rivers, surface water does not satisfy the total human requirements due to geopolitical issues, developmental activities, climatic issues etc. The birth places of three major rivers (Ganges, Brahmaputra, Meghna) of Bangladesh are beyond the borders and Bangladesh receives a very little amount of water during dry season. Bangladesh has almost no control over the flow of Ganges river due to the establishment of Farakka barrage by India. The northern part of Bangladesh has been suffering from water scarcity due to Teesta barrage, an infrastructure at Gazaldobain in India, which has diverted 85% of water flow of Teesta River without Bangladesh's concern. The lack of control over the flow of water in transboundary rivers have put Bangladesh in a very perilous state which has created a negative impact on the economy, livelihood and the ecosystems. For this reason, the dependency on ground water is increasing day by day in Bangladesh. According to FAO, approximately 79% of irrigation depends on groundwater in Bangladesh. In Bangladesh, groundwater supplies 98% and 80% of fresh water for drinking & irrigation purposes respectively (Shamsudduha et al., 2012). It has been measured by 2011 Bangladesh Census that primarily groundwater supplies are accessible to 31 million households of Bangladesh where tube wells, tap water, dug wells are being used to access this ground water . Extraction of groundwater from deep aquifers is a popular mitigation strategy which has been adopted in last couple of decades for drinking-water supply in the Bengal basin (Burgess et al., 2010). As the uses of underground water have increased, acute water crisis looms over the country. Population growth, industrial expansion, urbanization, agricultural development, unscientific exploitation of groundwater has played a crucial role to exacerbate this situation. Water scarcity is one of the major environmental barriers in the northern part of Bangladesh that decrease the crop productivity and other developmental activities. Especially, the water scarcity is experienced from late July to early November in this region and people call this period "*Mora Kartik*", which in turn often led to drought situations, unemployment and food insecurity. Inadequacy of fresh water is also a pertinent issue for the people who are living in the country's south eastern hilly region. To fetch drinking water is one of the major challenge to the women of hilly area and they have to walk few miles for collecting drinking water. Many villages of Rangamati, Khagrachhari and Bandarban districts in Chittagong hilly area are suffering an acute crisis of water due to drying up of natural springs. It has been claimed by the experts and local families that maximum springs and streams in these villages are highly affected by some anthropogenic and natural factors such as stone extraction, deforestation, landslides, flash flood etc. In 2021, Bandarban health engineering department stated that, 70% of inhabitants do not have water supply in four remote upazila of Bandarban district namely Ruma, Thanchi, Rowangchhari, and Alikadam. The current scenario of the water scarcity issue in the Chittagong hill tract (CHT) is going from bad to worse as groundwater has fallen to 150 feet. With increasing demand of underground water, the layer of groundwater is decreasing throughout the whole country. So, it is urgently needed to conserve the groundwater availability for sustainable development. Both conventional and advanced method have been used for identifying groundwater resources (Arefin, 2020). Conventional method is very expensive and time consuming, conducting with field survey while analytical hierarchy process (AHP), shannon entropy (Zabihi et al., 2015), weighted overlay method, frequency ratio (Guru et al., 2017), random forest model (Naghibi et al., 2015), logistic regression model (Pourtaghi & Pourghasemi, 2014) and weighted aggregation method (WAM) are the example of advanced method for delineating groundwater potential zone (Arefin, 2020). Analytic hierarchy process (AHP) combined with geospatial tools have been treated as a convenient, environmentally friendly and economically-efficient approach to as certain the groundwater availability zone (Ishizaka & Labib, 2011; Machiwal et al., 2011; Maity & Mandal, 2019). Numerous researches have been carried out by different scholars in different places globally for exploring potential underground water zones using GIS & remote sensing in Central Eastern Desert, Egypt (Abdalla, 2012); Vaigai upper basin, Tamil Nadu (Seenipandi & Chandrasekar, 2013); Coimbatori district, South India (Kom et al., 2022) Gumani river basin, India (Mahammad & Islam, 2021a); Damudar Fan Delta, India (Mahammad & Islam, 2021b); Burdur, Turkey (Sener et al., 2005); Comoro watershed, Timor Leste (Pinto et al., 2015); Ghana (Gumma & Pavelic, 2013); Paschim Medinipur district, India (Bhunia et al., 2012). Studies have also been carried out by different researchers in Bangladesh for evaluating the groundwater resource using geospatial techniques in Dhaka City, Bangladesh (Arefin, 2020); barind tract NW Bangladesh (Rahaman et al., 2018); north west region of Bangladesh (Sresto et al., 2021); Dinajpur district, Bangladesh (Rana et al., 2022). Though many studies have been performed in different localities of Bangladesh for locating groundwater potential zone, there is no intensive research work that considers the whole country as the study site. So, to replenish this research gap, this research was performed. As many as 12 parameters such as elevation, slope, physiography, soil types, soil texture, soil porosity, topographic wetness index (TWI), modified normalized difference water index (MNDWI), curvature, rainfall, drainage density, land use land cover (LULC) have been integrated, applying analytical hierarchy process based geospatial technique to give a wider vision of groundwater availability in the study area.

2 Study Area

Bangladesh is considered in this research as the study site. It is situated in the southern side of the Himalayan mountain region while southern part of the country opens into the Bay of Bengal. Bangladesh shares its land boundaries with India and Myanmar, and lies in within 20° 34′ to 26° 38′ N latitude and 88° 01′ to 92° 41′ E longitude. The country has been crisscrossed by 310 rivers and consists of four significant river systems: the Brahmaputra-Jamuna, the Ganges-Padma, the Surma-Meghna and the Chittagong region river system which dominate the whole country. A humid & warm climate along with six several types of season is observed in Bangladesh. In winter, the minimum average temperature is 15° Celsius while the average maximum temperature rises to 34° Celsius in summer. An average of 1733 mm of annual rainfall has been recorded in the monsoon season (Uddin et al., 2019). Though Bangladesh is a riverine country, it has experienced 9 major droughts during last 45 years (Rahaman et al., 2018). More than half portion of the country is less than 10 meter of mean sea level (Uddin et al., 2019). As a result, maximum land portion of the country is used for crop production which requires a huge amount of water for irrigation purpose. In the study area, irrigation is mostly dependent on groundwater during dry season. Groundwater also provides a major source of drinking water. Considering the above, Bangladesh (Fig. 1) has been chosen as the study site in this research.

3 Data Sources and Methodology

To complete the research, available and reliable data are very much essential. To conduct this study several data sets have been collected from secondary data sources. Twelve different types of thematic maps have been prepared from various spatial datasets and existing maps (Table 1). These twelve thematic layers have played a significant role for exploring groundwater availability in the present study. The Shuttle Radar Topographic Mission (SRTM—30 m resolution) data is used to derive the elevation, slope, drainage density, curvature and TWI in this research. The LULC map for the year of 2020 is collected from the GlobeLand30. The value of MNDWI from 1/1/2020 to 31/12/2020 is produced from LANDSAT image having 30-m resolution. From the NASA POWER Data Access Viewer, the annual precipitation data is collected for the year of 1981–2015. Soil related thematic layers and physiography map have been collected from Bangladesh Agriculture Research Council (BARC) and U.S. Government's open data portal respectively. The flow chart presented in

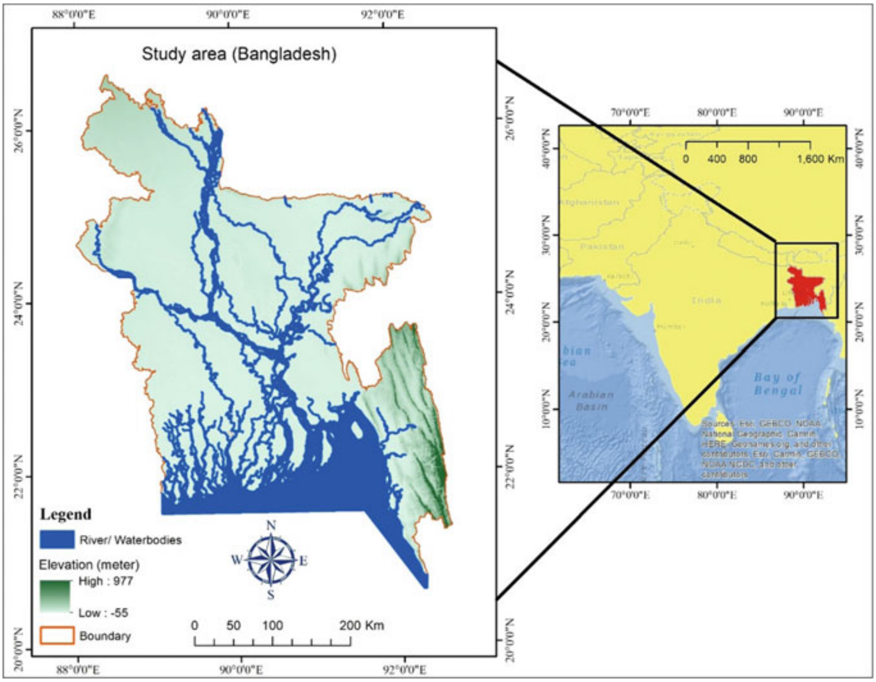

Fig. 1 Study area

Fig. 2, presents the methodology employed in this paper. The groundwater availability zonation map has been made after combining the all 12 thematic layers by using overlay operation in Arc GIS software, while analytical hierarchy process (AHP) has been considered to provide weightage value of every single thematic layer. Roy et al. (2020) and Biswas et al. (2020) also adopted AHP based geospatial techniques to determine ground water potential zone in red-lateritic zone of West Bengal as well as in Uttar Dinajpur of India respectively, which share border with north western part of Bangladesh. These two regions possess similar climatic and physiographic characteristics like our study area. Prior to the overlay method, all the vector data were transferred into raster format. Respective spatial layers were also rearranged assigning the measurement ranging from 1–10. The ranking has been done based on literature search and field observation (Roy et al., 2020). In the next stage, the spatial analyst tools in ArcGIS environment is used to superimpose all spatial layers for making the ground water availability area map (Behzad et al., 2019) (Table 1).

Table 1 Data sources for the study

Data	Sources	Year
Digital elevation model (DEM)	(USGS 1 arc second), UTM-45, WGS 1984	2014
Land use land cover map (LULC)	GlobeLand30	2020
Curvature	DEM (USGS 1 arc second), UTM-45, WGS 1984	2014
MNDWI	Landsat 5 (TM) & Landsat 8 OLI, United States Geological Survey Earth Explorer	2020
Slope	DEM (USGS 1 arc second), UTM-45, WGS 1984	2014
Drainage density	DEM (USGS 1 arc second), UTM-45, WGS 1984	2014
TWI	DEM (USGS 1 arc second), UTM-45, WGS 1984	2014
Soil types	Bangladesh Agriculture Research Council (BARC)	1988
Soil porosity	Bangladesh Agriculture Research Council (BARC)	1988
Soil texture	Bangladesh Agriculture Research Council (BARC)	1988
Rainfall	NASA POWER Data Access Viewer	1981–2015
Physiography	Data.gov	2001

3.1 Analytical Hierarchy Process (AHP)

At first, Saaty (1980) had introduced Analytical Hierarchy Process (AHP) and most researchers have considered it as statistical tool (De Felice et al., 2015). The consolidation of AHP and geospatial techniques have been employed to integrate geomorphologic, topographic and climatic data for the delineation of groundwater stock in the current study site. In AHP, different steps have been followed to find weights for each class and consistency ratio. Stages which have been followed in the process of analytical hierarchy process (AHP) (Pramanik, 2016) are given below.

Step 01—To specify the objective as well as describe the attributes.

