

**ASSESSMENT OF ALTERED LAND USE PATTERN ON THE
MIDDLE GANGA RIVER HYDRODYNAMICS USING
GEOSPATIAL MODELLING**

Thesis submitted to the
Saurashtra University, Rajkot (Gujarat)



For the award of the degree of
Doctor of Philosophy

in

Wildlife Science

by

Sk. Zeeshan Ali

Under the supervision of
Dr. Syed Ainul Hussain

Wildlife Institute of India
Chandrabani, Dehradun - 248001
Uttarakhand, India



**भारतीय वन्यजीव संस्थान
Wildlife Institute of India**

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SAURASHTRA UNIVERSITY

P.G.T.R. Section, Main office,

First Floor, University Road,

Rajkot - 360 005(Gujarat)

Phone No. : 2578501

Fax:(0281)2586983

www.saurashtrauniversity.edu

Ph.D. REGISTRATION CERTIFICATE

Reg. No: 19190

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This is to certify that **Sk. Zeeshan Ali** has been registered as a Ph.D. Scholar under the Supervision/Guidance of **Dr. Syed Ainul Hussain, Wild Life Institute of India, Dehradun** in **Wildlife Science** Subject, Faculty of Science.

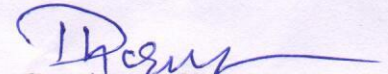
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Sk. Zeeshan Ali

(Sk. Zeeshan Ali)

Date : 01.05.2025

Place: Dehradun



Hussain

(Dr. Syed Ainul Hussain)
Supervisor

पत्रपेटी सं० 18, चन्द्रबनी, देहरादून – 248 001, उत्तराखण्ड, भारत
Post Box No. 18, Chandrabani, Dehradun - 248 001, Uttarakhand, INDIA
ई.पी.ए.बी.एक्स. : +91-135-2640114, 2640115, 2646100 फ़ैक्स : 0135-2640117
EPABX : +91-135-2640114, 2640115, 2646100 Fax: 0135-2640117
ई-मेल / E-mail : wii@wii.gov.in वेब / Website: www.wii.gov.in



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(Dr. Ruchi Badola)
Dean

Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun

(Dr. Syed Ainul Hussain)
Supervisor



Date : 01.05.2025

Place: Dehradun

पत्रपेटी सं० 18, चन्द्रबनी, देहरादून – 248 001, उत्तराखण्ड, भारत
Post Box No. 18, Chandrabani, Dehradun - 248 001, Uttarakhand, INDIA
ई.पी.ए.बी.एक्स. : +91-135-2640114, 2640115, 2646100 फ़ैक्स : 0135-2640117
EPABX : +91-135-2640114, 2640115, 2646100 Fax: 0135-2640117
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Main Office, First Floor,

University Road

Rajkot - 360 005 (Gujrat)

Phone No.: 2578501

Fax: (0281) 2586983

www.saurashtrauniversity.edu



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Dean

Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun



(Dr. Syed Ainul Hussain)

Supervisor



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Wildlife Institute of India

THESIS SUBMISSION CERTIFICATE

**For award of the degree of
Doctor of Philosophy**

Registration No. 19190

This is to certify that **Mr. Sk. Zeeshan Ali**, S/o **Mr. Sk. Ansar Ali**, a Ph.D. Student in Wildlife Science from Saurashtra University and Wildlife Institute of India, has provisionally submitted his Ph.D. thesis, subject to verification of the related documents, under the supervision of **Dr. Syed Ainul Hussain**. The title of his Ph.D. thesis is “**Assessment of altered land use pattern on the Middle Ganga River hydrodynamics using geospatial modelling**”

The Pre-Ph.D. Viva of the Research Scholar was held on **21.03.2025**.

(Dr. Ruchi Badola)
Dean

Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun

(Dr. Syed Ainul Hussain)
Supervisor



Date : 01.05.2025

Place: Dehradun

पत्रपेटी सं० 18, चन्द्रबनी, देहरादून – 248 001, उत्तराखण्ड, भारत
Post Box No. 18, Chandrabani, Dehradun - 248 001, Uttarakhand, INDIA
ई.पी.ए.बी.एक्स. : +91-135-2640114, 2640115, 2646100 फ़ैक्स : 0135-2640117
EPABX : +91-135-2640114, 2640115, 2646100 Fax: 0135-2640117
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चन्द्रबनी, देहरादून, उत्तराखण्ड
Chandrabani, Dehradun - 248 001



(Dr. Ruchi Badola)

Dean

Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun

(Dr. Syed Ainul Hussain)
Supervisor

पत्रपेटी सं० 18, चन्द्रबनी, देहरादून – 248 001, उत्तराखण्ड, भारत
Post Box No. 18, Chandrabani, Dehradun - 248 001, Uttarakhand, INDIA
ई.पी.ए.बी.एक्स. : +91-135-2640114, 2640115, 2646100 फ़ैक्स : 0135-2640117
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LIST OF ABBREVIATION

GRB	Ganga River Basin
LULC	Land Use Land Cover
ADCP	Acoustic Doppler Current Profiler
MGR	Middle Ganga River
CGWB	Central Ground Water Board
MLC	Maximum Likelihood Classification
RI	River
SB	Sand Bar
IS	Island
BL	Barren land
WB	Water Body
Fr	Forest
AG	Agriculture
BU	Built up
GL	Grassland
E-Flow	Environmental flow
SDG	Sustainable Development Goal
RS	Remote Sensing
GIS	Geographic Information System
MNDWI	Modified Normalized Difference Water Index
ALOS	Advance Land Observing satellite

JAXA	Japan Aerospace Exploration Agency
USGS	United States Geological Survey
FCC	False Colour Composite
SWIR	Short Wave Infrared
BEU	Basic Ecological Unit
SAC	Space Application Centre
MoEFCC	Ministry of Environment Forest and Climate Change
NWIA	National Wetland Inventory and Assessment
ADV	Acoustic Doppler Velocimeter
SWAT	Soil and Water Assessment Tool
HEC-HMS	Hydrologic Engineering Centre's Hydrologic Modeling System
UAV	Unnamed Aerial Vehicle
AHP	Analytical Hierarchical Process
MCDM	Multi Criteria Decision Making
NBSS & LUP	National Bureau of Soil Survey and Land Use Planning
SEDAC	Socioeconomic Data and Applications Centre
DSS	Decision Support System
CR	Consistency Ratio
CI	Consistency Index
RCI	Random Consistency Index
WOA	Weighted Overlay Analysis
CR	Conservation Reserve

LIST OF PUBLICATIONS

Peer reviewed journals

- **Ali, S.Z.**, Mani, A., Guha, S., Badola, R., Hussain, S. A. (2025). Assessment of fluvial stressor dynamics and riverine habitat resilience to environmental flow in the middle Ganga River. Discover Applied Sciences. **Electronic ISSN 3004-9261**.
- **Ali, S.Z.**, Guha, S., Mani, A., Menon, A.N.R., Barthwal, S., Badola, R., Hussain, S. A. (2025). Delineation and mapping of riverine wetlands in the middle Ganga River using geospatial technology. The Indian Forester. **ISSN 0019-4816** and **eISSN 2321-094X**.
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- **Ali, S.Z.,** Mani, A., Guha, S., Sharma, S., Khatun, M., Barthwal, S., Badola, R., & Hussain, S.A. (2024). Assessment of riverine habitat vulnerability to geomorphological changes in the Middle Ganga River [Oral presentation]. In Proceedings of the International Conference. Vallabh Govt. College, Mandi, India. February 14-15, 2024.
- **Ali, S.Z.,** Barthwal, S., Badola, R., & Hussain, S.A. (2023). Impact of dams and barrages on riverine habitat connectivity in the Middle Ganga River [Poster Presentation]. In Proceedings of the 50 Years of Project Tiger and First Indian Conservation Conference. Mysuru, India. April 10, 2023.

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EXECUTIVE SUMMARY

Rivers are essential in the Earth's hydrological and ecological processes, serving as link between the atmosphere, land, oceans, and sustaining variety of functions like agriculture, industry, and biodiversity conservation. The Ganga River is one of the most important among world's large river systems due to its ecological, cultural, and socio-economic significance in the Indian subcontinent. In spite of its sacred nature and pivotal position in sustaining the lives and livelihoods of millions, the Ganga River is subject to anthropogenic pressure due to fast urbanization, industrialization, population expansion, and uncontrolled land use and water management practices.

This research concentrates on the middle Ganga River (MGR), which flows from Bhimgoda barrage at Haridwar, Uttarakhand to the Gomti River confluence at Kaithi, Varanasi, Uttar Pradesh, covering about 1000 km in length. This segment passes through ecologically sensitive and densely populated regions, including protected areas such as Rajaji National Park, Hastinapur Wildlife Sanctuary, Upper Ganga Ramsar site and Kachhua Wildlife Sanctuary. Principal tributaries entering the Ganga River along this stretch are right-bank rivers like the Ramganga, Garra, Gomti, and left-bank tributaries such as the Yamuna, Chambal, and Tamas. The basin consists of intricate geological and geomorphological structures developed by Himalayan orogenic processes and subsequent sedimentation.

The objectives of this study are, (1) Assessment of Land Use Land Cover (LULC) alteration in upper and middle catchment of the Ganga River, (2) Identification of drainage in upper and middle catchment of the Ganga River, (3) Determination of

existing flow regime in middle Ganga River, and (4) Prediction of future scenarios based on existing development plan in upper and middle catchment of the Ganga River.

The research methodology integrates remote sensing, GIS, hydrological and ecological assessments with machine learning techniques to analyze land use land cover (LULC) changes along the middle Ganga River. Methods such as Analytic Hierarchy Process (AHP), Artificial Neural Networks (ANN), and Random Forests are used to prioritize stressors, model land dynamics, and forecast future scenarios of LULC and habitat for aquatic biodiversity. These approaches capture complex interactions among environmental, socio-economic, and policy factors, enabling accurate prediction of LULC changes and their ecological and socio-economic impacts.

The findings reveal substantial LULC transformation over recent decades, driven primarily by agricultural expansion, urban sprawl, deforestation, and infrastructure development. Floodplains and wetlands have increasingly been converted into croplands and urban areas. Agricultural runoff along with fertilizer and pesticides have led to eutrophication, lowering water quality and impacting aquatic life. Land degradation and deforestation, particularly in the upper basin, have increased surface runoff and soil erosion, leading to sedimentation and turbidity that affects aquatic habitats.

Geomorphological modification, especially the development of dams and barrages, has largely disturbed the natural flow regime of the Ganga River. It fragments the river longitudinally, modify sediment transport dynamics, form upstream reservoirs, and

lower discharge at downstream. The downstream sections of barrages witness decrease in flow, depth, creation of braided channels, sandbars, and isolated pools, which are favourable habitat for species like Gharial (*Gavialis gangeticus*) and river turtles but less favourable for deep-water dwellers such as Gangetic River dolphin (*Platanista gangetica*). On the other hand, the upstream regions, with wider and deeper waters, provide favoured living spaces for large aquatic mammals but do not provide appropriate basking and nesting sites for reptiles due to submergence of sandbars and islands.

Hydrological evaluations indicate a distinct seasonal fluctuation. Water abstraction for irrigation, municipal use, and industry further intensifies low flow conditions during the dry season, affecting the availability of linked deep pools and habitat fragmentation. These alterations jeopardize ecological connectivity, lower aquatic diversity, and compromise essential ecosystem processes like nutrient cycling, sediment transport, and floodplain replenishment.

Biodiversity surveys validate the declining occurrence of major aquatic species. Gangetic river dolphin is stressed by habitat fragmentation, reduced dry-season flows, and sound pollution. Fish migration is hindered by barrages, and hypoxic situations brought about by eutrophication and pollution constrain reproductive success in most aquatic species. The bathymetry and longitudinal connectivity of the river are vital to species distribution and community structure which are being threatened by anthropogenic forces.

The research also highlights the ecological value of floodplain habitats, sandbars, and wetlands. They offer essential breeding, feeding, and refuge grounds for aquatic and

semi-aquatic organisms. Nevertheless, encroachment, pollution, and changed flow regimes have caused degradation. In this regard, wetlands are vital in filtering out pollutants, flood moderation, and promoting biodiversity. Rehabilitation of these habitats are important for ecological restoration of the middle Ganga River.

An integrated approach of river basin management is advocated for these interconnected challenges. Strategies to conserve must comprise the revival of riparian forests, seasonal upkeep of river islands, sandbars, and adoption of environmental flows (E-flows) replicating natural hydrologic variability. Protection of minimum flows, particularly in dry season, is crucial in ensuring aquatic biodiversity as well as linking fragmented habitats. Elevation gradients and topographic changes need to be taken into account while controlling the spatial pattern of conservation zones.

GIS and remote sensing technologies provide the capacity to map stressor distributions and track LULC changes at temporal scale. AHP facilitates data-driven decision-making by determining the relative importance of various stress factors and delineating high-priority areas for freshwater biodiversity conservation. Planning at the sub-basin and catchment scales is required for the management of water quality, flood risks, and habitat sustainability. Institutionalization of long-term ecological monitoring should be done to determine the efficacy of conservation measures and modification of management strategies accordingly.

The involvement of local communities is essential to ensure the success of conservation and river management in a sustainable manner. Conservation education and extension programs help to engage community stewardship and enhance

ecological awareness about the Ganga River. Cultural values and traditional knowledge systems related to the river also helps to aid in conservation objectives.

This study highlights the interactions between land use transformation, hydrological processes, geomorphology, and biodiversity in the middle Ganga River. It underscores the imperative for interdisciplinary research integrating ecological science, hydrology, geomatics, and socio-economic planning. It emphasizes the imperative of paradigm shift in the Ganga River, away from infrastructure-intensive strategies towards Integrated River Basin Management (IRBM). It stresses safeguarding environmental flows (E-flows) to maintain aquatic ecosystems, along with adaptive measures for hydrological restoration, land use planning, and pollution management. Participatory governance, combining local knowledge with scientific information, and adaptation to climate-driven hydrological changes through nature-based solutions are essential for sustainable management and restoration of the Ganga River and its biodiversity. The combined strategies are intended to restore the ecological integrity, biodiversity, and resilience of river systems, promoting sustainability, cultural continuity, and inter-generational equity.

CHAPTER 1

INTRODUCTION

1.1. General introduction

Rivers are an essential parameter for Earth's climate system as they ensure the linkage between the atmosphere and the ocean. River water is free from pollution at its source and considered safe to be consumed by most living organisms on Mother Earth. Rivers also play a crucial role in the establishment of various sectors, such as irrigation, animal husbandry, agricultural and household purposes (Hayder et al., 2020). In many parts of the world, rivers are the only source of water to support socio-economic development. However, the increasing global human population, industries, and urbanisation have caused degrading river health, which greatly impacts both river and riverine biodiversity (Ighalo et al., 2020; Sami et al., 2021).

River hydrodynamics is a significant factor in biotic assemblages (Trivellone et al., 2017) of the lotic ecosystem. It determines the integrity of hydrologic and biotic factors in a river. It deals with flowing water, river geomorphology, and sediment transport. The sediment transfers with the river water, maintains the nutrient balance throughout the river course, and forms the river habitat for aquatic life. Monitoring and quantifying the river flow is essential not only for the sustainable management of this valuable resource but also for predicting future conditions (Zakharova et al., 2020). River is a linear object on earth, originates from a highland headwater and flows towards moderately elevated area

forming upper zone of the river, it flows further towards low elevated areas forming middle zone and afterwards flows towards its confluence forming lower zone of the river. River flows through narrow channels with high slope in upper segment. Deep gorges, steep slope, boulders, gravels and pebbles are main characteristic features of upper segment, whereas river flows through wide channels with moderate slope in middle segment. Mid river channel, sand bars and floodplain are main characteristic features of middle segment of river. In lower segment river forms larger flood plain as the slope is very low. The alluvial deposition forms the fertile and nutrient rich alluvial plain. Wide river channel, broad flood plain, meanders and mid river islands are main characteristics in lower segment of river.

India has a large dendritic network of perennial and seasonal rivers with spatio-temporal variation in aquatic resources. Ganga River is one of the most densely human populated rivers (Sinha & Kurunthachalam, 2014) in Asia with immense socio-economic and ecological value. The Ganga is the 20th longest river in Asia and the 41st longest in the world. The Ganga River Basin (GRB) is India's largest catchment area basin with a landmass of 26% area (8,61,404 km²) and around 43% of its population. The Ganga, a cradle of human civilization from ancient time. It is most sacred river in the world and deeply revered by the people in India. The GRB is an example of extraordinary variation of altitude, climate, land use and cropping pattern. The GRB has large number of water resource assets and surface water bodies which is covered by 11 states and most of its area is covered by the state of Uttar Pradesh i.e., 28.02% of the total basin area. The other

states in embraces of GRB are Uttarakhand, Bihar, Jharkhand, West Bengal, Madhya Pradesh, Rajasthan, Chhattisgarh, Haryana, Himachal Pradesh and Delhi.

The GRB is bounded by outer Himalayan thrust sheet belt in the northern part and in south by Bundelkhand craton and its constituents, Aravalli-Delhi ridge in the west to the Rajmahal hills in the east and finally joins the Bay of Bengal. The GRB has filled with alluvial sediment of Quaternary period in most of the part and some areas are covered with sediment of Upper Proterozoic. The GRB is one of the largest alluvial plain in the world. Geomorphology of the Ganga River is largely controlled by the Himalayan tributary and southern tributary that are flows through the cratonic region. Sediments laid by these tributaries plays an important role for formation of such large alluvial plains (Shukla, 2016; Sinha et al., 2017).

The Ganga River is joined by a number of major Himalayan tributaries such as the Yamuna, Ramganga, Ghaghra, Gandak, Kosi before its confluence in the Bay of Bengal. The mighty Brahmaputra River also meets the Ganga River and forms a major delta. Apart from the Himalayan tributaries flowing from the north, there are also a number of southern tributaries joining the Ganga system draining through the Indian craton and Deccan basalt terrain and some of the important tributaries are Chambal, Ken, Betwa, Sone, and Punpun River. The GRB has developed due to continent-continent collision of the Asian and Indian plates which give rise to the formation of Himalayan orogenic belt. Ganga foreland basin has developed in the front of this orogenic belt. GRB is situated on the under thrusting flexed Indian plate. The Indian plate is still under thrusting the Asian plate and

makes this basin tectonically active due to compressional forces. Geologically the Himalayan region is composed of four geological units which is separated from a major thrust system, Tethyan sedimentary series, higher Himalayan crystalline series, lesser Himalaya, and the outer Himalaya. The Tethyan sedimentary series is present largely on the southern edge of the Tibetan plateau and is composed of the Palaeozoic to Mesozoic carbonates and clastic sediments. The higher Himalayan crystalline rock mainly consists of orthogenesis, paragenesis, migmatites and highly metamorphosed sediments which contain upto 8000 m high peaks of the Himalaya. The lesser Himalaya has break in a slope and shows more subdued topography compared with higher Himalaya that is composed of metamorphosed and unmetamorphosed Precambrian sequences. The outer Himalayan belt consists of recently uplifted Siwaliks of Miocene-Pleistocene detrital sediments as for example coarse sediments, coarse sandstone, clays and conglomerates. The northern Indian craton region of the basin consists of the Aravalli Range, Bundelkhand Plateau, Vindhyan range and the Malwa Plateau and lastly Chotanagpur plateau that are composed of rocks of various ages ranges from Archean to Proterozoic ages. The Ganga alluvial plain composed of alluvial sediments that are derived from the Himalayan and the northern Indian craton region during the late Pleistocene-Holocene. The bedload sediments in the proximal part of the Ganga River are mainly composed of 81% quartz, 3% feldspar, 3% mica, 4% rock fragments and 8% heavy minerals namely blue and brown varieties of tourmaline, colourless garnet, zircon and muscovite are the dominant phases (Singh et al., 2007).

Drainage network of the Ganga River mainly consists of a numerous number of rivers that act as tributaries. These tributaries are classified into three categories on the basis of their source area characteristics: (i) Himalayan-source rivers, (ii) Ganga alluvial plain-source rivers (iii) northern Indian craton source rivers. Rivers that are originating from the central Himalayan orogenic belt region are considered as main tributaries, that are perennial in nature, showing L-shaped longitudinal profiles. The origin of the Ganga plain tributaries are from the interfluvial area of Himalayan river and exhibits a smooth longitudinal profile with moderate sediment supply, little erosional capacity and single sinuous course (Singh et al., 2007).

The Ganga is a tropical monsoon river. Its annual hydrology is characterised by low flows during the post and pre monsoon season and by extremely high flows during the monsoon season from heavy rainfall. The flood cycle is very peaked and indicates a rapid increase in the discharge during July and the first half of the September. The rate of the rise and fall of the river discharge is rapid and generally uniform (Singh et al., 2007). The aquatic resources have been exploited by community over the years which has altered the production and carrying capacity of ecosystem. Many developmental activities carried out to improve river hydrodynamics representation in large scale through implementation of multiple stakeholders along the river.

1.2. Objectives

- Assessment of Land Use Land Cover (LULC) alteration in upper and middle catchment of the Ganga River.
- Identification of drainage in upper and middle catchment of the Ganga River.
- Determination of existing flow regime in middle Ganga River.
- Prediction of future scenarios based on existing development plan in upper and middle catchment of the Ganga River.

1.3. Research questions

- What is the pattern of Land Use Land Cover (LULC) alteration on multi temporal scale in upper and middle catchment of the Ganga River?
- What are the drainage networks contributing to the main stem Ganga River?
- What is the present scenario of discharge in the main stem Ganga River?
- What will be the future scenario of Land Use Land Cover (LULC) and river habitat in the main stem Ganga River?