Step 02—To build up a decision matrix, $D_{M \times N}$.

$$
\begin{array}{cc}
 & \begin{array}{cccccc} Attribute & 1 & 2 & 3 & -- & N \end{array} \\
D_{M*N} = & \begin{array}{c|cccc|}
1 & d_{11} & d_{12} & d_{13} & -- & d_{1N} \\
2 & d_{21} & d_{22} & d_{23} & -- & d_{2N} \\
3 & d_{31} & d_{32} & d_{33} & -- & d_{3N} \\
- & - & - & - & -- & - \\
- & - & - & - & -- & - \\
M & d_{M1} & d_{M2} & d_{M3} & -- & d_{MN}
\end{array}
\end{array}
$$

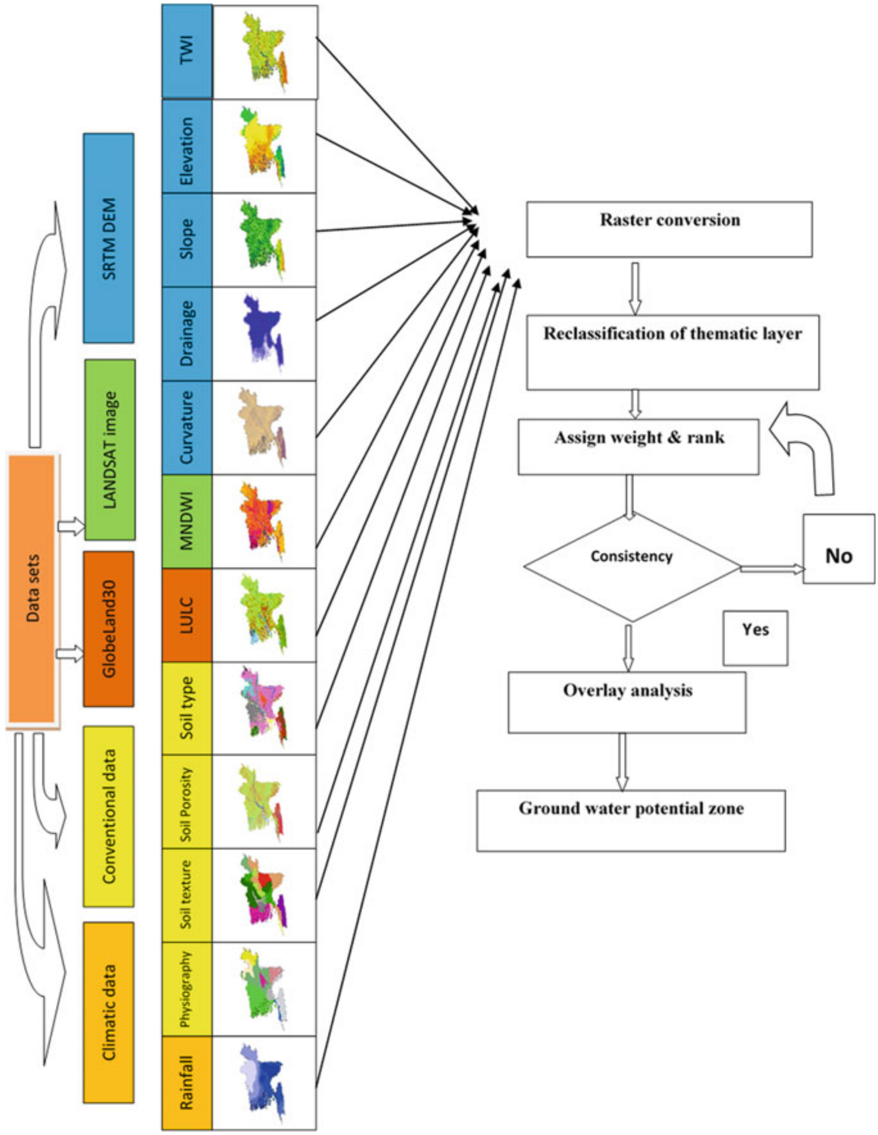

Fig. 2 Flowchart of methodology *Source:* Modified from Rana et al. (2022)

Step 03—Creating a pair wise comparison matrix (PWCM) (Table 4) with AHP evaluation scale (Table 2) (Saaty, 1980).

Step 04—Computing the geometric mean (G.M) of i th row (Table 5).

Table 2 Description of AHP evaluation scale (Saaty, 1980)

Intensity of importance	Definition
1	Equally important
3	Slightly important
5	Quite important
7	Extremely important
9	Absolutely important
2,4,6,8	Intermediate values of relative importance
Reciprocal of above values	If activity i has relative significance of a_{ij} when compared with activity j, then j has importance $1/a_{ij}$ when compared with i

$$\mathrm{G.M} = [\prod_{(i=1)}^{N} a_{ij}]^{1/N} \tag{1}$$

Step 05—To calculate the normalized weight of geometric mean of i^{th} row.

$$W = \mathrm{G.M} / \sum_{(i=1)}^{N} \mathrm{G.M} \tag{2}$$

Step 06—Finally Consistency ratio (C.R) has been calculated for justifying the coherence of the judgments.

The idea of uncertainty and inconsistency in AHP method are found out with the help of consistency index (CI) and consistency ratio (CR) (Saaty, 2004). Eq. 3 has been used to calculate Consistency ratio (CR) (Saaty, 1980).

$$\mathrm{C.R} = \mathrm{C.I/R.I} \tag{3}$$

Here, C.I indicates consistency index and R.I is the Saaty's ratio index (Table 3). The following Eq. 4 has shown the calculation of consistency index.

$$\mathrm{CI} = (\lambda\max - N)/(N - 1) \tag{4}$$

Here, λmax=eigenvalue. The judgment of the pairwise comparison matrix is ideally consistent and performed correctly when the value of CR is equivalent to zero. Besides, a consistency ratio (CR) value of ≤ 0.1 indicates an allowable inconsistency. The values are needed to be re-examined, amended and reevaluated when the value of CR is greater than 0.1 (Arulbalaji et al., 2019; Pinto et al., 2015) (Table 6).

Table 3 Saaty's ratio index (Saaty, 1990)

n	1	2	3	4	5	6	7	8	9	10	11	12
R.I	0.0	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

Table 4 Pairwise comparison matrix for all parameters

Main Criteria	SL	LULC	EV	DD	RF	MNDWI	PHY	ST	STex	SP	CV	TWI
Slope	1	2	2	3	3	4	5	5	6	7	8	9
LULC	1/2	1	2	3	3	4	5	6	7	7	8	9
Elevation	1/2	1/2	1	2	2	3	4	5	5	6	7	8
Drainage density	1/3	1/3	1/2	1	2	3	3	4	5	6	7	8
Rainfall	1/3	1/3	1/2	1/2	1	2	3	3	4	5	6	7
MNDWI	1/4	1/4	1/3	1/3	1/2	1	2	3	3	4	5	6
Physiography	1/5	1/5	1/4	1/3	1/3	1/2	1	2	3	3	4	5
Soil Type	1/5	1/6	1/5	1/4	1/3	1/3	1/2	1	2	3	3	4
Soil texture	1/6	1/7	1/5	1/5	1/4	1/3	1/3	1/2	1	2	3	3
Soil Porosity	1/7	1/7	1/6	1/6	1/5	1/4	1/3	1/3	1/2	1	2	3
Curvature	1/8	1/8	1/7	1/7	1/6	1/5	1/4	1/3	1/3	1/2	1	2
TWI	1/9	1/9	1/8	1/8	1/7	1/6	1/5	1/4	1/3	1/3	1/2	1

4 Result and Discussion

The next part focuses on the analysis and interpretation of the study. This section represents generation of thematic layers and determination of groundwater potential zone in Bangladesh.

4.1 Data Analysis

This section describes the spatial layers which have been considered in this study. Depending on the availability of the data, twelve spatial layers are generated for this paper. The availability of groundwater in the study area mainly depends on these twelve layers where highest weightage is assigned to slope owing to its excellent ground water recharge ability. Other layers also have vital role in evaluating groundwater availability area. Notable aspect of these twelve spatial layers are elaborated in the next part.

Table 5 Normalized weight calculation for all the thematic layers

Main Criteria	SL	LULC	EV	DD	RF	MNDWI	PHY	ST	STex	SP	CV	TWI	G.M	Weight
Slope	1	2	2	3	3	4	5	5	6	7	8	9	3.86	0.216
LULC	1/2	1	2	3	3	4	5	6	7	7	8	9	3.54	0.198
Elevation	1/2	1/2	1	2	2	3	4	5	5	6	7	8	2.61	0.146
Drainage density	1/3	1/3	1/2	1	2	3	3	4	5	6	7	8	2.08	0.117
Rainfall	1/3	1/3	1/2	1/2	1	2	3	3	4	5	6	7	1.65	0.093
MNDWI	1/4	1/4	1/3	1/3	1/2	1	2	3	3	4	5	6	1.18	0.066
Physiography	1/5	1/5	1/4	1/3	1/3	1/2	1	2	3	3	4	5	0.87	0.049
Soil Type	1/5	1/6	1/5	1/4	1/3	1/3	1/2	1	2	3	3	4	0.66	0.037
Soil texture	1/6	1/7	1/5	1/5	1/4	1/3	1/3	1/2	1	2	3	3	0.50	0.028
Soil Porosity	1/7	1/7	1/6	1/6	1/5	1/4	1/3	1/3	1/2	1	2	3	0.38	0.021
Curvature	1/8	1/8	1/7	1/7	1/6	1/5	1/4	1/3	1/3	1/2	1	2	0.29	0.016
TWI	1/9	1/9	1/8	1/8	1/7	1/6	1/5	1/4	1/3	1/3	1/2	1	0.22	0.012

CR value = 0.042 and $\lambda max = 12.68$

Table 6 Assignment of normalized weight and ranking to all thematic layers

Thematic layer	Classes	Weight (W)	Rank (r)
Slope (degree)	0–2.025	0.216	10
	2.026–6.364		8
	6.365–13.6		6
	13.61–24.01		4
	24.02–73.77		2
LULC	Artificial surface	0.198	2
	Cultivated land		5
	Sand bar		6
	Shrubland		6
	Grass land		7
	Forest		8
	wetland		9
	Water bodies		10
Elevation	(-55 to 3) meter	0.146	10
	(4–10) meter		9
	(11–30) meter		7
	(31–75) meter		5
	(76–300) meter		4
	> 300 m		2
Drainage density (km/sq.km)	0–0.5208	0.117	10
	0.5209–0.7966		8
	0.7967–1.057		6
	1.058–1.294		4
	1.295–1.953		2
Rainfall (mm/year)	1001.11–1245.99	0.093	2
	1245.99–1422.02		3
	1422.02–1585.70		5
	1585.70–1725.98		7
	1725.98–2126.24		8
MNDWI	−0.6787 to −0.3122	0.066	2
	−0.3121 to −0.1789		4
	−0.1788 to 0.021		6
	0.02101–0.3153		8
	0.3154–0.7373		10

(continued)

Table 6 (continued)

Thematic layer	Classes	Weight (W)	Rank (r)
Curvature	−18.76 to 0.1309	0.016	1
	−0.1308 to 0.2989		2
	0.299–17.78		3
Thematic layer	Classes	Weight (W)	Rank (r)
Soil porosity	(20–30) %	0.021	3
	(31–40) %		4
	(41–50) %		6
	(51–60) %		8
	(61–70) %		9
Soil texture	Sandy	0.028	10
	Clay		3
	Loam		7
	Silt		6
	Sandy loam		9
	Sandy clay		8
	Sandy clay loam		5
	Silty clay		5
	Silty clay loam		6
	Silty loam		6
	Clay loam		4
	Loamy sand		7
Soil types	Calcareous Alluvium	0.037	9
	Noncalcareous Alluvium		8
	Calcareous Floodplain Soil		10
	Noncalcareous Floodplain Soil		9
	Brown Hill Soil		6
	Grey Piedmont Soil		6
	Peat		6
	Brown Mottled Terrace Soil		4
	Acid Sulphate Soil		5
	Acid Basin Clay		4

(continued)

Table 6 (continued)

	Forest		7
	Urban		2
	Red-Brown Terrace Soil		4
	Waterbodies		10
	Black Terrai Soil		3
	Grey Terrace Soil		3
Thematic layer	Classes	Weight (W)	Rank (r)
Physiography	Barind tract	0.049	2
	Coastal plain		8
	Delta		7
	Depression		5
	Fan		4
	Flood plain		9
	Hills		2
	Madhupur tract		4
	Tippera surface		5
TWI	2.3056–6.6104	0.012	2
	6.6105–7.8288		4
	7.8289–9.4532		6
	9.4533–12.052		8
	12.053–23.018		10

Source Modified from Rana et al. (2022)

4.1.1 Slope

Slope, an important topographic criteria for indicating groundwater availability is expressed as the steepness of the land surface (Arulbalaji et al., 2019; Kumar et al., 2016). The runoff infiltration rate and quality of sedimentation are measured by slope and it also provides essential input on the features of geologic and geodynamic processes operating at spatial scale (Acharya et al., 2019; Biswas et al., 2020). Higher slope values are considered as stepper surface and suitable for low infiltration along with little groundwater recharge. Besides, lower slope values indicate plane surface along with high water infiltration rate and more groundwater recharge (Adiat et al., 2012; Kumar et al., 2016). The slope map is generated from digital elevation model (DEM) using spatial analyst tool in Arc GIS platform. Besides, this map (Fig. 3a) varies from 0° to 73.77° and it has been reclassified into 5 classes namely flat (0–2.025)°, gentle (2.026–6.364)°, medium (6.365–13.6)°, high (13.61–24.01)°, very high (24.02–73.77). The categories occupy 54.50%, 37.87%, 4.57%, 2.33%, 0.73% study area, respectively. The Maximum part of the site consists of flat slope

(0 to 2.025)°, which encompasses the district of Jessore, Narail, Gopalganj, Shariatpur, Chandpur, Satkhira, Khulna, Bagerhat, Pirozpur, Jhalakati, Barguna, Barisal, Patuakhali, Bhola, Lakshmipur, Noakhali, and Feni.

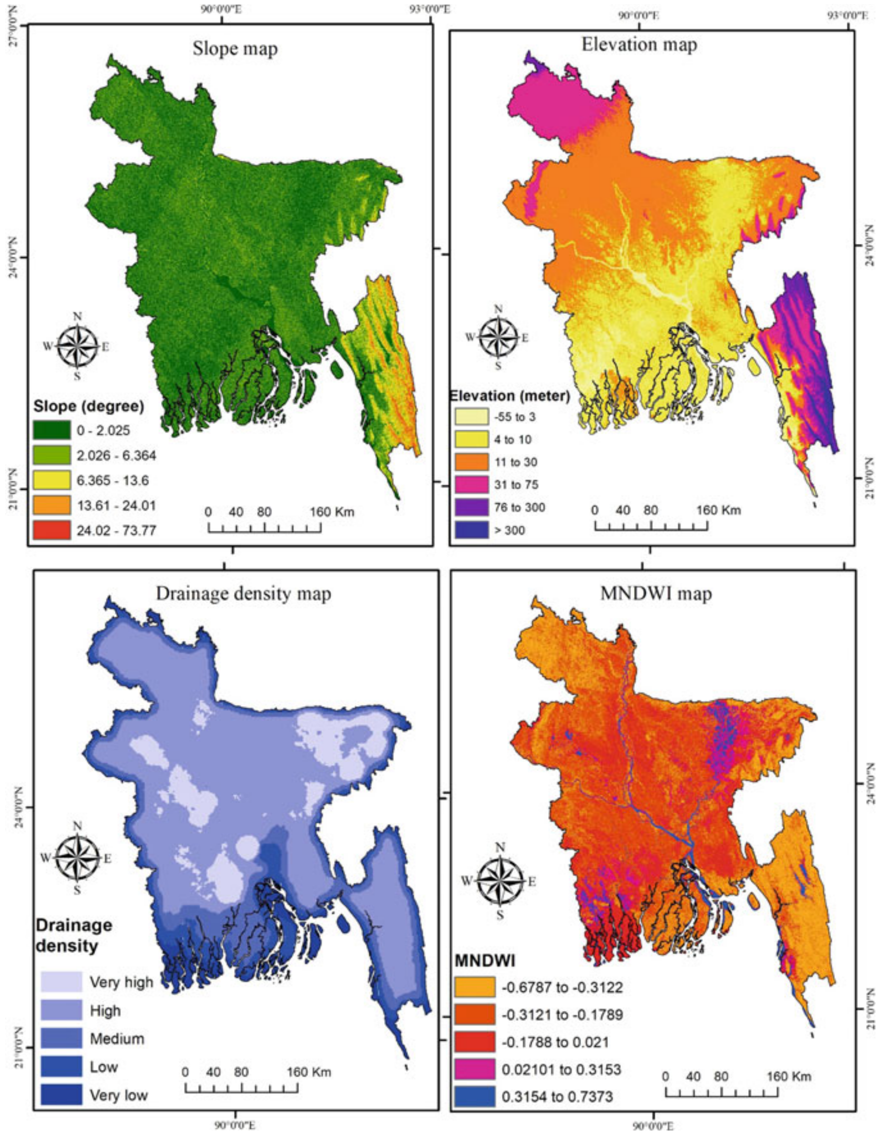

Fig. 3 **a** Slope map (2014), **b** Elevation map (2014), **c** Drainage density map (2014), **d** MNDWI map (2020)

4.1.2 Elevation

The elevation map of Bangladesh (Fig. 3b) is prepared by plotting SRTM DEM data in Arc GIS software. A low elevated area contains higher efficient water recharge sources than the high elevated area. For this reason, high rank has been given to the low elevation and low rank to the high elevation in this research (Rana et al., 2022). The elevation of our studied area differs from 55 m to 977 m and is categorized into six classes namely (−55 to 3) meter, (4–10) meter, (11–30) meter, (31–75) meter, (76–300) meter, > 300 m. The largest area is covered by (11–30) meter elevation which include the district of Sherpur, Jamalpur, Mymensingh, Bogura, Sirajganj, Tangail, Gazipur, Gaibandha, Rajshahi, Natore, and Pabna.

4.1.3 Drainage Density

Drainage density has a key role in examining land surface to demarcate groundwater availability zone (Ganapuram et al., 2009). Drainage density can be described as the reflection of topographic characteristics (Manap et al., 2013). Several terrain related information such as run-off, infiltration, relief and permeability-related information can be easily measured from drainage density. According to Waikar and Nilawar (2014), higher value of drainage density exists in stepper or high elevated region while lower value of drainage density expand in a flat surface with abundant vegetation. An area with low drainage density is more capable for high groundwater availability than the region with high drainage density. For this reason, it has been put high rank to low drainage density and low rank to high drainage density in this research. Lastly, the drainage density map of Bangladesh (Fig. 3c) has been classified into five categories- very low (0–0.5208) km/km^2, low (0.5209–0.7966) km/km^2, medium (0.7967–1.057) km/km^2, high (1.058 - 1.294) km/km^2 and very high (1.295–1.953) km/km^2. Very low drainage density covers only 6.69% area, while very high drainage density occupies 11.73% area.

4.1.4 MNDWI

Xu (2005) first developed the idea of modified normalized difference water Index (MNDWI) to extract the information of the land surface water. Generally, MNDWI is applied to determine the presence of water bodies as well as ground cover by eliminating atmospheric noise and terrain disturbances. Generally green and SWIR bands have been adopted to find the value of MNDWI (Biswas et al., 2020).

$$\text{MNDWI} = (\text{Green} - \text{SWIR}) \div (\text{Green} + \text{SWIR}) \quad (5)$$

The MNDWI map of Bangladesh (Fig. 3d) is prepared from Landsat image in Google Earth Engine and reclassified into 5 categories namely very low (−0.6787 to

−0.3122), low (−0.3121 to −0.1789), medium (−0.1788 to 0.021), high (0.02101–0.3153), very high (0.3154–0.7373). These classified areas are captured by 29.45%, 42, 17.38%, 6.51%, 4.66% land of the study site respectively. In this research, high rank has been assigned to high MNDWI value and vice versa.

4.1.5 Curvature

Curvature is expressed as the nature of topographic profile and it represents the morphology of the regional topography (Nair et al., 2017; Vijith & Madhu, 2008). A non-negative value of curvature is characterized by convex surface, while a negative value of curvature refers to concave surface. On the contrary a null value of curvature indicates a flat surface. Water tends to slow down in convex profile and aggregate in concave profile (Arulbalaji et al., 2019). The spatial distribution of curvature map (Fig. 4d) has been grouped into 3 classes such as (−18.76 to − 0.1309), (− 0.1308 to 0.2989) and (0.299–17.78). These categories contain 16.82%, 77.22%, 5.96% area of the total land in our study area respectively. Considering the groundwater potentiality, high curvature area such as some parts of the Chittagong and Sylhet division have been given high rank than that of the low curvature area.

4.1.6 Rainfall

Rainfall performs as a primary source of ground aquifer recharge as well as it is considered as a major component of hydrological cycle (Biswas et al., 2020). The infiltration rate is influenced by the intensity and duration of rainfall. In this study, rainfall data of the years 1981–2015 have been used which had been downloaded from the website of NASA POWER Data Access viewer. The annual rainfall map of Bangladesh is generated using IDW interpolation method in GIS environment and the value ranges from 1001.109 mm to 2126.24853 mm. This spatial distribution of annual rainfall map (Fig. 4a) has been categorized into five extensive classes such as (1001.109924–1245.99218) mm/year, (1245.992188–1422.02429) mm/year, (1422.024292–1585.70251) mm/year, (1585.702515–1725.98242) mm/year, (1725.982422–2126.24853) mm/year. High rank is given to high value of rainfall due to carrying high infiltration rate and low rank is assigned to low rainfall value for carrying low infiltration rate. High rainfall region includes the coastal areas of Chittagong and northern part of Sylhet district, while it has been observed that the minimum rainfall is recorded in the northern and western parts of the study area.

4.1.7 TWI

The term TWI stands for "Topographic Wetness Index" and at first (Beven & Kirkby, 1979) introduced the concept of TWI. It is one of the dominant variable that is