1.4. Review of literature

1.4.1. Land Use Land Cover

Land is the area on earth on which natural and anthropogenic activities are being conducted. Land use is being shaped under the influence of two aspects of human needs and environmental factors. The land use determines anthropogenic interventions on the earth surface area which indicates pattern of land utilization by people (Foley et al., 2005), whereas land cover deals with the biophysical state on the earth surface, physical land classes, such as open water, forest, and cropland can be described as Land Cover (Li et al., 2017). These two dimensions of earth surface resource studies are different, so that they are used properly in studies of land and immediate subsurface (Turner et al. 1994). The understanding of land use land cover change has become complex over the last decades. In the beginning, the studies were concerned mostly with the physical aspect of the change, but in the research agenda on global environmental change it has been recognised that land surface processes influence climate change because of the land use cover change. In mid 1970s, it was recognized that land cover change modifies surface albedo and surface atmosphere energy exchanges, which have an impact on regional climate (Otterman, 1974; Charney & Stone, 1975) and much broader range of impacts of land use land cover change on ecosystem, goods and services were further identified and primary concern are impacts on biotic diversity worldwide (Sala et al. 2000), soil degradation (Trimble & Crosson, 2000), and the ability of biological systems to support human needs (Vitousek, 1997; Praveen, 2017). Recent rapid rate of exploitation has

brought unprecedented changes in ecosystems and environmental processes at local, regional and global scales. Presently, land use land cover changes encompass the environmental concerns of human population including climate change and biodiversity depletion. Presently, the monitoring and mediating the adverse consequences of land use land cover change while sustaining the production of essential resources has become a major priority around the world (Erle & Pontius, 2007). Unsustainable human activities are becoming key environmental concern as they deteriorate the quality of water. The relationship between land use and water quality helps in identifying threats to water quality of rivers (Ding et al., 2015) to sustain aquatic biodiversity.

1.4.2. River morphology

The Indo-Gangetic plain is the largest alluvial tract in the world. It formed due to collision between Indian and Asian plates. The river basin formed with progressive thrust sheet building in the Himalaya (Lyon-Caen & Molnar, 1985; Singh, 1996). In response to the temporal thrust sheet loading which is divided into three part i.e., Ganga plain, Brahmaputra plain and Indus plain. The Ganga plain is confined between Delhi-Aravali ridge in the west to the Rajmahal hills in the east. The Ganga plain is geomorphologically unique, where various river channels are draining into to the main stem Ganga River from the south-east direction. The Ganga River forms Piedmont zone which is adjacent to the Himalayan foothills. It forms the northern limit of the Ganga River. The zone incorporates gravelly Bhabar and sandy Terai areas. The Piedmont zone is made of discrete coalescing

alluvial fans (Shukla & Bora, 2003). The Ganga plain system shows six major geomorphic surfaces of regional extent based on morphostratigraphy proposed a relative hierarchy and chronological scheme for these geomorphic units. The upland terrace surface is considered to be the oldest, acting as the basement of deposition for rest of the geomorphic surfaces. It comprises fine grained material and this surface deposits show strong mottling, extensive development of calcrete and lack preservation of primary physical structures and organic matter. The deposits have formed by interfluvial or doab sedimentation.

The Marginal Plain Upland surface is located at the south of axial Ganga River. This surface is categorized into mottled silt, interbedded silt and mud, channelized sand, variegated clayey silt and cross bedded calcrete lithofacies, the succession represents sedimentation in sloping topographic depressions, small sandy gravelly ephemeral channels networking the Marginal Plains. The Megafan Surface is mainly sandy and represents sedimentation under conditions of higher sediment-water discharge and higher regional slopes than present days. The valley Terrace surface developed within the river valleys under high rainfall and sediment inputs. This surface characterized by rippled and cross bedded silt, sand and lensoid units of silty mud (Singh, 1996).

1.4.3. River discharge and water flow

River discharge is one of the most important and frequent targets for remote sensing in hydrology. Discharge is the product of river flow area and velocity, or the volume of water passing a specified point at an instant time. The method truly capable of measuring discharge is a bucket and a stopwatch: literally quantifying a volume of collected water for some given time period. This is obviously impractical for all but the smallest streams, and as such the most respected discharge estimates come from an Acoustic Doppler Current Profiler (ADCP) or weir equations. These techniques are commonly referred to as measurements, but they are in fact approximations of discharge (albeit accurate approximations), and are themselves subject to error, especially at very high and very low flows. Stream gauges are discharge estimates as well that transform automated measurements of river stage to discharge via an empirically calibrated rating curve. The data points to calibrate such curves are normally driven by ADCP estimates of discharge.

River sensitivity is a system response characteristic that describes the severity of a response to a disturbance, relative to the magnitude of the disturbance force (Schumm, 1991; Downs & Gregory, 2004; Fryirs, 2017). There are 3 different aspects that allow us to assess river sensitivity to a disturbance event, as defined by Downs & Gregory (1995, 2004). Firstly, how possible is it for a river to change? The probability of river change relates to the balance of driving and resisting forces acting in a fluvial system. Where a driving force exceeds the resisting forces, morphological change is likely to occur as the river planform adjusts in response to the attributes associated with the disturbance, for

example a river channel may widen in response to increased discharge during a flood event. Secondly, how probable is it for a river to change significantly? This describes how close the fluvial system is to particular thresholds, which determine the type of changes that may occur. For example, previous disturbance events may have triggered morphological responses which cause a river reach to be more sensitive to future morphological change. Finally, the process to recover the river describes whether change is reversible and, if so, how long the system takes to recover or relax following a disturbance event, relative to the recurrence interval of the disturbance. There are many definitions of river sensitivity in literature, some more complex than others. Although the definitions presented above are some of the more comprehensible, in practice assessing river sensitivity is complicated, due to the complexity, nested nature and non-linear response of fluvial systems to disturbances (Fryirs, 2017).

Anthropogenic pressure, discharge of river leads to alter river channel and aquatic habitats. Rivers under anthropogenic stress resulted into flow fragmentation, land use changes and regulation. The system tends to present attenuated and delayed peaks in flat terrains with well-developed floodplains (Tabarestani & Zarrati, 2015). Water quality degradation has taken place also due to industrial and municipal water discharge to the river that cause a decline in freshwater biodiversity. Variables like river morphometry, water depth, land use along river, water flow are crucial for river hydrodynamics (Kasprak et. al., 2018). Habitat characteristics, presence of particular species suggests that most aquatic fauna of flowing water are habitat specific and physical habitat variables including flow regimes plays critical roles in the maintenance of their richness. This approach

integrates broad concepts about river hydrodynamics and habitat change with a new framework of land use alteration in various stretch with different flow regimes and their benefits to river ecosystems.

CHAPTER 2

STUDY AREA

2.1. Course of the Ganga River

The Ganga River is one of the longest rivers in the world and the longest in India (Tandon & Sinha, 2018). The Ganga River originates from Gaumukh of Gangotri glacier in the Himalayas in northern state of Uttarakhand, India and flows with the name of Bhagirathi River. The Alaknanda River meets with the Bhagirathi at Devprayag. The accumulated flow of Bhagirathi and Alakananda River travels south with the name of Ganga River (Trivedi et al., 2010). The Himalayan course of the Ganga River reaches the Gangetic plain at Haridwar, Uttarakhand (Dimri et al., 2021). Small tributaries meet the Ganga River also namely Kedar Ganga, Jadh Ganga, Kakora Gad, Jalandhari Gad, Siyan Gad, Asi Ganga and Bhilangna river in the Himalayan course of the Ganga River. The Ganga River flows through steep slope and deep gorges of the upper and lower Himalayan valleys and forms the upper segment of the from Gangotri to Haridwar, Uttarakhand (WII-NMCG, 2019).

From Haridwar, the Ganga River flows south-east through the state of Uttar Pradesh. The river flows through the upper slope of Satpura and Vindhya hills and turns at north-east direction and forms an arc upto Varanasi, Uttar Pradesh. In this segment, various tributaries meet the Ganga River. The major rivers like Ramganga, Garra, Duar, Loni and

Gomti River join from the north direction. Yamuna and Tamas River join from the south direction in the Ganga River. The river flows through gentle slope in this region. This stretch lies at upper slope of the old igneous rock belt and forms the middle segment of the Ganga River from Haridwar to Varanasi, Uttar Pradesh (WII-NMCG, 2019). From Varanasi, Uttar Pradesh the Ganga River flows in the east direction through the states of Bihar and Jharkhand in the lower Gangetic plain till Ganga Sagar, West Bengal. The Ghaghra, Gandak, Kosi and Fulhar River joins from the north direction and Sone, Ajay, Damodar, Rupnarayan River join from the south direction in this stretch of the Ganga River. The Ganga River divides into two major channles at Farakka, West Bengal. The main stem river flows towards east and enters in Bangladesh as the Padma River, whereas another stream flows towards south direction with the named Hooghly River and meet the Bay of Bengal at Ganga Sagar, West Bengal. The river flows through lower slope in this segment. This stretch lies at Lower Gangetic plain. The downstream stretch of this segments also comes under the zone of tidal influence and forms the lower segment of the Ganga River. The total length of the Ganga River is about 2525 km.

2.2. Geology of the Ganga River basin

The Indian subcontinent is situated on the top the Indian tectonic plate which is a minor plate within the Indo-Australian Plate. About 225 million years ago, India was a large island situated at the Australian coast and a vast ocean known as Tethys which separated India from the Asian continent. During breakup of the large continent Pangaea about to

200 million years ago, India began to shift northward due to plate movement, as a result two continental landmass India and Eurasia collided with each other and formed mountain range the Himalayas. Plate movement also created a vast landscape at immediate south of the emerging Himalayas, which having gradually been filled with sediment borne by the Ganga River and its tributaries, form the foreland basin named as Indo-Gangetic plain. Ganga foreland basin has developed on the under thrusting flexed Indian plate. The Indian plate still under thrusting the Asian plate which makes it tectonically active due to compressional forces (Agarwal, 1977, Qureshi & Kumar, 1992). The Indian subcontinent is divided into four major physiographic subdivisions, i.e., (i) Himalaya, (ii) Indo-Gangetic plain, (iii) Arid region, (iv) Peninsular India. The Indo Gangetic plain is representing extensive alluvial plain formed by the Ganga, Indus and Brahmaputra Rivers and their tributaries, which is also separated the Himalayan range from the Peninsular India (Singh, 1996).

The Indo-Gangetic basin is evolved with progressive thrust sheet building in the Himalaya (Shukla, 2016; Lyon-Caen & Molnar, 1985; Singh, 1996). The Ganga River basin is bounded by the Himalaya orogenic belt with deep valleys and glaciers in north, the Ganga alluvial plain in middle and hills and plateau of the northern Indian craton in south, which comprises 21.6%, 55.4% and 23% of the basin area respectively. Studies carried out by numerous geophysical surveys, deep drilling by Oil and Natural Gas Corporation Ltd. (ONGC) and several shallow depth boreholes by Central Ground Water Board (CGWB) suggested that the basement of this Indo-Gangetic plain is dissected by a number of lineaments, faults and structural highs which controlled the basin fill (Sastri et al., 1971;

Rao, 1973). The basin filled with sediments that are eroded mainly from the Himalayan and the Peninsular India. Approximately 70% of water is contributed to the Ganga basin from the Himalayas and 30% from the cratonic part (Singh, 1996).