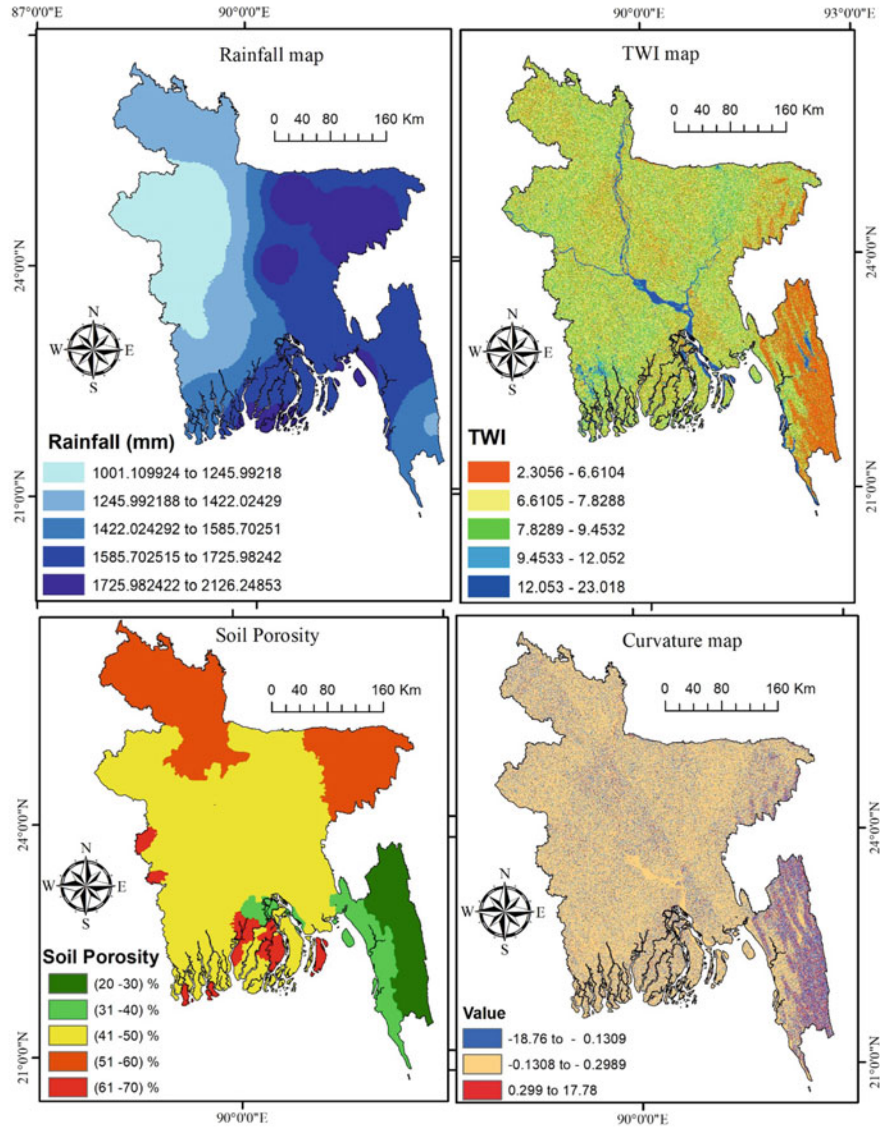

Fig. 4 **a** Rainfall map (1981–2015), **b** TWI map (2014), **c** Soil Porosity map (1988), **d** Curvature map (2014)

generally used to quantify the assessment of water availability in a surface that has been affected by the impact of water accumulation (Biswas et al., 2020; Mokarram et al., 2015). The TWI map of Bangladesh (Fig. 4b) has been made from SRTM DEM data with the help of GIS platform (Ågren et al., 2014; Biswas et al., 2020).

$$T.W.I = \ln \frac{A}{\tan \beta} \quad (6)$$

Here, A is denoted for the specific catchment, while tan β is indicated for the slope angel of the particular grid. As high TWI is characterized by high water availability than low TWI, high rank has been assigned to high TWI value and vice versa. According to the classification system the TWI map (Fig. 4b) is divided into five classes-very low (2.3056–6.6104), low (6.6105–7.8288), moderate (7.8289–9.4532), high (9.4533–12.052), very high (12.053–23.018). Very low TWI covers 21.83% area, while very high TWI spreads over only 3.77% area. The very high TWI occupies the region of coastal area while very low TWI area covers the area of south eastern hilly region of the country.

4.1.8 Soil Porosity

The porosity of soil is characterized by its pore space and refers to the portion of soil's volume in which solid materials are being found (Nimmo & Park, 2004). Soils with higher porosity indicates more pore space and capable for higher infiltration rate than those with lower porosity. For this reason, high rank is put to the higher porosity and low rank to the lower porosity in this study. The spatial variation of soil porosity map is classified into following categories- very low, low, medium, high, very high (Fig. 4c). These categories are covered by 8.73%, 6.53%, 56.49%, 24.44%, 3.82% land of the study site respectively.

4.1.9 Land Use and Land Cover

Land cover is expressed as the biophysical cover on the geosphere while land use expressed as a connection between land cover and human action on the earth's surface (FAO, 2000; Islam et al., 2021). Land use land cover (LULC) play a vital role in the occurrence and distribution of groundwater in any area. LULC can be considered as a major controlling factors in groundwater recharge processes by providing important information on penetration rate, soil moisture, groundwater necessities and surface water dependency in a region (Seenipandi & Chandrasekar, 2013). The LULC map of Bangladesh (Fig. 5a) has been extracted from the GlobeLand30. The National Geomatics Center of China developed GlobeLand30 by using a Pixel-Object-Knowledge approach and it is a worldwide land cover data product which resolution is 30 meter. The total accuracy of LULC map of Bangladesh is 85.72% and Kappa coefficient is 0.82. The LULC map of the study area has been split into 8 LULC categories, namely: cultivated land, forest, grassland, wetlands, shrubland, artificial surface, sand bar and water bodies. The rank has been given to the LULC features on the basis of hydrological characteristics, groundwater availability, infiltration rate etc. Overwhelming majority of the land of Bangladesh is covered by cultivated land (61%) which stretches over the western part of the country especially

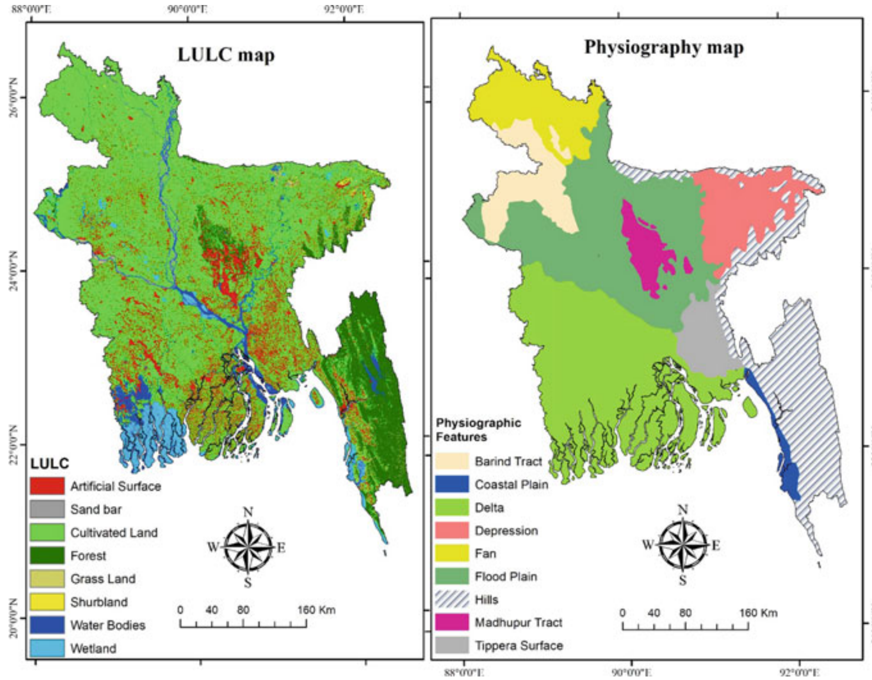

Fig. 5 **a** LULC map (2020), **b** Physiography map (2001)

in the district of Dinajpur, Rangpur, Thakurgaon, Tangail, Jessore, Pabna, Rajshahi, Bogura. Mymensingh.

4.1.10 Physiography

Physiographic unit refers to a homogeneous region containing similar physical characteristics. Every physiographic unit has a uniform geomorphic history and topographical features which differentiates it from the adjacent regions. The physiography map of Bangladesh was collected as shapefile from U.S. Government's open data portal for the year of 2001. It (Fig. 5b) is divided into nine different categories and these are Barind tract, Coastal plain, Delta, Depression, Fan, Floodplain, Hills, Madhapur tract, Tippera surface. These categories contain 6.27%, 1.35%, 29.29%, 7.64%, 7.94%, 24.02%, 16.68%, 2.85%, 3.95% area of the total study area respectively.

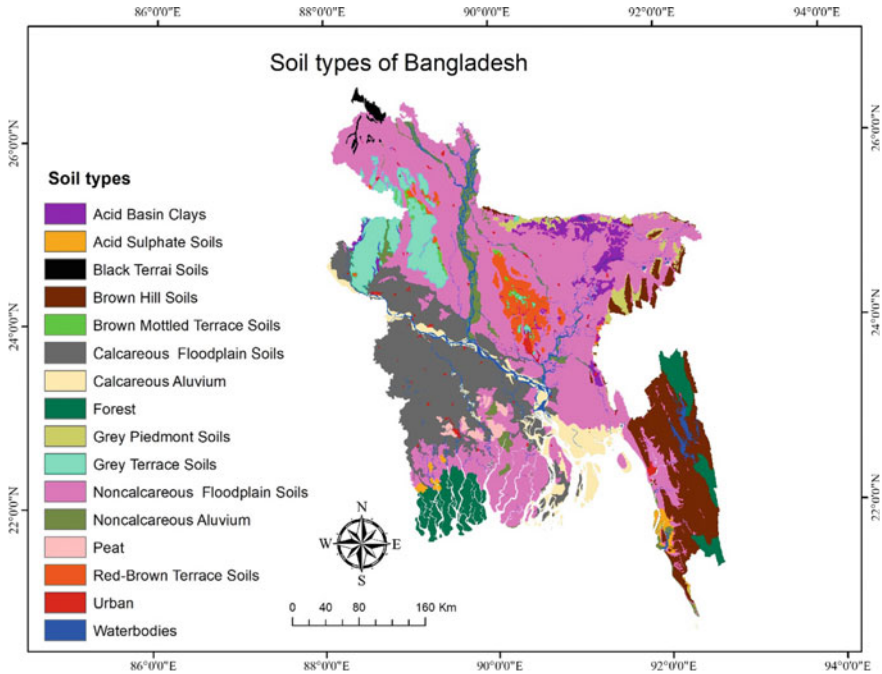

Fig. 6 Soil types of the study area (1988)

4.1.11 Soil Types

Soil types plays a significant role to dominate groundwater recharge in a specific region (Das, 2017; Ibrahim-Bathis & Ahmed, 2016). The soil data was downloaded from Bangladesh Agriculture Research Council (BARC) to prepare the soil map of Bangladesh (Fig. 6). In this study, thirteen different types of soil are found, and these are acid basin clay, acid sulphate soil, black terrai soil, brown hill soil, brown mottled terrace soil, calcareous floodplain soil, calcareous alluvium soil, grey piedmont soil, grey terrace soil, noncalcareous floodplain soil, noncalcareous alluvium soil, peat, red-brown terrace soil. A significant part of the study site consists of flood plain soil which is adjacent to and formed by alleviating rivers. Finally, different types of soil have been ranked on the basis of ground water holding ability, penetration rate, rainfall infiltration rate etc.

4.1.12 Soil Texture

Soil texture is considered as a remarkable parameter to locate groundwater availability in a space. The ratio of sand, silt, and clay in the soil is called soil texture. It is the vital inherent factor that affects infiltration rate, permeability and water holding capacity. It is evident that sandy soil group is capable for high infiltration rate, where clay soil group provides the least infiltration rate (Jhariya et al., 2021). The soil texture map (Fig. 7) is prepared as per the scheme of Bangladesh Agriculture Research Council (BARC). The major part of the study area (Chapai-Nawabganj, Pabna, Rajshahi, Natore, Kushtia, Chuadanga Meherpur, Jhenaidah, Kurigram Rangpur, Lalmonirhat, Sunamganj, Sylhet, Netrokona, Habiganj, Moulvibazar) is dominated by clay loam soil and silty loam soil, indicating very low to medium infiltration rate.

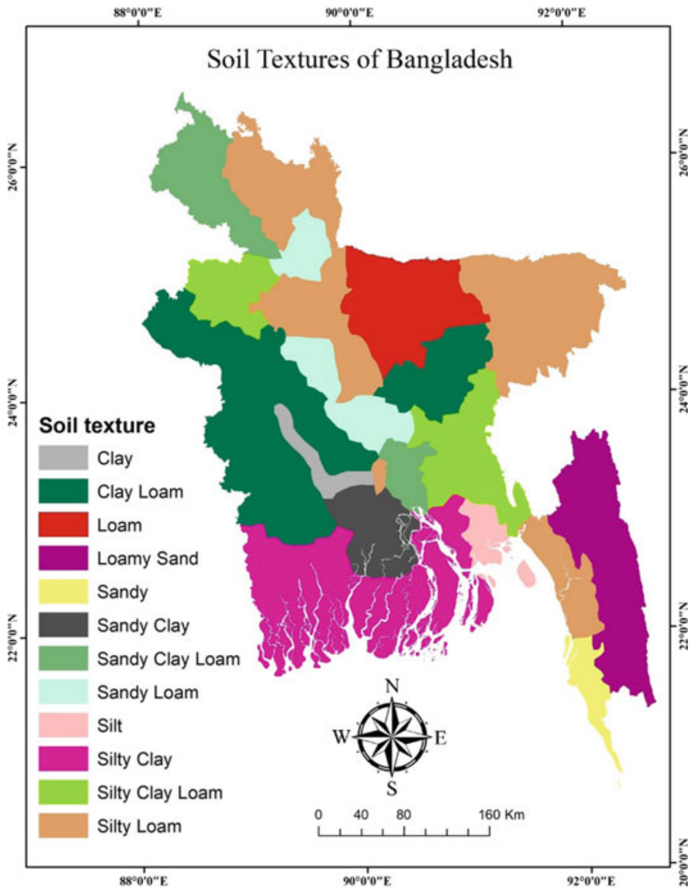

Fig. 7 Soil texture map (1988)

4.2 Delineation of Ground Water Availability Zone

Groundwater is a renewable resource, but this valuable life sustaining resource has decreased due to several types of man-made and natural factors. Proper management and monitoring of groundwater condition has a great importance for ensuring sustainable development of an area (Rahaman et al., 2022). Application of GIS, RS and AHP have been adopted in this study for the evaluation of groundwater availability zone in Bangladesh. The final ground water availability or potential zone map (Fig. 8) has been split into into five categories namely, poor, low, moderate, high, and excellent zone. These categories of ground water potentiality zone are covered by 0.38%, 20.20%, 58.33%, 16.33%, 4.76% area of Bangladesh, respectively. In the study site, Dinajpur, Rangpur, Thakurgaon, Nilphamari, Joypurhat, Naogaon, Chapainawabganj, Rajshai, Kurigram, Bogura, Rangamati, Khagrachari, Bandarban, Gazipur and Dhaka belong to “Low-poor” ground water potential zone, while “Excellent” ground water potential zone includes Netrokona, Kishoreganj and coastal districts of Bangladesh. Furthermore, it is noticeable that high ground water availability zones contain the features of low elevation, flat slope, low to medium drainage density and high value of TWI, MNDWI, curvature and rainfall. On the contrary, high slope, elevation, drainage density and low value of rainfall, TWI, MNDWI and curvature have been indicated by low to poor groundwater availability zones.

5 Conclusion

The use of groundwater continues to increase globally especially for drinking and agricultural purposes. The demand of the groundwater has recently increased at an alarming rate in Bangladesh leading to the decrease in the availability of the groundwater. The agriculture production of this country is highly dependent on groundwater. In this study, AHP based geospatial techniques have been used. This technique is widely used and efficient method for the demarcation of groundwater availability areas. The outcome of this study reveals five categories of ground water availability area in the study site: poor, low, moderate, high, and excellent. In the study area, 20.58%, of the area is classified as being “low—poor” groundwater availability area; 58.33% as a moderate groundwater potential zone; 16.33% as a high groundwater availability area; and 4.76% as an excellent groundwater potential area. The study also finds that the “high—excellent” groundwater potential zones represent the coastal region including the district of Jessore, Narail, Gopalganj, Shariatpur, Chandpur, Satkhira, Khulna, Bagerhat, Pirozpur, Jhalakati, Barguna, Barisal, Patuakhali, Bhola, Lakshmipur, Noakhali, and Feni which contains low value of elevation, slope, drainage density and high value of TWI, MNDWI, curvature and rainfall. Besides, the result of this research has also revealed that the north western portion of Bangladesh (the district of Dinajpur, Rangpur, Thakurgaon, Kurigram,

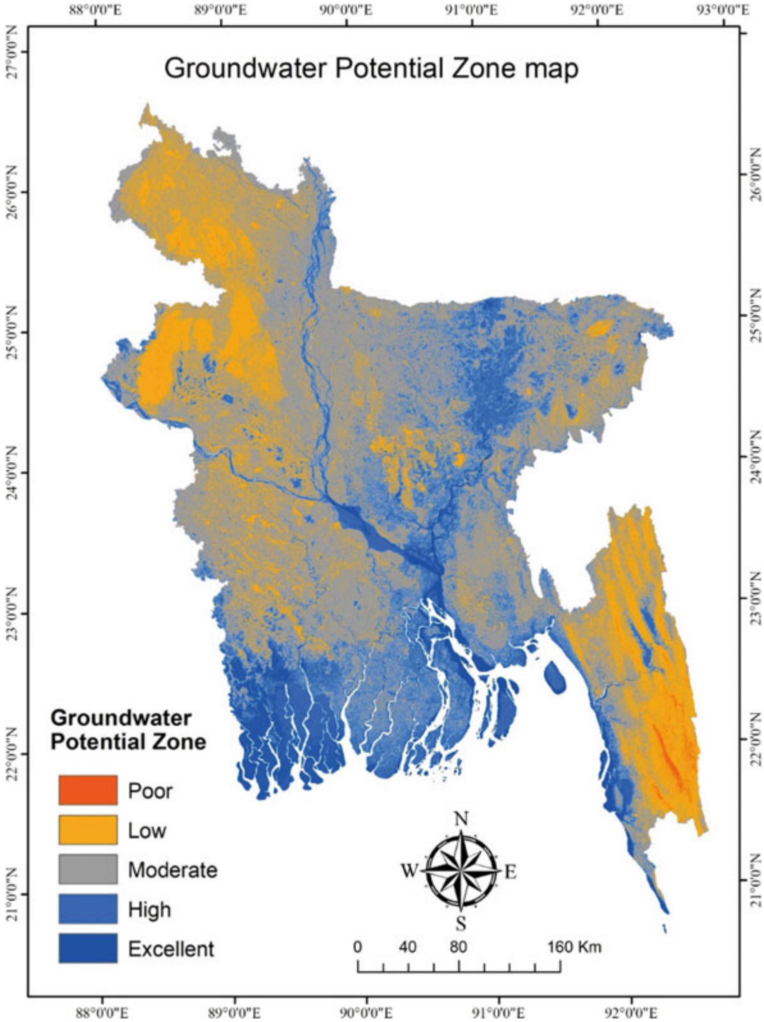

Fig. 8 Ground water potential zone map (2020)

Pabna, Nilphamari, Chapainawabganj, Joypurhat, Naogaon), hilly region (Rangamati, Khagrachari, Bandarban), Gazipur, Narayanganj and Dhaka district contain poor groundwater availability zone as this region is occupied by high slope and elevated area along with a low amount of rainfall. Finally, it can be said that the main findings of this study might be helpful for a fruitful selection of favorable area for the withdrawal of groundwater. In addition, the methodology of this study could be replicated in a region with similar characteristics of Bangladesh.

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The Mayo Tsanaga, Kaliao and Mizao (Maroua, Far North Cameroon): A Geoheritage for Socio-Economic Activities

Ghislain Zangmo Tefogoum, Merlin Gountié Dedzo, Lucas Bouba, Irène Mafo Dongmo, and Hyacinthe Zouyane Nouhou Dama

Abstract The Far North of Cameroon is endowed with an impressive number of under-exploited geotourism potentialities; specifically in the North and Far North regions. The Far North region, in particular the town of Maroua, which was chosen for this study, is characterised by other natural potentialities, in particular the watercourses known locally as "Mayo". The latter play an important role in the socio-economic balance of the city of Maroua and therefore of a large part of the Far North Region. This work aims to analyse the different socio-economic activities developed in and around these different Mayos which constitute a major geological heritage for the city of Maroua. To achieve these objectives, bibliographic, field and laboratory studies were conducted on several sites of these mayos. These studies showed that the activities carried out by the population on the waterways of the city of Maroua are numerous and diversified, including (1) the opening of sand quarries for the various constructions in the city of Maroua; (2) the manufacture of cinder blocks and paving stones and other accessories for constructions; (3) agriculture which consists of the production of millet, sorghum, maize, onions, mangoes… (4) Breeding of oxen, sheep, goats and horses; (5) Fishing, which allows part of the population to have fish that are essential for nutrition; (6) Laundry, washing dishes and swimming, which are practised by the population to clean their clothes, plates and to have fun; (7) Sport, which consists of the practice of football and physical exercises to get in shape by certain inhabitants of the city of Maroua; (8) Geo-education: The mayos constitute a real natural laboratory for the education of students from several institutions of the University of Maroua. Thus, hydrological, hydrogeomorphological and sedimentary processes are experimented by the students; Finally, (9) the mayos play an important role in the purification of the city of Maroua and the reduction of floods. These anthropic activities at the level of the mayos have been increasing for years and are practiced for the most part throughout the year. This is linked to the fact that the mayos offer a fringe of the population many vital resources to which they do

G. Zangmo Tefogoum (✉) · L. Bouba · I. Mafo Dongmo · H. Zouyane Nouhou Dama
Département of Earth Sciences, University of Maroua, Maroua, Cameroon
e-mail: zangmotefogoum@gmail.com

M. Gountié Dedzo
Department of Life and Earth Science, High Teacher Training College, University of Maroua, Maroua, Cameroon

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not necessarily have access. These include drinking water, water for domestic use and building materials. The Mayos are a geo-heritage whose exploitation methods remain mostly archaic and contribute to the catastrophic movement of masses on the banks. Thus, the competent authorities of the city of Maroua must implement a policy of sustainable management of these resources in order to limit the material losses linked to the mass movements that it encourages.

Keywords Maroua · Mayos · Geoheritage · Socio-economic activities

1 Introduction

Nature, through its biotic and abiotic components, offers mankind exceptional potentialities favourable to their blossoming and development. Thus, several civilisations were born and developed simply because of the presence of certain natural resources in their region. Man thus appears as an unshakeable heir to the riches that nature offers him. This highlights the notion of geoheritage. Geoheritage belongs to all, and forms part of the natural richness of our planet. Its destruction is almost always irreversible (Carcavilla et al., 2019). Cameroon, like many countries in the world, is endowed with a fairly diversified geoheritage offering opportunities for agricultural (Zangmo Tefogoum et al., 2011, 2014 and 2021), geoeducational (Zangmo Tefogoum et al., 2017), geotourism and recreational activities (Zangmo Tefogoum et al., 2017, 2020, Ziem A Bidias et al., 2020). Furthermore, according to the work of Mafo Dongmo (2019) and Nouhou Dama (2020), the Far North of Cameroon is endowed with an impressive number of under-exploited geotourism potentialities; specifically in the North and Far North regions. The Far North region, in particular the city of Maroua, which was chosen for this study, is characterised by other natural resources that are conducive to the life and development of the population. Among these resources are the temporary streams called '*Mayos*' (Kaïnaramsou et al., 2019; Zangmo Tefogoum et al., 2021) that cross the city. Water is life and river, being the most important source of water, is the life line for human being (Ahmed et al., 2015). However, these rivers play an important role in the socio-economic equilibrium of the city of Maroua and thus of a large part of the Far North Region. They provide the population with vital resources which, unfortunately, they often do not have access to. This work aims at analysing the different socio-economic activities developed in the different Mayos which constitute a major geological heritage of the city of Maroua.