The Himalayan region is composed of four geological units which are separated by major thrust system, i.e., (i) Tethyan sedimentary series, (ii) Higher Himalayan crystalline series, (iii) Lesser Himalayan and (iv) Outer Himalaya. The Tethyan sedimentary series is present on the southern edge of the Tibetan plateau and is comprised of Palaeozoic-Mesozoic carbonates and clastic sediments. The higher Himalaya crystalline series situated up to 8000 m high peaks in the Himalaya, consists of orthogenesis, paragenesis, migmatites and highly metamorphosed sediments. The lesser Himalaya has break in a slope and more subdued topography compared to the higher Himalaya, and comprised of metamorphosed and unmetamorphosed Precambrian sequences. The outer Himalayan belt consist of recently uplifted Siwaliks of Miocene-Pleistocene detrital sediments, namely coarse sandstone, clays and conglomerates. The northern Indian craton region of the basin consist of the Aravalli hills, Bundelkhand plateau, Vindhyan hills, Malwa plateau and Chotanagpur plateau which consists of various rock types mostly Archean and Proterozoic ages (Oldham, 1917; Molnar, 1984).

The Ganga alluvium plain extends from the Himalayan foothills (Siwalik hills) in north to the Bundelkhand-Vindhyan-Hazaribug plateau in south (Singh et al., 2019). Aravalli-Delhi ridge in the west to Rajmahal hills in east. The southern margin of the Gangetic plain is irregular and at many places outcrops of rocks protruding out of the alluvium,

whereas the northern margin is identified by the exposure of the Siwalik rocks (Singh, 1996). The Ganga alluvial plain represents alluvial filling of sediment derived from the Himalaya and northern Indian craton region during the late Pleistocene-Holocene (Singh et al., 2007). The basin area also supplies sediments from erosion of the Himalaya orogenic belt and the northern Indian craton regions, slope erosion of the Himalayan foothills and sheet erosion of the Ganga alluvial plain. Bedload of the sediment in the proximal part of the Ganga River are mainly composed of 81% quartz, 3% mica, 4% rock-fragments and 8% heavy minerals, brown and blue varieties of tourmaline, colourless garnet, zircon and muscovites are the dominant minerals (Singh et al., 1993).

Several major tributaries meet the Ganga River during its course. The Himalayan rivers join the Ganga River from the northern bank except the Yamuna River. The southern bank tributaries are primarily originated at the cratonic part of the peninsular India, which is major source of gaining thick alluvial sediment deposits in the geological past (Sinha et al., 2017; Shukla et al., 2018). A number of groundwater fed streams originating from the alluvium which meet the major streams. The rivers of the Ganga plain exhibit several types of channel pattern and channel size (Karunakaran, 1979; Narain & Kalia, 1982; Qureshi & Kumar, 1992; Singh, 1996, Agarwal, 1977). Drain network of the Ganga basin also facilitate pathways for water and sediment discharge from river basin to the Ganga-Brahmaputra delta and the Bay of Bengal region.

The Ganga plain is broadly subdivided into three regions (Singh, 1987; Singh & Ghosh, 1992; Singh & Ghosh, 1994; Singh, 1996). The western Ganga plain shows a more

irregular topography and incision of the drainage; whereas, the eastern Ganga plain (Bihar) shows uniform terrain and less entrenchment by the drainage. From north to the south, the Ganga plain can be identified into four distinctive regions (Prakash & Kumar, 1991), i.e., (i) Bhabar belt, (ii) Terai belt, (iii) Central alluvial plain and (iv) Marginal alluvial plain. These areas show distinctive landforms, characteristic deposits and specific tectonic setting. The vast alluvial plain is broadly subdivided into (i) Old Alluvium (Bhabar) and (ii) New Alluvium (Khadar) (Pascoe, 1973). The areas of Bhabar and Terai are collectively known as Piedmont Zone.

The Bhabar Belt is a 30 km wide region of gravelliferous sediment adjacent to Himalaya with steep slopes and ephemeral streams. Whereas, Terai belt is 10 to 50 km wide low-lying area adjacent to the Bhabar belt with extensive formation of swamps, ponds, small sandy river. Central alluvial plain is the area comprises major part of the Ganga plain situated between Bhabar-Terai belt and the axial river. The drainage is aligned to the South-east direction. Marginal alluvial plain is situated at south of the Ganga River sloping towards north (Singh, 1996).

2.3. Study site

The middle Ganga River (MGR) extends from Haridwar, Uttarakhand (Downstream of Bhimgoda Barrage) to Kaithi, Varanasi, Uttar Pradesh (Confluence of Gomti River in the Ganga River) (Figure 2.1). This segment is covering approximately 1000 km length which lies between 25° 20' N to 28° 10' N and 78° 10' E to 83° 04' E. The stretch is flowing

through the state of Uttarakhand and part of Uttar Pradesh. Human pressure is very high along the Ganga River in this region. Major towns like Haridwar, Bijnor, Narora, Farrukhabad, Kannauj, Kanpur, Prayagraj, Varanasi are located beside the Ganga River in this stretch. The MGR receives water primarily from the glacier melted water and rainwater but the major tributaries in the upper and middle segment of the Ganga River namely, Ramganga, Garra, Gomti River feeds the main stem Ganga River through their extensive drainage network from the right bank, whereas the drainage of Yamuna, Chambal and Tamas River enriches the Ganga River from the left bank. The biodiversity value is high in segments of the MGR and potential habitats for aquatic biodiversity is also present in this area (Rai et al., 2024). The Ganga River flows through Rajaji National Park, Hastinapur Wildlife Sanctuary, Upper Ganga Ramsar site and Kachhua Wildlife Sanctuary in middle segment. Ramganga and Yamuna are the major tributaries of Ganga River in MGR which is considered as most fertile alluvial plain in north India. Rainfall, subsurface water flow and snow melt water from the Himalayas are the main source of water in the river. The western side of the region receives less rainfall in comparison with the eastern side. Main soil type is Fertile Eutric Cambisols which is suited for intensive cultivation (Nicholls et al., 2018). Extensive agriculture land with wide variety of crops, expanding urban area present in the region. Production of various crops, particularly flood recession farming is major livelihood option for the local people beside the Ganga River (Singh et al., 2021). Population growth in the Ganga River basin has resulted in expansion of agricultural land, urbanization, early-stage industrialization with extensive use of water for irrigation, industry, public supply and depletion in forests (Behera et al., 2014).

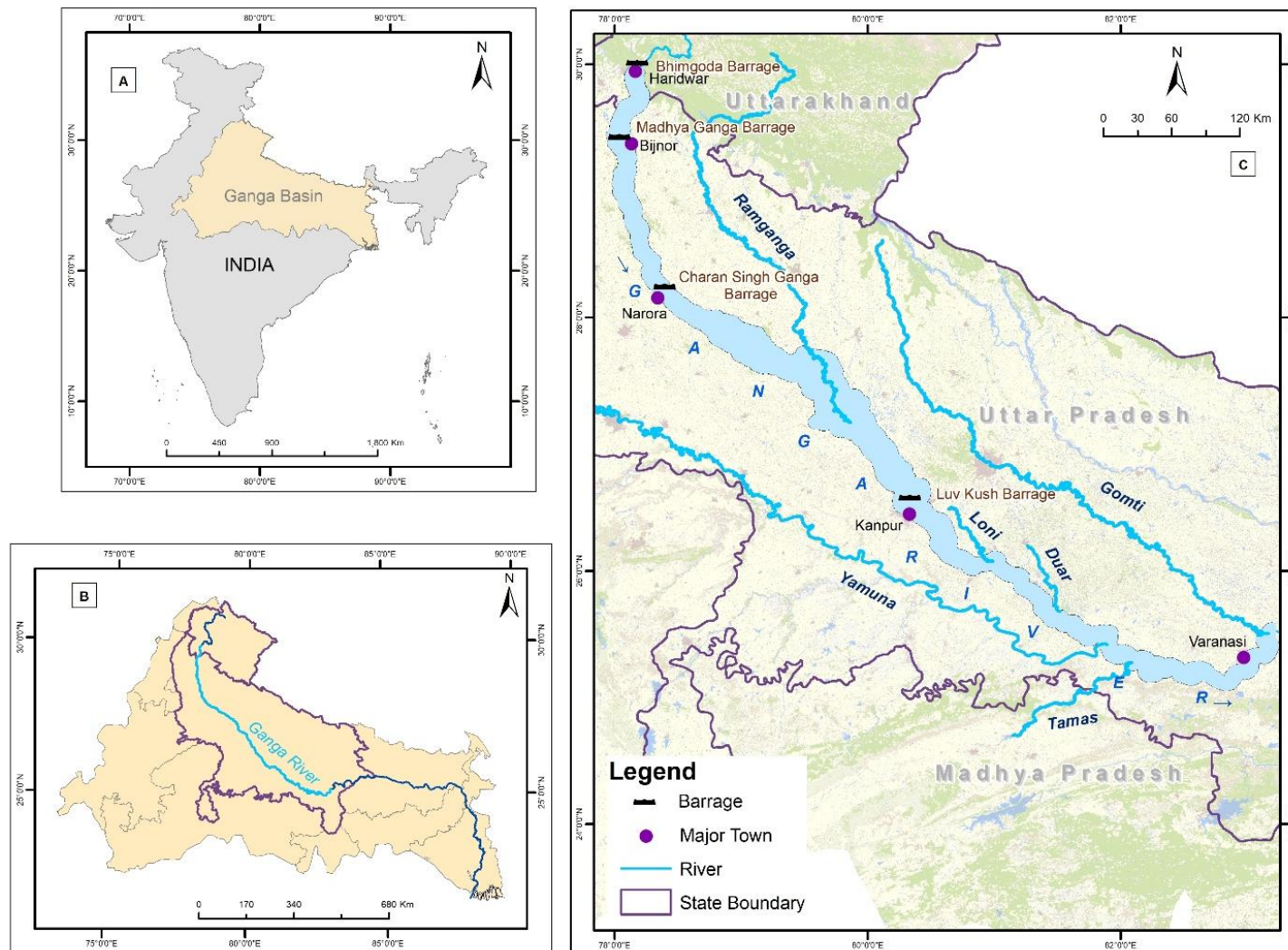


Figure 2.1. Map of study site

2.4. Physical and morphological condition

The MGR, represents a critical section of the Ganga River's course through northern India. The segment of river traverses a diverse array of physical and morphological features that have been evolved by geological processes, hydrological dynamics, and climatic factors over the years. The riverscape support a rich variety of ecosystems, habitats, and human settlements. The MGR flows through the fertile plains of northern India, characterized by a dynamic landscape that includes meandering river channels, floodplains, oxbow lakes, and wetlands (Pal & Pani, 2019). The river's course is channelized by its interactions with the surrounding topography, the deposition of alluvial materials and influence of seasonal monsoons. Physical characteristics of the Ganga River channel in this stretch are highly variable, with changes in width, depth, and flow dynamics influenced by both natural and anthropogenic factors. The river channel is broad and meandering. The depth of the river also diverse along its course. Studies reported that, deeper sections with higher flow are found near the confluence with tributaries in major rivers (Riley et al., 2015). The MGR exhibits a braided river pattern, particularly during the monsoon season, when the river experiences high discharge rates due to heavy rainfall in the catchment area. Braided rivers are formed by several small channels separated by sand bars and river islands (Wyżga et al., 2016). During the dry season the river tends to narrow, and several channels dries up, leaving behind exposed gravel beds and sandbars due to the reduced water volume. Erosion and sedimentation are two key processes behind the morphology of the MGR (Raj & Singh, 2020). The Ganga carries a heavy sediment load, much of which is derived from the Himalayan region through the tributaries. As the river flows through the

plains, it deposits large quantities of silt, clay, sand, and gravel, enriching the floodplain and contributing to the fertility of the soil. This process is most evident in the form of alluvial plains and delta-like structures, which are important for agricultural production. The river's fast-moving waters erode the banks in high discharge period, contributing to the formation of undercut cliffs and the widening of the river's channels (Gao et al., 2021). In some areas, the Ganga has created steep, eroded banks that stand in stark contrast to the flat floodplains. These eroded sections are often marked by the deposition of alluvial fans, where the river slows down and drops its sediment load. As the river meanders, the erosional process on the outer bends of the river is more pronounced, while sediment is deposited on the inner bends, forming sandbars, gravel bars, and point bars (Taye et al., 2020). Over time, this sediment deposition leads to the formation of oxbow lakes. These oxbow lakes, which are formed when the river changes course, represent distinct features of the river's morphology and provide valuable aquatic habitats.

Floodplain is one of its most defining physical features. The Ganga River's floodplain is broad and fertile, extending over several kilometers in some places. The floodplain is created by the sedimentation of fine silt and sand deposited by the river during seasonal flooding (Suchodoletz, 2021). This alluvial soil is highly fertile and supports extensive agricultural activity, particularly the cultivation of rice, wheat, sugarcane and pulses. Floodplains also serve as important wetlands that support a rich diversity of plant and animal life (Holgerson et al., 2019). These wetlands are particularly prominent in areas like the region around Kanpur and near Varanasi, where the river is flanked by numerous small lakes, ponds, and marshes. These wetlands provide vital ecosystem services, such

as water purification, flood control, and habitat for migratory birds and aquatic species (Ghosh, 2021; Singh et al., 2022). The flora of the wetlands includes reeds, aquatic grasses, and water lilies, while the fauna includes a variety of fish species, amphibians, reptiles, and birds. The river undergoes rapid shifts in flow and morphology where tributaries join the main stem river (Liu et al., 2020). The added water from these tributaries contributes to flooding and shifts in the river's course, while also introducing different sediment types, further altering the morphology of the Ganga River's channel. Urbanization along the banks of the Ganga River, particularly in cities like Kanpur and Varanasi, has led to the modification of riverbanks and the construction of ghats, embankments, and roads. This human intervention has altered the natural river morphology, leading to the loss of wetlands and changes in the sedimentation patterns.

2.5. Climatic condition

The MGR flows through one climatic region namely Temperate Dry Winter Hot Summer region (following Köppen classification system) (Peel et al., 2007), which is located in the southern part of Uttarakhand and entire Uttar Pradesh. It flows through two biogeographic zones, i.e, Himalaya (2), Gangetic Plain (7) and three biotic provinces i.e, West Himalaya (2B), Upper Gangetic Plain (7A), Lower Gangetic Plain (7B) (Rodgers et al., 2002). The Himalaya region is mountain areas and occupy about 7.2% of the country's landmass. The Gangetic plain is relatively homogenous and defined by the Ganga River system (Rudra, 2020). It occupies about 11% of the country's landmass. This region is

very fertile and extends upto the Himalayan foothills. Climatic condition of the MGR is influenced by combination of geographical, meteorological, and seasonal factors. This region, is characterized by complex climate that ranges from humid subtropical to semi-arid, with significant seasonal variation in temperature, rainfall, and humidity. The area along the Ganga River is vital not only for its ecological importance but also for its cultural, agricultural, and economic significance. The climatic conditions in this region profoundly impact the livelihood, agriculture, and daily life of the inhabitants by increasing monsoon flows and enhancing dry season flows, which is threatening water supplies and ecosystem services (Whitehead et al., 2018).

The MGR passes through the northern plains of India that covers, wide range of geographical features, the Shivalik foothills, the plains of Uttar Pradesh, and the fertile Gangetic plains. The region lies in the monsoon belt of India, and is heavily influenced by the southwest monsoon, which brings significant rainfall during the summer months. The river itself is the life support of the region, and its course affects the physical landscape, climate and microclimates of the surrounding areas. The climate of the region is marked by extremes in temperature, particularly between the hot summer months and the cold winter months. During the summer, from March to June, temperatures in this region remain above 40°C (104°F) during the day, particularly in May and June, which are typically the hottest months. The heat during this time can lead to increased evaporation from the river, causing lower water levels in certain stretches. The humidity also rises during these months. As the monsoon sets in, typically from late June to September, temperatures decrease slightly, though they remain warm and humid

(Swarnkar et al., 2021). The region receives moderate to heavy rainfall during this period, which helps to reduce the temperature and provide some relief from the summer heat. However, the humidity level during the monsoon remains quite high, and air becomes thick with moisture, which can feel oppressive for the residents. Winter in the MGR region, from November to February, brings a drastic shift in climatic conditions. Temperatures during the winter months can drop to around 5°C to 10°C (41°F to 50°F) in the night and early morning hours, while daytime temperatures typically range between 15°C to 25°C (59°F to 77°F). The cold weather is accompanied by dense fog, especially in the mornings, which can severely affect visibility (Shrestha et al., 2018). The fog is a significant feature of winter in this region, as it tends to linger throughout the morning, gradually clearing by the afternoon.

The MGR region is heavily influenced by the monsoon, which is the most critical climatic event of the year. The southwest monsoon, which typically begins in June and lasts until September, brings a significant amount of rainfall to the region. This is a period of great importance for agriculture, as the Ganga River and its tributaries provide irrigation to vast areas of the riverscape. The river's floodplains are replenished with nutrient-rich silt, making them highly fertile and capable of supporting extensive agricultural activities. Annual rainfall varies across the MGR region, with the western part (near Haridwar) receiving slightly less rainfall than the eastern part (near Varanasi). Haridwar, located near the foothills of the Himalayas, experiences an average annual rainfall of about 1200 mm to 1500 mm, while Varanasi, which is further downstream in the plains, receives around 1000 mm to 1200 mm annually. The majority of the rainfall occurs during the

monsoon season, with a peak in July and August. During the monsoon, the Ganga River often swells, resulting in flooding in certain areas, particularly in low elevated regions. The river's flooding is both a blessing and a challenge for the people living along its banks. On one hand, it replenishes the soil and provides water for crops; on the other hand, it may cause significant damage to infrastructure, homes, and farmlands. The unpredictability of monsoon rainfall also poses a challenge, as areas can experience varying amounts of rainfall, leading to either drought or flooding (Krishnamurthy & Shukla, 2000). Humidity in the region is typically high throughout the year, but it reaches its peak during the monsoon months. The wind patterns in this region are also influenced by the seasonal changes. During the summer, hot winds blow from the northwest, making the heat more intense. In the winter, cooler winds from the north and northeast reduce the temperature, especially at night. The wind can also contribute to the formation of fog during the winter months, as moist air cools and condenses.

2.6. Biodiversity and areas of conservation significance

The MGR flows through two ecoregions namely Terai-Duars savanna and grasslands (at the boundary between the Himalayas and the Indo-Gangetic plain), Upper Gangetic Plains moist deciduous forests (at the state of Uttar Pradesh), As the Ganga River flows through these vast variety of ecoregions, the river surrounding areas are rich in biodiversity. The Ganga River is home to about 200 species of fishes, 49 species of amphibians, 13 species of turtles, 4 species of Crocodylidae, 177 species of migratory and resident birds and 4

species of mammals (WII-GACMC, 2018). Many of them are declared as threatened by IUCN. These includes Ganges shark (*Glyphis gangeticus*), Golden mahaseer (*Tor putitora*), Indian narrow-headed softshell turtle (*Chitra indica*), Indian peacock softshell turtle (*Nilssonia hurum*), Indian softshell turtle (*Nilssonia gangetica*), Indian spotted turtle (*Geoclemys hamiltonii*), Northern river terrapin (*Batagur baska*), Three-striped roofed turtle (*Batagur dhongoka*), Gharial (*Gavialis gangeticus*), Mugger crocodile (*Crocodylus palustris*), Black-bellied tern (*Sterna acuticauda*), Sarus crane (*Antigone antigone*), Greater adjutant (*Leptoptilos dubius*), Indian skimmer (*Rynchops albicollis*), Oriental small-clawed otter (*Aonyx cinerea*), Smooth-coated otter (*Lutrogale perspicillata*) and Gangetic dolphin (*Platanista gangetica*). In the first meeting of the National Ganga River Basin Authority (NGRBA) chaired by then Honourable Prime Minister Dr. Manmohan Singh on Monday, 5 October 2009 the Gangetic dolphin (*Platanista gangetica*) was declared by the government of India as National Aquatic Animal. Following protected areas are located in the MGR.

The Rajaji National Park: It is situated along the north-western extreme of the Terai-Arc Landscape (TAL) and was established in 1983 (Harihar et al., 2008). Total area of this national park is about 820 km² and it is very important protected area for the conservation of Asian elephant (*Elephas maximus*), Bengal tiger (*Panthera tigris*), leopard (*Panthera pardus*), Himalayan black bear (*Ursus thibetanus laniger*) and sloth bear (*Melursus ursinus*).

Upper Ganga Ramsar site: The river stretch between Brijghat to Narora was designated as Ramsar wetland of international importance in the year 2005. This shallow river stretch provides important habitat for the Gangetic dolphin, gharial, crocodile, turtles, otters, several species of fishes and medicinal plants.

Hastinapur Wildlife Sanctuary: This sanctuary was established in the year 1986 to conserve the fast vanishing, unique Ganga River grassland-wetland complex (Khan & Abbasi, 2015). It is located on the western bank of the Ganga River and spared over 2073 km² are in five districts of Uttar Pradesh namely Muzaffarnagar, Bijnor, Meerut, Ghaziabad and Jyotiba phule Nagar. It is an important protected area for the conservation of the swamp deer (*Rucervus duvaucelii*), smooth-coated otter and gharial.

Kachhua Wildlife Sanctuary: The 30 km stretch of the Ganga River located at downstream of Ganga-Yamuna confluence at Prayagraj, Uttar Pradesh. This sanctuary was established in 2020. Since 1989, this sanctuary was located in 7 km stretch in south bank of the Ganga River, opposite to the Varanasi city from Rajghat to Ramnagar, Varanasi in Uttar Pradesh for the protection of turtles.

2.7. Demography

The demographic conditions of the MGR, stretching from Haridwar in Uttarakhand to Varanasi in Uttar Pradesh, are characterised by a rich tapestry of historical, cultural, social, and economic factors. This stretch of the river is home to some of the most densely populated and historically significant regions in northern India (Das et al., 2024). A

complex interplay between urbanization, rural settlements, religious significance, agricultural dependence, and migration patterns marks the population distribution along the Ganga. Understanding the demographic condition of the middle Ganga region involves examining population density, rural-urban divides, socio-economic aspects, and the diverse communities that rely on the river for various purposes. These factors play a pivotal role in shaping the socio-cultural and economic landscape of the region, influencing everything from agricultural practices to urban infrastructure and social development (Shukla et al., 2018).