2 Study Area

Maroua city is traversed by temporal streams locally call *Mayos* namely, Mayo Tsanaga, Mayo Kaliao and Mayo Mizao. These streams are found between 10°31′30″-10°36′30″N and 14°09′30″-14°25′30″E (Fig. 1). The Mayo Tsanaga is

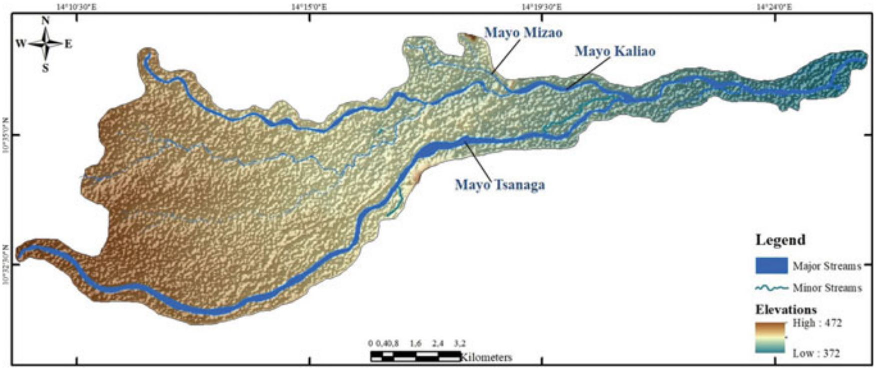

Fig. 1 Location map of the major streams in Maroua city

found on the southern limits of the Maroua city where few people has settled. On the contrary, Mayos Kalioa and Mizao are found in the central part of the city where the population is mostly developed. notably the Mayo Tsanaga, the Mayo Kaliao and the Mayo Mizao. These rivers originate in the Mandara Mountains and characterise the Mayo Tsanaga watershed (Sighomnou, 2003). The Mayo Tsanaga appears larger followed by the Mayo Kaliao and finally the Mayo Mizao, which appears smaller.

3 Matériel Et Méthode

To complete this work, we carried out several bibliographical studies, field work and laboratory work. This work was carried out alternately in the different study areas.

3.1 Bibliographic Research

Bibliographic research was carried out through documents (dissertations, articles, reports, etc.) available in libraries and on the Internet. This work allowed us to highlight the shortcomings of these previous studies and to define the theme of this work. In addition, it allowed us to delimit the study area.

3.2 Fieldwork

The fieldwork took place in several stages at the level of the main watercourses. It started with an inventory of the different socio-economic activities carried out by the population on the different rivers, their spatial distribution and their impact on their lives. This was made possible on the one hand through exchanges with the populations on the type of activity they carry out and the reasons that lead them to solicit the mayos for their activities, and on the other hand through field observations throughout the year. We used GPS to take the coordinates of the areas of the watercourses that were solicited. This phase is followed by descriptions of each activity and analysis of their impact on the well-being of the population.

3.3 Laboratory Work

The laboratory work made it possible to delimit the study area and to draw up several maps, in particular maps showing the location of the study area and the potential of the various watercourses. This work was carried out using certain software and platforms, in particular ArcGIS 10.4.1, Adobe Illustrators, Google Earth Pro and OpenTography. The data was collected and used in ArcGIS 10.4.1. Some data, in particular the areas suitable for the opening of sand quarries, were vectorised in Google Earth Pro, imported into ArcGIS 10.4.1 and exploited on a raster obtained in the OpenTopography platform to produce certain maps. Adobe Illustrators was used to perfect certain maps, especially in their labelling.

4 Results

The activities carried out by the population on the waterways of the city of Maroua are numerous and diversified. These activities include the opening of sand quarries, the manufacture of breeze blocks and others, agriculture, animal husbandry, washing, dishwashing, drinking water, swimming and bathing, sports (jogging, football), geo-education…. These activities are practised by a large part of the population, of both sexes and an age range between 5 and 65 years.

4.1 Opening of Sand Quarries

This is one of the most widespread and profitable activities in the city of Maroua. The quarries are opened along the entire length of the streams and consist of collecting sand on the bed of these streams; more precisely, on the preferential deposit zones during the passage of water during rainy periods (Fig. 2a, b). Generally, the collection is done with shovels in order to load the trucks and tricycles of variable dimensions, which are used to transport the sand to the different construction areas. In addition, other generally small quarries are opened not far from the banks by the local population. It consists of filling bags with sand and transporting them to the inhabited

Fig. 2 Pictures of activities related to the streams: **a** and **b** sand quarries; **c** manufacture of cinder blocks; **d**farms

areas. The opening of quarries is intensively practiced during the dry season and also during the non-rainy days of the rainy season.

4.2 Manufacture of Cinder Blocks and Other Products

Several areas for the manufacture of cinder blocks are found on the banks of the streams in the city of Maroua. This activity is facilitated by the presence of sand in the nearby streams and consists of the manufacture of cinder blocks which are then marketed (Fig. 2c). Some of this production is done under order from interested parties. In addition, other construction objects, especially decorative paving stones and balusters, are also produced and marketed on site. This activity is carried out throughout the year, although there is a high level of production in the dry season.

4.3 Agriculture

This is one of the most widespread activities along the banks of the rivers. Crops are diverse and include millet, sorghum, maize, onions, mangoes, etc. These products are consumed directly in households and then marketed. In practice, water from rivers is used to water crops through an irrigation system established for the purpose. With the exception of white millet, all other crops are grown in the rainy season.

4.4 Breeding

Livestock farming is an activity practised on certain riverbanks. Indeed, these banks are covered by several grassy species that favour this activity. The most dominant species are cattle, sheep, goats and horses. Generally, grazing is carried out by children and adults of both sexes. This activity is carried out on the banks and in the interior of the streams.

4.5 Drinking, Washing, Dishwashing, Bathing and Laundry

Mayo water is used by many households as a drink. Generally, they are most in demand during the dry season. Indeed, during this period, the minor bed of the streams is often dug by the population to search for the small trickle of low water which presents a rather clear water which they collect to consume either on the spot, or put in tanks such as buckets, cans, basins, calabashes, cups and thereafter transported towards the various households as reserves of drink. As the Mayo River offers water in the rainy season, several families converge almost every weekend and some rare days of the week, mainly between 6am and 6 pm, to carry out some household chores such as washing clothes and dishes (Fig. 3a). Thus, dirty dishes and clothes are collected mostly throughout the week to be washed on those weekends. In addition, some people use the mayos as a place for bathing and swimming (Fig. 3b,c). This act is carried out throughout the rainy season and the two months that follow it, namely mid-October and mid-November. Another activity is also carried out at the edge of the mayos; this is the laundry. This consists of cleaning cars, trucks, motorbikes and tricycles.

4.6 Sport

The mayos are places where people practice sports. Several sports are practised by people of all ages, especially in the dry season, i.e. from mid-September to May.

Fig. 3 Pictures of activities related to the streams: **a** laundry; **b** and **c** swimming; **d**., **e** and **f** football stadia

These are mainly (1) football: several stadiums are sporadically created along the bed of the mayos. There are several football teams that play against each other every day in the afternoon (Fig. 3d, e, f); (2) physical fitness exercises practised by some inhabitants of the city of Maroua during the same periods, but more in the morning and late evening.

Fig. 4 Outdoor training of students of the University of Maroua

4.7 Geoeducation

The mayos are increasingly considered as real natural laboratories for the training and research of students from several institutions of the University of Maroua (Fig. 4). The deposits of clay, silt and sand in strata that make up the bed of the mayos and the erosion patterns observed in certain places highlight the hydrological, hydrogeomorphological and sedimentary processes. In addition, the banks of the mayo offer a succession of deposits that allow students to understand the pedological processes and natural phenomena such as the mass movements that occur there.

4.8 Importance in Purifying the City and Reducing Flooding

Watercourses play an important role in the purification of the city of Maroua and its surroundings. Indeed, the wastewater from most households and some private and public structures is irrigated to them, which carry it further outside the city. This purification of the city is more important during the rainy season, when the mayo is supplied with enough water and with considerable flow. In addition, the courtyards of the city of Maroua are the places where most of the city's water is transported. This transport is done through specially built gutters or naturally during rainfall in the city. All this contributes to limiting flooding in a significant number of neighbourhoods in the city of Maroua.

5 Discussion

As the saying goes, “water is life”. River being an open system has direct and indirect influences on human economy and occupancy (Ahmed et al., 2015). Rivers have been the backbone for nearly all human settlements for generations (Adoloye, 2009). Thus, Streams in urban areas constitute a real geoheritage and are also quite solicited for various uses. According to Schindler et al. (2014) and Böck et al. (2018), riverscapes deliver to people a broad range of ecosystem services including freshwater, building material, and food. They also regulate our environment through, for example, air and water purification, and climate and flood regulation. Moreover, cultural services, such as recreational, spiritual, educational, and therapeutic activities, are also diverse (Wantzen et al., 2016). The demographic growth in the world’s major cities is significant. It is even more important in urban areas crossed by rivers. The population of the Far North region is growing, as in 2010 it was 3,480,414 inhabitants, i.e. an urban population of 839,031 inhabitants and a rural population of 2,641,383 inhabitants. The urban population, which largely comprises the city of Maroua, grew by an estimated rate of 2.6% between 2005 and 2010. At this rate, it could double its population by the year 2037, i.e. reach 1,678,062 inhabitants. This clearly shows that the mayos have been in greater demand for decades by this growing population, whose dependence on the mayos is even greater. In fact, it is seen that the daily life of the river-bank dwellers begins centring on river and ends in rivers (Buzarboruah, 2014). The growing urbanisation of the city of Maroua, linked to this demographic growth, has led the population to embark on various constructions. Thus, the streams are quite solicited through the opening of sand quarries. This sand is the result of the erosion of the Mandara Mountains, followed by the transport and deposit of sediments on the bed of the mayos. This sand is the primary material for any construction project in the city. There is an exponential demand for sand and a high production in the manufacture of breeze blocks and others in the dry season, which contrasts with the high demand from the population following the acceleration of work in the various construction sites in the city of Maroua.

This is a sector that recruits a fair number of unemployed people in search of a stable job. Generally, in the quarries, it takes about 4 to 6 people to fill a truck and 2 people to fill a tricycle. The presence of water in the mayos favours seasonal agriculture on the banks. This activity is the main occupation of some families. The products of this activity are used as food for the family, the neighbourhood and even the city. The vegetation developed in certain places on the banks of the watercourses favours pastoral activity, which is one of the sources of meat supplies for the town. During grazing, the animals can drink directly from the mayos. The presence of the mayos in the town of Maroua facilitates the practice of this activity at certain times of the year, as the actors no longer need to drive their livestock away from the town to graze. The town of Maroua is in a zone where rainfall is very low. As a result, there is a problem of water supply for multiple use. This situation is also aggravated by poverty in some families. Despite the efforts of the government, the problem of water supply remains a real concern, given that the demand for water is more significant due to the demographic growth in the region. Faced with this situation, a fringe of the population is obliged to rush to the mayos to take advantage of the water that is there to carry out their activities, notably, laundry, washing, bathing… A part of the population also uses this water as a drink, especially during periods of low water. Water from the river is a basic natural resource, essential for various human activities.

More and more green spaces are being used for multi-faceted construction, which means that the open spaces used for sports and recreational activities are being reduced. This situation has led the city's youth and adults to flock to the mayos to create football stadiums and spaces for physical exercise on their beds. These mayos thus become in the dry season, places of blossoming for many people in the city of Maroua. The streams constitute the lowest points of the city of Maroua; thus, favouring the irrigation of waste water from the households, for the most part, located on their periphery. These watercourses thus constitute natural tools for purifying the city's water. In addition, the relief of the city is dominated by a pediplain and a poorly permeable soil which favours flooding phenomena in the city. This situation has led the government to build water channels to the various mayos to reduce flooding in certain areas of the city. Moreover, these rivers play an important role in the training of students from the various institutions in the city of Maroua. They offer hydrological, geomorphological, sedimentological and pedological features that are essential for student training and research. Several practical courses are given in these environments during the academic year. Doctoral level research work is also carried out by students. The streams of the city of Maroua are, like many other in the world, important for the socio-economic balance. Indeed, as stated by Sadoff and Grey (2002), human settlement has almost always been close to water, because of the essential role water plays in human life and economic endeavour. As stated by Walteros and Ramírez (2020) in Latin America, the situation is similar to that of Maroua and above because urban streams provide a variety of services, including fishing, recreation, gravel and sand mining, and in some cases, even water supply for irrigation. They are thus vital for the populations of these areas. However, many rivers are in a critical state worldwide while their ecosystem services are altered (Albert, 2020). Hence, these streams cans be damaged or destroyed because of the overexploitation of his resources (Khorooshi et al., 2016). This is due to the worldwide urbanization that has greatly accelerated this process (Bonnefond et al., 2021). Thus, sustainable management of these resources is important and crucial. The competent authorities, together with environmental experts, must develop strategies for the management, protection and geoconservation of this geological heritage. The focus should not only be on the present, but also on future generations.

6 Conclusion

The watercourses of the city of Maroua, notably the Tsanaga, Kaliao and Mizao mayos, constitute a geological heritage that ensures the socio-economic balance of the city. They favour the practice of several economic, social, sporting and recreational activities. These activities include the opening of sand quarries, the manufacture of breeze blocks and others, agriculture, animal husbandry, washing, dishwashing, drinking water, swimming and bathing, sports (jogging, football), geo-education… These watercourses are thus useful for the survival of the city of Maroua. Sustainable management of this resource is necessary. The competent authorities, together with experts, must look into this issue in order to ensure sustainable activity for the population and above all to preserve these waterways for future generations.

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River Tourism in India: Its Role and Significance

Sanjukta Sattar

Abstract Tourism and river are intricately linked in terms of source of attraction and unique experience. Rivers are found to be major tourism resource offering spectacular settings, recreational opportunities, waterfront landscapes. Various activities like river cruises, water sports like sailing and rafting and the riverbank landscape contributes to the immense potential of river tourism and its role in the development of places along its banks. The local culture and heritage generally being connected with the river makes various places along the river, destination of cultural tourism also. In India, which is the land of many rivers, river tourism holds much potential as a form of sustainable tourism. The places get identified by the river flowing by it, the beautiful natural setting and the various river-based activities attracting tourists, thus branding those places as river tourism destinations. Promotion of river tourism can help in preservation of natural environment and cultural heritage of the region as well as add to the employment opportunities of the local population.

In this context, this paper will attempt to explore the development of river tourism in India and its various contributions in terms of conservation of the river and its surrounding environment as well as creating opportunities for sustainable livelihood of the river-based community. The paper will begin with an introduction to river tourism through a discussion on the relationship between river and tourism, roles of river tourism and the various activities related river tourism. In the following section an overview will be presented about the various river tourism destinations in India. Based on some of the popular river tourism destinations in India, in the third section of the paper an attempt will be made to understand the symbiotic relation between river and tourism by exploring the nature of tourism related activities centered on the river and the riverfront. The paper will end by drawing conclusions about the role and significance of river-based tourism development especially as an endeavour towards the achievement of sustainable development goals.

Keywords River tourism · Ecosystem · Culture · Sustainable development

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S. Sattar (✉)
Department of Geography, University of Mumbai, Mumbai, Maharashtra, India
e-mail: sanjukta.sattar@geography.mu.ac.in

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1 Introduction

Rivers and tourism shares a close bonding. Both are intricately linked as a source of attraction and unique experience. “Rivers provide solitude, beauty and interesting history that appeal to local recreationists and tourists” (World Tourism Organisation, 2016). Rivers are found to be a major tourism resource offering spectacular settings, recreational opportunities, waterfront landscapes (Prideaux et al., 2009). The cultural environment characterised by the river-based activities often adds to the touristic attractions of the destination. In addition to the pristine natural setting, various activities like river cruises, water sports, religious rituals and practices enhances the scope of river tourism and its role in the development of tourist destinations along its banks. It is found that rivers, as a form of Inland water, are gaining “importance for leisure and tourism and the activities associated with them and the investments promoted for their qualification are diverse” (Fernandes et al., 2020). As the local culture and heritage exhibits the influence of the river flowing by, a blend of cultural tourism and nature-based tourism characterises those destinations. Also the livelihood of the inhabitants of those destination which may be predominantly river-based gets further diversified when these places develop into tourist destinations. In this process just as employment and income generation gets enhanced, awareness about the preservation of the natural environment and the cultural heritage is also created through the promotion and the development of these places located by the river into tourism destinations. The beneficial economic and social impacts on the local population often incentivises them to participate and get involved in the tourism development, simultaneously taking interest in the conservation of the environment and preservation of their culture. As in case of any other economic activities tourism based on natural resources like water should be carried out following necessary measures for protection and conservation of the environmental resources. The sustainability of river tourism lies in the fact that “like other types nature-based tourism, river tourism is closely related to the principle of living in harmony with nature, integrating with the environment” (Tekin, 2017). Hence river tourism plays multiple roles as a source of entertainment and leisure, employment and income generation and as a means for the conservation of the environmental resources. If planned and operated following the tenets of sustainability it can become the icon of sustainable tourism and sustainable development.

In this context, this paper attempts to explore the development of river tourism in India and its various roles and significant contributions in terms of conservation of the river and its surroundings environment as well as creating opportunities for sustainable livelihood of the river-based community. The paper begins with an introduction to river tourism followed by section highlighting the relationship between river and tourism, its roles and the different activities related to it. In the following section an overview is presented about the different river tourism destinations in India. The relationship between river and tourism and its link to sustainable development has been critically discussed with reference to some of these destinations in India known for river tourism. The paper concludes with a few observation and arguments about the role and significance of the river-based tourism especially as an endeavour towards the achievement of sustainable development goals. This paper is based on qualitative research methodology using data mainly obtained from the various online sources and some reports and journal articles.

2 River and Tourism

Rivers are natural streams of water flowing through channels sculpting and reshaping the landform over which it flows. It is one of the sources of water resource in flowing state consisting various abiotic and biotic components which makes up the river ecosystem. The river ecosystems (riverscapes) encompass ecological, social and economic processes (ecosystem functions) that interconnect organisms (ecosystem structure), including humans, over some time period (Stanford et al., 2017). The human beings who live along the river or are using riverway for the purpose of transportation, interact with main components of the river ecosystem. Apart from the direct use of river water for various activities, human beings also enjoys the pristine natural beauty of the flowing water body and the landform carved out by the river, the flora and fauna characterizing the river ecosystem. This attracts many people to visit the riverside locations for spending few days away from the regular place of residence, and over the time such places develop into tourist destinations. Hence, rivers constitute a significant tourism resource as it provides spectacular settings, recreational opportunities, waterfront landscape, also in many places used as a significant transport corridor and essential source of water for human consumption. Various other activities also characterise the riverside destinations with the purpose of meeting the demands of the visitors as well as the local inhabitants. Also, many of the great rivers of the world have since long provided the backdrop and source of inspiration of some of the famous travel writings (Prideaux et al., 2009). Often, the cultural heritage of the settlement along the river basins adds to the attraction of the place to the tourists. With regard to river tourism, "the aesthetic value, ethnic diversity and social ethos" (CUTS International, 2019) enhances the scope of tourism development in these places. Also, promotion of river tourism and river cruises helps in employment and income generation which supports the lives and livelihoods of riverine people in relatively remote locations (CUTS International, 2019). Resorts and cafeterias along the rivers, the shops selling local handicrafts, services like tourist guides are some among various other employment opportunities created with the development of river tourism. Studies (Shakiry, 2007; Van Balen et al., 2014) have explored the potential of river tourism in terms of major contribution to the local economies through value addition, employment generation, generation of port revenues and monetary impact. This indicates the close link between river and tourism. Their relationship is quite symbiotic in nature as development of river basin and tourism development when planned following the tenets of sustainable development, complements each other. Therefore sustainability of river systems that supports tourism as well as other activities is a necessity. In fact well-planned river tourism can prevent degradation of river ecosystem by creating more sustainable livelihoods for local communities and also create environmental awareness among the tourists.

The physical, ecological and human aspects of river tourism have been studied by many researchers (Prideaux et al., 2009) who have unravelled its unique combination of natural and cultural tourism resources. Based on the different attractional factors linked to rivers determining the purpose of visit by the tourists, the different typologies of river tourism have been identified like nature-based tourism, religious tourism, river cruising, cultural and historical tourism, white-water rafting (Cooper, 2009). A variety of activities are found to be related to river tourism. Since the major constituents of the river tourism is based on water, so many of the activities are either on the surface, subsurface or down beneath the water. These includes water adventure tourism activities like white-water rafting, kayaking, river- cruising, fishing, angling, etc. Hence river tourism is quite multi-faceted in nature. Well-planned coordination of these activities in relation to the different attractions can attract different types of tourists as well as spread the tourist season throughout the year which in turn will lengthen the period of employment and income generation.

3 River Tourism Destinations in India

India is a land of rivers and there are a number of tourist destinations based on the various attractions and activities linked to river. Many of the rivers and the riverine hinterland not only offers picturesque natural setting and are rich in biodiversity, but are also found to have suitable characteristics for introducing activities like scintillating water sports, camping and non-conventional holiday experiences. The rivers also offer soothing and relaxing experiences as well as divine environment for spiritual revelations. Some of the rivers e.g. Ganga, Yamuna, Narmada, Godavari etc. are considered holy and auspicious according to Hindu religion and hence are important destinations of religious tourism and pilgrimage. Also, many of the rivers like Ganga, Yamuna, Pennar, Mandovi, to mention a few, which skirts various ancient ruins, historical monuments, forts, palaces, temples are having historical connections and cultural significance. In case of most of the rivers, more than one attractional factor draws the tourists to visit those river-based destinations (Table 1). All these diversifies the activities linked to tourism which broadens the scope of river tourism and its impacts. As a result, river tourism is picking up in India with more and more tourists of all types exploring the various activities like cruises, water sports, camping and trekking along the riverfront. With the implementation of National Waterways Act in 2016 tourism via waterways has been emphasized. Inland Waterways Authority of India (IWAI) had taken initiatives to promote river tourism and also encouraged participation of private sectors for development of river tourism related activities.

There are also many places located by the rivers which have all the potential of being developed into ideal river tourism destinations yet not explored. In some of the existing tourist destinations by the river, the river based touristic attractions are yet to be tapped or are in the early stage of development. Though tourism has

Table 1 Some river tourism destinations in India

Destination	State/union territory	River	Main attractions	Tourism typology
Bhedaghat, Jabalpur	Madhya Pradesh	Narmada	a. Natural attraction —Dhuandhar falls b. Religious attraction—Chausath Yogini Temple	1. Nature-based Tourism, 2. Religious tourism
Haldia	West Bengal	Haldi	a. Natural attraction—river view b. Cultural attraction—heritage locations, river port	1. Nature-based tourism, 2. Cultural tourism
Nandprayag & Karnprayag	Uttarakhand	Alaknanda	a. Natural attraction—snow-capped mountain—view, river confluence b. Adventure sports c. Pilgrimage	1. Nature-based tourism, 2. Adventure tourism, 3. Religious tourism
Majuli	Assam	Brahmaputra	a. Natural Attraction—pristine pollution free fresh water environment b. Cultural attractions—cultural heritages	1. Nature-based tourism, 2. Cultural/heritage tourism, & 3. Religious tourism
Williamnagar	Meghalaya	Simsang	a. Natural attraction—large riverine plain, forest covered mountains, waterfalls, limestone caves, b. Cultural attractions—food festivals, wine festivals, dance and singing competitions, beauty pageants	1. Nature-based tourism, 2. Cultural tourism

(continued)

Table 1 (continued)