The population along the MGR is concentrated primarily in the plains of Uttar Pradesh, with significant urban and rural settlements situated along the riverbanks. This region is one of the most populous in India, with some of the largest cities located along its course (Tandon & Sinha, 2018). Haridwar, although an important religious site, is relatively smaller compared to other cities further downstream, such as Kanpur, Prayagraj, and Varanasi, which are major urban centres. The population density in this stretch of the river is high, particularly in cities like Kanpur and Varanasi, which are among the largest cities in Uttar Pradesh. Varanasi, in particular, is a city of immense religious and significance with cultural history, drawing millions of pilgrims every year (Pandey et al., 2023). Urbanization around the river results from historical development and the natural resources the river provides. The Ganga's water serves as an important resource for agriculture, industry, and domestic consumption (Matta et al., 2020), making the areas along its banks densely populated with people who depend on it for their livelihoods. The population density along the Ganga is influenced by the fertility of the river's floodplains,

which support agriculture. The plains of the Ganga Basin are some of the most fertile in the world, and as such, they have supported human settlement for thousands of years (Matin & Behera, 2017). From Haridwar to Varanasi, the river flows through some of the most agriculturally productive regions in India, including parts of the Doab region between the Ganga and Yamuna rivers, which is home to large agricultural communities. The population along these fertile plains has historically been both agrarian and dependent on the river's resources, resulting in high rural population densities in many parts of the region. Urbanization along the region has accelerated significantly over the last century, with the growth of cities such as Kanpur, Prayagraj, and Varanasi. These cities have become major economic hubs, driven by their proximity to the river, the agricultural wealth of the surrounding region, and industrial development. Kanpur, for example, is an important industrial city, historically known for its textile mills and, more recently, for manufacturing and commercial activities (Rai, 2021). Similarly, Varanasi, known for its textile and handicraft industries, has experienced significant growth in trade, tourism, and services (Naik & Bhardwaj, 2024). Migration plays a key role in the demographic makeup of the region. The Ganga has historically been a corridor for migration (Jha, 2014). Migrants from rural areas surrounding the Ganga often move to urban centres in search of employment, better infrastructure, and improved living standards. This rural-to-urban migration has contributed to the rapid growth of these cities and the expansion of slums and informal settlements along the river. Moreover, the river's religious significance attracts pilgrims from all over India (Kumar, 2017). This seasonal influx of pilgrims contributes to temporary population surges, which can strain local infrastructure,

sanitation, and water resources. The constant movement of people, combined with the region's historical and cultural importance, creates a dynamic demographic situation. While urbanization is a significant trend in the region, much of the population still resides in rural areas. Agriculture remains the primary occupation for a large portion of the population, particularly in the districts surrounding the river. The fertile alluvial soil deposited by the Ganga and its tributaries makes the region highly suitable for the cultivation of crops like rice, wheat, sugarcane, and vegetables (Kumar et al., 2020). The presence of the river ensures a reliable water supply for irrigation, which is crucial for sustaining agriculture, particularly during the dry season when groundwater resources are limited.

Rural populations along the MGR are often small-scale farmers, who rely on traditional agricultural practices (Singh et al., 2021). However, over the years, there has been a gradual shift towards more mechanized forms of farming, especially in areas close to urban centres like Kanpur, where commercial agriculture has expanded. The socio-economic conditions of population along the MGR are influenced by a combination of traditional livelihoods, urbanization, and economic diversification (Kumar et al., 2017; Das et al., 2020). The rural areas are predominantly agrarian, but the rise of industrialization, particularly around cities like Kanpur and Allahabad, has led to the development of new economic activities. These urban centres have seen the growth of industries such as textiles, leather, sugar, and steel, which attract both skilled and unskilled labour from across the region.

However, despite the economic opportunities in urban areas, poverty remains widespread in both rural and urban settlements along the MGR. The gap between the urban rich and the rural poor is stark, with urban areas like Varanasi has significant inequality in income distribution (Pandey & Bhardwaj, 2021). The rapid urbanization of cities has also led to the expansion of slums and informal settlements, where millions of people live in inadequate conditions, with limited access to sanitation, clean drinking water, and healthcare. Urbanization negatively impacts on health of the Ganga River, leading to hydrological and geomorphological change and deterioration of water quality (Quadir, 2022). The lack of basic infrastructure in these urban centres further exacerbates the socio-economic divide. The population along the Middle Ganga is ethnically diverse, comprising various communities, castes, and linguistic groups. The communities in the MGR belong to different religious and social groups, including Hindus, Muslims, Sikhs, and others, each contributing to the social and cultural fabric of the area (Kala, 2018). Urbanization along the Ganga River also decrease groundwater recharge and groundwater quality (Misra, 2011), that requires an integrated approach for sustainable water management, river restoration and freshwater biodiversity conservation.

CHAPTER 3

DECADAL ALTERATION OF LAND USE LAND COVER

3.1. Introduction

Land Use Land Cover (LULC) is an important component of global environmental change. LULC and Climate Change are the primary drivers of hydrologic processes, influencing the available water resources and flow regimes in a river basin around the world (Bosch & Hewlett, 1982; Gashaw et al., 2018). Changes in LULC have substantial influence on the hydrologic characteristic of a river. Alterations in LULC impact the water resources availability and hydrological cycle (Costa et al., 2003; Bruijnzeel, 2004; Krause et al., 2009; Romanowicz & Booij, 2011). Translation of land cover for urban and agricultural uses often affects integrity of soil, nutrient fluxes, and assemblies of inherent species. LULC changes affect the exchange of water and energy between the earth's surface and have impact on dynamics of climate changes. Rapid anthropogenic activities such as urbanization, mining, agricultural activities lead to land cover modification and conversion from one land cover class to another. These anthropogenic activities with other climatic variables have raised concern about the effects of LULC changes on water, sediment fluxes, water and air quality, soil condition and ecosystem (Patidar & Behera, 2019). Such changes can disturb watershed hydrology by altering canopy interception, soil properties, infiltration, surface roughness, albedo and evapotranspiration. Therefore,

interactions among these factors at basin scale have a confounding effect that might result in variations in the timing and volumes of surface runoff and river flow (Li et al., 2015; Romanowicz and Booij, 2011; Zhang et al., 2012; Shrestha et al., 2017). The process of land use change in river basins has also been significantly influenced by urbanization. The rapid expansion of cities and towns in proximity to the Ganga River has led to the conversion of natural landscapes, such as forests, grasslands, and wetlands, into urban areas (Shafique et al., 2019). This urban sprawl often occurs along riverbanks, where the availability of water for drinking, sanitation, and industry makes these areas attractive for development. In many regions, particularly in countries with large populations, such as China, India, and parts of Africa, this transformation has led to the encroachment of urbanization on floodplains, reducing the natural resilience of these areas to flooding (Wang et al., 2021). The construction of roads, buildings, and infrastructure in flood-prone zones further exacerbates the risk of flooding, as natural floodplains are transformed into impervious surfaces, limiting the ability of rivers to dissipate floodwaters naturally (Mustafa et al., 2018; Park & Won, 2019). Globally the rivers are regulated by construction of dams and barrages. Dams, create reservoirs that inundate large areas of land, often displacing local communities and altering the natural flow regime of rivers. While dams may provide benefits such as hydroelectric power, water supply, and flood control, they also have adverse effects on the surrounding environment. These effects include changes in water temperature, sediment transport, and the disruption of aquatic habitats, all of which have lasting impacts on river ecosystems and biodiversity (Wu et al., 2019). It is reported in a study in Northeast China (Shen et al., 2013), changes

in built-up, cropland, forest, grassland and wetland were analysed from 1970 to 2004 that highlighted the effectiveness of forest and wetland protection and restoration projects. Decrease in ecosystem services value were found in Su-Xi-Chang region of Yangtze River delta, East China, due to the loss of cropland and water bodies by urban expansion (Yirsaw et al., 2016). In Bonsa catchment of Ankora river basin in Ghana, West Africa, land cover transitions from 1986 to 2011 showed that increase in population growth, agriculture expansion and increased surface mining activities were responsible for increased deforestation rate (Aduah et al., 2015). In Poland, the effect of LULC on ecological quality of rivers were analysed which showed decline in population of bryophytes due to the loss of forest (Zgola, 2014). Human induced LULC changes were revealed in Kagera Basin of Lake Victoria (Wasige et al., 2013). Role of socioeconomic and physical drivers on land degradation were identified in Vietnam (Vu et al., 2014).

3.1.1. Land Use Land Cover change

The middle stretch of the Ganga River has been transformed from its natural flow due to obstacles in the river course. This stretch serves as a habitat for gharial, mugger, turtles, and island-nesting birds, which are adversely affected by the construction of dams and barrages. These constructions and sand mining have disrupted the river's lateral connectivity. The middle Ganga River (MGR) is socioeconomically most important in India and highly stressed in terms of water resources due uncontrolled LULC activities. This chapter presents a comprehensive set of analyses to evaluate the LULC

transformation and geomorphological changes along the MGR and its effects on aquatic biodiversity. Previous study mentioned that tropical region experienced rapid land use land cover changes with association of climate change, that impact on the hydrological and geomorphological processes of the river system (Kayitesi et al., 2022). Land use affects watershed processes which operate the production, transport and storage of water also sediment, nutrients, metals and other pollutants. Human activities disrupted vegetation and destabilized soils have the potential to decrease soil infiltration, suppress groundwater recharge and increase runoff generation which resultant amplify flood frequencies, erosion and sediment production (James & Lecce, 2013). The driving factors responsible for LULC change in the combination of socioeconomic, demographic, and physical parameters. Also, these driving factors may operate independently at different levels in a simultaneous manner that may vary in time and space. The changing patterns of LULC and their driving factors have been studied in different countries at various scales. In India, the changing patterns of LULC with decrease in forest cover, expansion of cropland and increase in built-up areas (Tian et al., 2014). Another study reported on LULC changes in India (Roy et al., 2015), significant increase in built-up areas and cropland and decrease in fallow land, forest and wasteland have been identified during 1985 to 2005 using satellite images. It is reported that resulting runoff from urban areas also affects river water quality, often introducing pollutants such as heavy metals, chemicals, and untreated sewage into the Ganga River, which disrupts aquatic ecosystems and affects the health of communities that rely on rivers for drinking and agriculture (Trivedi, 2010). Industrialization has similarly altered LULC within in river catchments.

The construction of dams, hydropower plants, and industries within Ganga River systems has led to significant changes in river hydrology and land use patterns (Kumar et al., 2023). In addition, the expansion of industrial zones along riverbanks leads to the transformation of land cover from natural vegetation to man-made infrastructures, which further exacerbate water pollution. The Ganga River have been heavily impacted by industrial discharges, leading to severe water contamination and the decline of aquatic species. It is difficult to link the drivers of LULC change in a heterogeneous landscape because of uncertainty associated with misclassification and availability of data at diverse scales (Martinez et al., 2011). LULC change is dynamic in nature, and it is difficult to obtain real time information of LULC change through conventional methods. Satellite remote sensing along with GIS that brings different types of data at one platform for analysis has brought a new dimension to study LULC changes at varied scales (Wang et al., 2013).

Preliminary knowledge of land cover pattern is needed for understanding the impact of human interaction with the natural environment. The river channels in the MGR are having barrages, which transformed the Ganga River into multiple stretches. The downstream areas of barrages are water scarce stretches till the joining of tributary rivers in the mainstem Ganga River (Sinha et al., 2022; Kumar et al., 2023). Braided channels, sandbars and river islands are common characteristics at the downstream of barrages. The floodplain areas are also categorised in riverine wetlands, agriculture, grassland and builtup areas. Geographic information system techniques help to analyze the impact of several factors on the land cover changes along the Ganga River (Patidar & Behera, 2019).

Remote sensing is the field of research which help to know differing, constantly changing and expanding. Now a days multiple method is introduced to deduce multiple facets from the satellite remote sensing products. Anthropogenic activities are reason for rapid climate change which directly influences the land use land cover change. The changes in LULC influences enormous changes in surface water and physical characteristics of the region (Sinha et al., 2017), which effect water budget shortage and increase surface temperature. This shortage of water availability combined with increase surface temperature will decrease vegetation cover of the region. Demographic variation is one of the major causes for the LULC changes (Shukla et al., 2018).

3.2. Methodology

The key factors contributing to decadal alterations in LULC within river systems are climate change, human population expansion, urbanisation etc. The impacts of climate change on hydrological cycles, such as altered rainfall patterns, increased frequency of extreme weather events, and rising temperatures, have transformed LULC in river (Santy et al., 2021). These changes can be seen in shifting agricultural practices, water availability, and flood frequency. In some global river basins, changes in precipitation patterns have led to reduced water availability for irrigation and drinking, forcing agricultural lands to shift in response to water scarcity (Zhang et al., 2012; Hou et al., 2020; Chaubey et al., 2022). In the Mekong River Basin, altered rainfall patterns and increased temperatures have led to changes in cropping seasons and water storage

practices, as farmers adjust to the new climatic conditions (Sridhar et al., 2019). Similarly, changing climate has resulted in an increase in extreme weather events, such as floods and droughts, that further transform land cover and land use within river systems. For instance, more frequent and severe flooding in the Lower Mississippi River Basin in the United States has led to increased urban and agricultural land use conversion to flood defences, such as levees and embankments, which disrupt natural hydrological processes (Yasarer et al., 2020; Rajib et al., 2021). Satellite images play a vital role in geographic information. Satellite and remote sensing images providing quantitative and qualitative information. These technologies involve collecting data and images at regular intervals. The volume of data received at data centre is huge and it is growing extremely fast as technology has enhanced and data volume is also growing at an exponential rate. Thus, an efficient mechanism is needed to extract information from a vast number of satellite images. Satellite image classification is a powerful technique to extract information from an enormous number of satellite images (Dutta, 2019; Roy & Inamdar, 2019). Satellite image classification is a process of grouping pixels into meaningful classes and extracting valuable information from satellite images. It is a multi-step workflow. Satellite image classification involves interpretation of remote sensing images, spatial data mining, studying various vegetation types such as agriculture, forest, urban and determining various land uses in an area. Several methods and techniques are used for satellite image classification. Satellite image classification methods are broadly divided into three categories: (i) automated (ii) manual and (iii) hybrid. Automated satellite image classification methods use algorithms that applied systematically the entire satellite image

to group pixel into meaningful categories i.e. (i) supervised and (ii) unsupervised classification methods. Manual satellite image classification is robust and effective method but this method depends upon the analyst knowledge, and it consumes more time. Another one is the hybrid; this method combines the advantages of automated and manual methods. In hybrid method automated satellite image classification is used for primary classification and manual methods are used for refining classification and correcting errors (Figure 3.1).

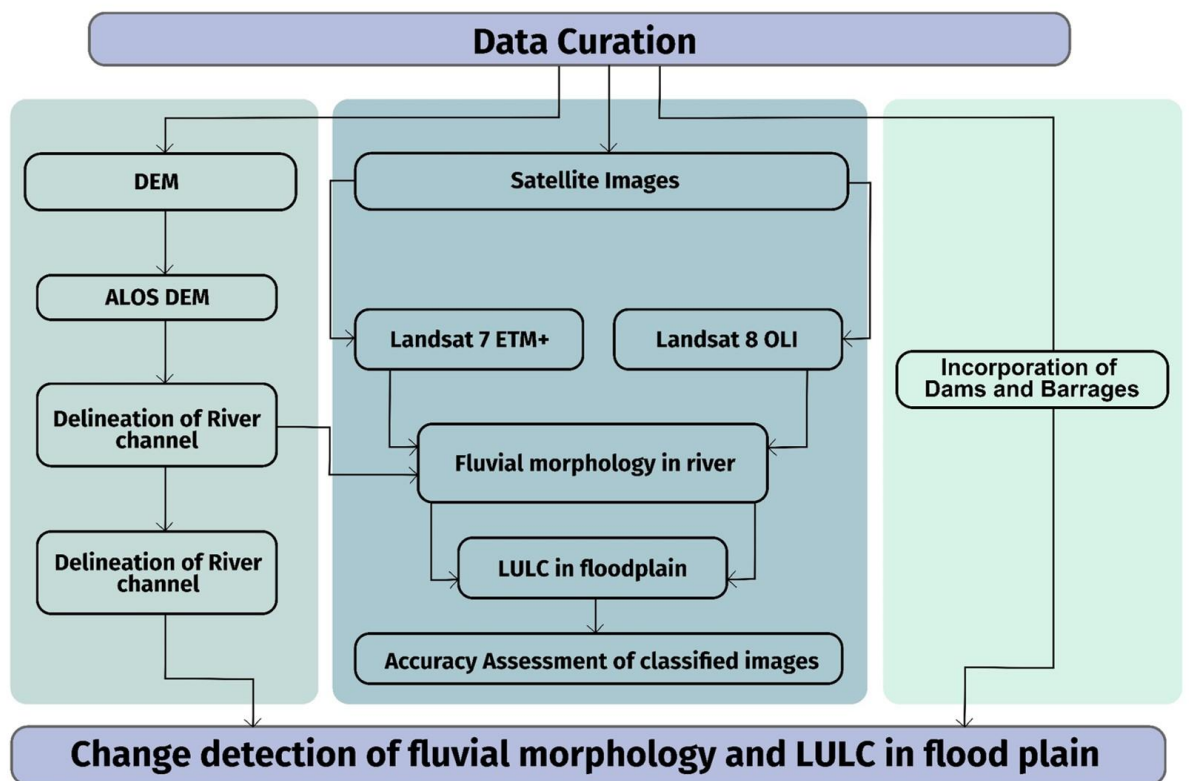


Figure 3.1. Methodology flow chart for Land Use Land Cover

3.2.1. Land Use Land Cover analysis

In this study, supervised classification has been used, which required input from analyst, known as training set. Samples taken for training highly affect the accuracy of the method. Training samples are two types, one used for classification and another for supervising classification accuracy. Under supervised image classification, Maximum Likelihood Classification (MLC) method is used which is statistical supervised approach for recognizing the pattern. It distributes pixels to appropriate classes based on probability values of the pixels. The MLC method is the widely used algorithm for supervised satellite image classification. To classify the multi-temporal images, the reference data was collected from field conducted in year 2023 and using Google Earth for year 2013 and 2003. The LULC maps with intervals of 10 years for 2003, 2013 and 2023 were prepared at 1:50,000 scale. The area within two banks of the river was classified in three geomorphological attributes, i.e., River, Sandbar, and Island whereas, the area of the flood plain was classified in six classes, i.e., Barrenland, Waterbody, Forest, Agriculture, Builtup, and Grassland. The first image was acquired in 2003 from Landsat 7 ETM+, the second image was acquired in 2013 using Landsat 8 OLI and the third image was acquired for the year 2023 using Landsat 8 OLI (Prasad et al., 2020). The satellite images are taken from United States Geological Survey (USGS) Earth Explorer with free cloud cover (Pandey et al., 2022). The images were classified by object-based classification system by the on-screen visual classification method using ArcGIS version 10.6.1 software for delineating land use layers spatially (Puig et al. 2002) to analyze the land use change dynamics (Ara et al., 2023) over temporal scale and digital image classification method

using ERDAS Imagine version 2016. The change among the derived LULC classes over the decade were done using change detection method (Patidar & Behera, 2019; Ara et al., 2023). The study was carried out in two parts, geomorphological change analysis within the river belt and LULC change analysis in the floodplain. The Ganga River was divided into two lateral segments depending upon channel width and proximity to the river bank, (i) Riverbed and (ii) Floodplain. Satellite image data derived from the Landsat (Table 3.1) and Survey of India topographical sheets (Table 3.2), were used in the present study.

Table 3.1. Source of satellite images used to derive Land Use Land Cover classes

Satellite	Path/Row	Date	Resolution	Source
Landsat 8 OLI	144/041	08.03.2023	30 m	https://earthexplorer.usgs.gov/
	144/042	08.03.2023		
	146/039	06.03.2023		
	146/040	06.03.2023		
	142/042	02.03.2023		
	142/043	02.03.2023		
	143/042	01.03.2023		
	145/041	15.03.2023		
Landsat 8 OLI	142/042	15.04.2013	30 m	https://earthexplorer.usgs.gov/
	142/043	15.04.2013		
	144/041	13.04.2013		
	144/042	13.04.2013		
	146/039	11.04.2013		
	146/040	11.04.2013		
	143/042	03.04.2013		
	145/041	06.05.2013		
Landsat 7 ETM+	142/043	11.03.2003	30 m	https://earthexplorer.usgs.gov/
	146/039	07.03.2003		
	146/040	07.03.2003		
	142/042	23.02.2003		
	144/041	21.02.2003		
	144/042	21.02.2003		
	145/041	01.04.2003		
	143/042	18.03.2003		

Table 3.2. List of topographical sheets used

Source	Topographical Sheet Number
Survey of India (SOI), Govt. of India	53J04 53K01 53K05 53G14 53K02 53K06 53G15 53K03 53G16 53K04 53H13 53L01 53L05 53L02 53L06 53L03 53L07 53L08 53L12 53L16 54I09 54I13 54M01 54M05 54M09 54I14 54M02 54M06 54M10 54M14 54M07 54M11 54M15 63A03 54M12 54M16 63A04 54N13 63B01 63B05 63B02 63B06 63B10 63B03 63B07 63B11 63B08 63B12 63B16 63F04 63F08 63C13 63G01 63G05 63O02 63G06 63G10 63G14 63O07 63O03 63K15 63K11 63G11 63K07 63G15 63K03 63O04 63K16 63K12 63K08 63K04

The images were rectified radiometrically, as well as geometrically to undergo object-based image classification to categorize all pixels from the Landsat images into different LULC classes (Bansal et al., 2016). For image classification, the data of ground truth were gathered on the field site. The images were classified by supervised image classification method using “maximum likelihood classification (MLC)”. The MLC method is the widely used algorithm for supervised satellite image classification. As the Supervised image Classification technique maintains basic land cover characteristics through statistical classification techniques, the images were classified using this method. To classify the multi-temporal images, the reference data was collected from field conducted in year 2023 and using Google Earth for year 2013 and 2003. The LULC maps with intervals of 10 years for 2003, 2013 and 2023 were prepared at 1:50,000 scale in nine classes as Table 3.3. In the present study, the area within two banks of the river was classified in three geomorphological attributes, i.e., River, Sandbar, and Island whereas,

the area of the floodplain was classified in six classes, i.e., Barrenland, Waterbody, Forest, Agriculture, Builtup, and Grassland.