Destination	State/union territory	River	Main attractions	Tourism typology
Kolkata	West Bengal	Hooghly	a. Natural attraction—lush greenery and serene atmosphere surrounding the river b. Religious attraction—temples and "ghats" having religious importance and as locations for religious rituals c. Heritage sites—heritage buildings and structures along the bank of the river d. Cultural attractions—'Ghats' or jetties having historical and cultural importance; Entertainment—Parks with landscaped gardens along the riverside and eateries	1. Nature-based tourism, 2. Religious tourism, 3. Heritage tourism, 4. Cultural tourism
Melli	Sikkim	Teesta	a. Natural beauty, b. Water sports—river rafting	1. Nature-based tourism, 2. Sports and adventure tourism
Varanasi	Uttar Pradesh	Ganga	a. Religious tourism—temples, rituals	1. Religious tourism
Haridwar	Uttarakhand	Ganga	a. Pigrimage—temples and hermitages b. Wildlife sanctuary—Chilla Wild Life Sanctuary	1. Religious tourism 2. Wildlife tourism
Jim Corbett National Park	Uttarakhand	Ramganga	a. National Park and Wildlife sanctuary	1. Wildlife tourism, 2. Nature-based tourism
Dhankar	Himachal Pradesh	Spiti	a. Natural beauty, trekking and jeep safaris, b. Cultural attractions,	1. Nature based tourism, 2. Adventure tourism, 3. Cultural tourism
Manali	Himachal Pradesh	Beas	a. Natural beauty	1. Nature-based tourism
Chadar	Ladakh	Zanskar	a. Natural beauty, b. Trekking on frozen trail of Zanskar	1. Nature-based tourism 2. Adventure tourism
Amarkantak	Madhya Pradesh	Narmada	a. Pilgrimage, b. Natural beauty	1.Religious tourism 2. Nature-based tourism

(continued)

Table 1 (continued)

Destination	State/union territory	River	Main attractions	Tourism typology
Khalwani	Gujarat	Narmada	a. Water rafting, b. Natural beauty	1. Adventure tourism, 2. Nature-based tourism
Kolad	Maharashtra	Kundalika	a. Natural beauty, eco-tourism camps b. River rafting	1. Nature-based tourism 2. Adventure tourism
Panjim	Goa	Mandovi	a. River cruise, b. Water sports, c. Forts and folk art, d. Bird watching	1. Nature-based tourism 2. Sports and Adventure tourism 3. Cultural tourism 4. Wildlife tourism
Kabini	Karnataka	Kabini	a. Natural beauty, b. Rich biodiversity,	1. Wildlife tourism 2. Nature-based tourism
Coorg	Karnataka	Barapole	a. Natural attractions, b. Water Sports	1. Nature-based tourism, 2. Sports and adventure tourism
Dandeli	Karnataka	Kali	a. Natural beauty, Jungle safari, Bird watching, b. Adventure sports—Kayaking, Rafting and Coracle rides	1. Nature-based tourism 2. Wildlife tourism 3. Adventure tourism

(continued)

Table 1 (continued)

Destination	State/union territory	River	Main attractions	Tourism typology
Bheemeshwari	Karnataka	Kaveri	a. Natural beauty, b. Water sports and adventure tourism	1. Nature-based tourism 2. Adventure tourism
Papikondalu	Andhra Pradesh	Godavari	a. Natural beauty b. River cruise	1. Nature-based tourism
Gandikota	Andhra Pradesh	Pennar	a. Historical building—fort, b. Natural beauty,	1. Cultural (fort) tourism 2. Nature-based tourism

Source Author's compilation of data based on "30 Top Places Near Rivers and lakes In India, 2022 | Best Lakes and Riverside Places in India", n.d.; "Forts in India" (n.d.); "Gandikota Fort - Grand Canyon of India" (n.d.); Kapoor (2015); "Spiti Travel and Tourism Guide" (n.d.)

much prospects for economic benefits, lack of tourism-oriented infrastructure, poor connectivity between the tourism sites and regulatory gaps in tourism policies for the transboundary rivers, have acted as hurdles for attaining the full potential (Nayak & Mishra, 2013 in CUTS International, 2019). So now special efforts are being made to tap the potential of river tourism. In Kerala, which is one of the southern-most states of India, the rivers have been identified for launching river tourism and adventure tourism circuits by linking various rivers. The proposed waterway projects will have 50 tourism spots on the banks of the rivers (*Times of India*, 2021). Goa located along the western coastline of India which is a popular destination for beach tourism is also blessed with 9 beautiful rivers joined by 42 small tributaries which are having some of the most unexplored and uncrowded destinations. These locations holds much potential for development of sightseeing spots, river cruises, water sports and adventure tourism activities. The rivers like Mandovi and Zuari and the other rivers have plenty of scope for creating facilities for adventure tourism and water sports activities, river cruises for experiencing the pleasant environment and natural beauty, and viewing as well as visiting the heritage building and the historical landmarks along the river. As a part of monsoon tourism, sunset cruises and white water rafting are among the different activities that are being arranged for attracting tourists even during the monsoon season when beach tourism activities are mostly closed. Such initiatives spread the tourist season keeping tourism activities functional almost throughout the year thus maintaining a continuous flow of income from tourism for those whose livelihood is based on this sector.

The mighty river Ganga or Ganges rises in the Himalayas flows down across the plains of the northern India and finally draining into Bay of Bengal. River Ganga is revered by the Hindus as a holy river and is home to major pilgrimage spots and venues for many religious festivals. The riverfront of Rishikesh, Haridwar, Varanasi and Allahabad draws large number visitors from different corners of India as well as from outside for attending various religious rituals and festivals. Religious tourism predominates the various tourism related activities in connection to river Ganga. Adventure tourism activities like river rafting, kayaking, also attracts many adventure spirited tourists to riverfront destinations on Ganga like Rishikesh. Few more destinations along Ganga have emerged as popular hubs of adventure tourism. Ganga Water Rally festival commencing from Prayagraj to Varanasi via Mirzapur and Chunar, draws participants from all over India and abroad. Introduction of luxury tourism which includes luxury cruises and floating hotels is in pipeline. All these projects will not only attract more tourists of different types but also will add to the number of employment opportunities and income generation of the river-based community. The riverfront development projects like building river promenades, parks and gardens in some of the major cities along the river like Haridwar, Allahabad, Varanasi, Kanpur Patna and Kolkata have also been undertaken to attract more tourist. This also aims at value addition and employment generation from river-based tourism in these cities.

In the North Eastern states of India river tourism is becoming popular though the full potential is yet to be explored and developed. Dawki in Meghalaya which is located on the bank of transboundary river Umngot and Chabimura in Tripura located in the upstream of River Gumti are some of the locations which have much potential for development of river tourism. Here the local tourist visits for enjoying the scenic beauty, rock carvings and caves along the river banks and taking part in boating, scuba diving, kayaking, snorkelling and cliff jumping (CUTS International, 2021) as a part of nature and adventure tourism. Community based tourism is practised in Chabimura (Tripura) and Shnongpdeng (Dawki, Meghalaya) and the tourism activities are managed by the tribal community with the support of Tourism Department. Traditionally these tribal communities depend on agriculture and fishing for their livelihood which is now getting supplemented by their engagement with the river tourism activities. Another interesting river tourism destination of North-East India is Majuli. Majuli is the world's largest river island in the river Brahmaputra located about 20 km from Guwahati. The exquisite natural setting and the unique cultural characteristics of Majuli attracts many tourists. This island which is inhabited by Mising tribal community is known as the cultural capital of Assam. Apart from the pristine natural wetlands attracting many migratory birds, the island's touristic attractions include the celebration of festivals like *Raasotsava,* the *Satras* (monasteries of the *Vaishnavite* sect) which are having museums where antique weapons, utensils, jewellery and other items of cultural significance are preserved thus helping in preserving unique culture and heritage of Assam. Traditional handicrafts like masks, unique pottery, ethnic stage performances and dance are the additional sources of attraction. White water rafting on river Teesta is another popular activity related to river tourism in the north-eastern part of India. Melli located in Sikkim is well known for river rafting.

In West Bengal River tourism is gaining importance and various projects are being envisaged like water taxi, house boat, floating restaurants, daily cruise in Kolkata and short cruises up and down the Ganges and in Sunderbans (FICCI, 2019). The heritage river cruise on river Hooghly has been designed to provide the tourists a ride into the history and heritage of Kolkata. The cruise will travel past the Armenian ghat, Nimtala ghat, Chandpal ghat, the Eastern Railway Headquarter which was built in 1952, Binoy Badal Dinesh Bagh (formerly known as Dalhousie Square, the CBD of Kolkata) among several other landmarks of the city along the river This is one of the examples of amalgamation of cultural tourism as the integral part of river tourism.

4 River Tourism and Sustainable Development

Rivers are source of tourist attractions like natural beauty, pleasant environment, river cruises, water sports as well as cultural attractions and religious significance. Ecotourism initiatives can contribute to the conservation of the river and the riverine environment. In fact, ecotourism is a popular way to enjoy water resources while still conserving the integrity of nature. River tourism integrates various river based activities for boosting tourism development and this in turn contributes to the development of the river hinterland also. This form of tourism while creating opportunities for presenting river as source of touristic attraction also combines with measures adopted for the protection and conservation of the river and its surroundings. Hence, sustainability of river systems that support tourism is important (Prideaux et al., 2009). Moreover when tourists get aware about the value of nature's assets e.g. rivers, lakes, forests etc. during their travels, it can motivate them to appreciate it and get connected with nature so much that they may take active interest in its protection and conservation. Also, when those having livelihood based on river tourism become aware about the sustainable use of river, they start adopting necessary measures for the protection and conservation of the river. The growing popularity of river tourism and the economic benefits that come along with it can change the community attitude towards conservation and promotion of the river and the riverfront. With collective action involving different stakeholders bringing in different resources and working towards a commonly agreed goal can bring about sustainable and positive result (Srinivas, 2016). Sustainability of river systems that support tourism as well as other river-based activities can be attempted by applying sustainable models for the management of river water resources which will have positive impact on the conservation of the environment, biodiversity and local ecosystems. Such initiatives have been taken in Chabimura in Tripura and Shnonpdeng near Dawki in Meghalaya where tourism activities are managed by applying community based tourism approach. In Chabimura which is located about 87 km away from Agartala the tourism activities are managed by a self-help group of Jamatia tribal community on lease for a five year period. In Shonpdeng the Village Development Committee manages all the activities related to adventure tourism and water sports, also takes care of the provisions like nature guide, fishing, as well as promotion of the artisans, local culture and cuisines (CUTS International, 2021). Here sustainably planned river tourism can act as one of the alternative livelihood opportunities to those who are engaged in stone crushing industry and underwater mining which are to be restricted due to the detrimental impacts of these activities on the river and the surrounding environment (CUTS International, 2021).

River tourism if planned sustainably can benefit the destinations in a number of ways by creating opportunities for sustainable livelihoods and improved local economy (Shakiry, 2007). Hence sustainable tourism can deliver benefits to all groups. For the conservation of river as well as for the welfare of the riverine communities who are directly or indirectly related to river-based tourism activities, planning and operation of river tourism development should be according to the tenets of eco-tourism and sustainable development.

5 Conclusion

Rivers are a major source of tourism resource in terms of attractive natural setting as well as man-made attractions and facilities created for recreation and enjoyment. The spectacular natural landscape along the river, facilities of river transport, water and adventure sports and the riverfront often embedded with landmarks representing the culture and heritage of the place contributes to the development of river tourism destinations often in integration with nature tourism, adventure tourism, religious tourism and cultural tourism. River tourism can also create awareness among all the stakeholders about conservation of the river and riverine environment and incentivise for planning and acting according to the tenets of ecotourism. This will also benefit the people residing along the river. In the Indian context also river tourism has a important role to play in terms of conservation of rivers and its surrounding environment as well as a form of sustainable livelihood for the local communities dwelling along the river. The country is blessed with many rivers and a number of places along the river have already emerged as popular tourist destinations with the principal features of attraction directly or indirectly related to the river. River tourism in India is multifaceted as majority of the tourist destinations by the river in India can be categorised under multiple tourism typologies catering to different types of tourists with different purposes of visit. By integrating river as the resource for tourism along with other factors of attraction the tourism resource base will expand and thus broaden the spectrum and scope of tourism in India which will also facilitate sustainable management and conservation of the rivers in India.

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