Table 3.3. Land Use Land Cover classes with descriptions

Serial No.	Class	Description
1	River	Areas covered with water channel
2	Sandbar	Areas with sand deposition located as foreland and isolate distributed sand structure in the river
3	Island	Upland areas located within the river with soil deposition and hard rooted vegetation growth.
4	Barrenland	Open areas along the river flood plain with no sign of agriculture or other land use practices.
5	Waterbody	Areas covered with small streams, reservoirs and wetlands
6	Forest	Areas covered with dense and moderate dense tree canopy cover (deciduous forests, evergreen forests, mixed forests)
7	Agriculture	Includes areas used for seasonal and annual crops, irrigated areas, commercial farms (sesame cultivations) and seasonal fallow lands
8	Builtup	Areas with human settlements
9	Grassland	Areas covered by grasses, grazing and pasture lands

To accomplish multi-temporal image classification and delineation of riverbank line, floodplain area ERDAS Imagine 2015 and ArcGIS 10.6.1 softwares were used, respectively. Training samples were selected in every LULC class based on the ground truth data, and Google Earth image for classification and validation of classified images.

3.2.2. Classification Error Matrix and Accuracy assessment

One of the most common means of expressing classification accuracy is the preparation of a classification error matrix (confusion matrix or contingency table). To prepare an error matrix first step is to locate ground reference test pixels or sample collection, based on which an error matrix is formed. There are many mathematical approaches in this regard. Generally, it is suggested that a minimum of 50 samples of each land use land cover classes should be included. If the study area is large or the numbers of land use land cover classes are more than 12, the sample should be 75 to 100. Data sampling use to be done using various procedures such as, random, systematic, stratified random, stratified systematic unaligned, and cluster. An error matrix compares the relationship between known reference data or ground data, and the corresponding results obtained from classification.

Accuracy assessment is important to know the extent of true representation of the ground truth represented over each LULC class. Assessment of classification accuracy is required for the degree of confidence in the classified image and the subsequent change detection (Samal & Gedam, 2015). The ground truth data were collected from each class for the year 2023 using handheld GPS, and subsequently data gathered from secondary sources like Google Earth, Landsat images, and Survey of India topographical sheets. The error matrix was developed the overall accuracy, user accuracy, producer accuracy, and kappa statistics of the classified images (Congalton, 1991, Lucia et al., 2019). The kappa coefficient (κ) value is classified as poor agreement for $\kappa < 0.4$, moderate agreement for

$\kappa = 0.4$ to 0.8 , and strong agreement for $\kappa > 0.8$ (Mishra et al., 2016).

$$\kappa = \frac{N \sum_{i=1}^r X_{ii} - \sum_{i=1}^r (X_{i+}) * (X + i)}{N^2 - \sum_{i=1}^r (X_{i+}) * (X + i)} \quad (1)$$

$$\kappa = \frac{(\text{Total} * \text{sum of correct}) - \text{sum of all the (row total} * \text{column total)}}{\text{Total squared} - \text{sum of all the (row total} * \text{column total)}}$$

Where,

r = number of rows in the matrix

X_{ii} = number of observations in row i and column i (the diagonal elements)

$X + i$ and X_{i+} = the marginal totals of row i and column i

N = number of observations

3.2.3. Decadal alteration of Land Use Land Cover

The decadal alteration of land use land cover in rivers has profound implications for both the natural environment and human societies that depend on ecosystems. Rivers are dynamic landscapes that are subject to constant change, influenced by a combination of natural processes and human interventions (Church, 2002; Datry et al., 2016). Over the last few decades, changes in land use land cover (LULC) within river systems have been driven by urbanization, agriculture, industrialization, and climate change, leading to significant transformations in hydrological patterns, water quality, biodiversity, and socio-economic activities (Martin et al., 2017; Shukla et al., 2018; Li et al., 2020). These

changes have become increasingly pronounced with growth in human population, agricultural intensify, and infrastructural developments that encroach upon river landscapes. Understanding these shifts, the forces behind is crucial for managing river systems in the future.

The alteration of LULC within river catchments has been notably driven by agriculture in context of the Ganga River (Santy et al., 2020). In the past few decades, agricultural expansion has often been one of the primary forces of change in Ganga River land use (Ara et al., 2023). The conversion of natural ecosystems such as forests and wetlands into agricultural land, particularly for cropping pattern in common. In many rivers globally, particularly in developing regions, the spread of irrigated agriculture has been a major driver of these changes. Irrigation systems, designed to support growing agricultural demand, divert large quantities of water from rivers, dramatically altering river flow patterns and ecosystem dynamics (Ren et al, 2019). For example, in the Indus River basin in Asia, the extensive use of irrigation for agriculture has significantly reduced the flow of the river, affecting downstream ecosystems and communities that rely on the river for water, food, and transportation (Anand, 2017). Similarly, in the Nile River basin, land use has shifted towards monoculture farming practices, leading to changes in vegetation cover and soil quality, which, in turn, impact river hydrology and sediment transport (Ebabu et al., 2019).

Deforestation and land degradation are also significant factors contributing to changes in land cover in river (Shafique et al., 2019). In many river systems, particularly in tropical

regions, forested areas have been cleared for agriculture, logging, and urban development. Deforestation in the upper catchments of river basins can lead to increased soil erosion, sedimentation, and altered river flow patterns downstream (Wasson, 2008). In the Amazon River basin, deforestation and agricultural expansion have contributed to significant soil erosion, leading to increased sedimentation in the river and a reduction in water quality (Francisco, 2024). This process has far-reaching consequences, as sedimentation can disrupt aquatic ecosystems, reduce the capacity of reservoirs, and affect water treatment processes for human populations.

Another significant aspect of LULC change in river is the loss of wetlands and floodplains (Mukherjee & Pal, 2021). Wetlands, which serve as important natural buffers against flooding, improve water quality by filtering out pollutants, and support a wide range of biodiversity, have been increasingly converted into agricultural or urban land. In many cases, these wetlands have been drained to make way for rice paddies, roads, or industrial developments, resulting in the loss of essential ecosystem services. The draining of wetlands and the conversion of floodplains to urban and agricultural land have led to increased flood risks, water pollution, and the loss of biodiversity (Anand et al., 2017).

In response to these challenges, there have been growing efforts to restore and sustainably manage land use and land cover in river systems. Integrated river basin management approaches, which involve the coordination of land use, water use, and environmental protection, have been adopted in many regions to ensure the long-term sustainability of river ecosystems. Strategies such as reforestation, wetland restoration, and the

establishment of protected areas have been employed to mitigate the impacts of land use change and improve river health. Additionally, advancements in technology, such as Geographic Information System (GIS) tools and remote sensing, have allowed for more precise monitoring of LULC changes in river, enabling better planning and management decisions.

In this study the LULC has been derived for 2003, 2013 and 2023 and changes among all classes are calculated and mapped. The change is analysed using ArcGIS 10.6.1 software using union analysis. Further, intersect analysis was carried out to check the slibers in all the temporal categories of different LULC classes. The area of each LULC class is calculated in different years and the rate of change was determined (Temesgen et al. 2014) for LULC categories to determine the amount of the changes experienced between the periods of the different LULC categories.

$$\text{Rate of change (km}^2\text{/year)} = \frac{(\text{Area in latest image} - \text{Area in previous image})}{\text{Time interval (in years)}}$$

3.3. Result

3.3.1. Land Use Land Cover and mapping

The LULC changes between 2003, 2013 and 2023 are carried out and summarized in Table 3.4 and the rate of change in LULC area per year is summarised in Table 3.5. It is observed that the river floodplain is dominated by agriculture with 66.94% area in 2003, 68.85% area in 2013 and 71.05% area in 2023 whereas, grassland is the least dominated class with 0.29% area in 2003, 0.44% area in 2013 and 0.35% area in 2023 in the river floodplain. The geomorphological features in river belt are observed with maximum area of river channel covering 3.35% area in 2003, 2.97% area in 2013 and 3.81% area in 2023 whereas, Islands are the least dominated geomorphological feature covering 3.04% area in 2003, 1.18% area in 2013 and 1.06% area in 2023. The sand bars are a very prominent feature present within the river channels as point bar, mid bar and lateral bar covering 3.22% area in 2003, 3.60% area in 2013 and 2.69% area in 2023. The shift in agricultural land use changes the fluvial morphology (Keesstra et al. 2005). The gradual increase of agriculture in the floodplain, increase of sandbars in the river bed, and declining trend of the river channel depict the shifting agricultural practices from the floodplain area to the dry riverbed from 2003 to 2013. The vegetation may be recruited on sand bars due to decrease in discharge and lead to transform in sand bars to a vegetated area (Woo et al. 2010). The low flow, leads to the channel bar widening through the lateral accretion of dunes onto the margins of the initial bar core and the sand bars in the river bed transformed into the agricultural areas due to low base flow (Ashworth et. al., 2000) of river in lean

season, but after the regulation in water allocation in the Ganga River system and the flow guideline in the Ganga River implemented by the Gazette of India dated 10th October, 2018, Govt. of India, maintained the minimum water flow to integrate aquatic biodiversity in the Ganga River system naturally. As a result, it is observed that the river channel area increased from 2.97% to 3.81% between 2013 and 2023. The thematic classes are shown in LULC map for year 2003 (Figure 3.2), 2013 (Figure 3.3) and 2023 (Figure 3.4).

Table 3.4. Land Use Land Cover area (km²) of 2003, 2013 and 2023

Serial No.	LULC Class	Area (km ²)			Area (%)		
		2003	2013	2023	2003	2013	2023
1	River	606.79	536.53	688.61	3.35	2.97	3.81
2	Sandbar	582.24	650.97	486.22	3.22	3.60	2.69
3	Island	550.12	213.65	192.13	3.04	1.18	1.06
4	Barrenland	1464.75	1384.19	793.20	8.10	7.65	4.38
5	Waterbody	654.03	661.82	749.36	3.61	3.66	4.14
6	Forest	1150.47	1161.51	1161.92	6.36	6.42	6.42
7	Agriculture	12111.52	12458.35	12856.47	66.94	68.85	71.05
8	Builtup	921.87	947.42	1103.00	5.09	5.24	6.10
9	Grassland	52.28	79.64	63.15	0.29	0.44	0.35

Table 3.5. Change in area (km²) and Rate of change of Land Use Land Cover of 2003, 2013 and 2023

Serial No.	LULC Class	Change area (km ²)			Rate of change in area (km ²) / Year		
		2003-2013	2013-2023	2003-2023	2003-2013	2013-2023	2003-2023
1	River	-70.26	152.08	81.82	-7.03	15.21	8.18
2	Sandbar	68.73	-164.75	-96.02	6.87	-16.48	-9.60
3	Island	-336.47	-21.52	-357.99	-33.65	-2.15	-35.80
4	Barrenland	-80.56	-590.99	-671.55	-8.06	-59.10	-67.16
5	Waterbody	7.79	87.54	95.33	0.78	8.75	9.53
6	Forest	11.04	0.41	11.45	1.10	0.04	1.15
7	Agriculture	346.82	398.14	744.96	34.68	39.81	74.50
8	Builtup	25.55	155.58	181.13	2.56	15.56	18.11
9	Grassland	27.36	-16.49	10.87	2.74	-1.65	1.09

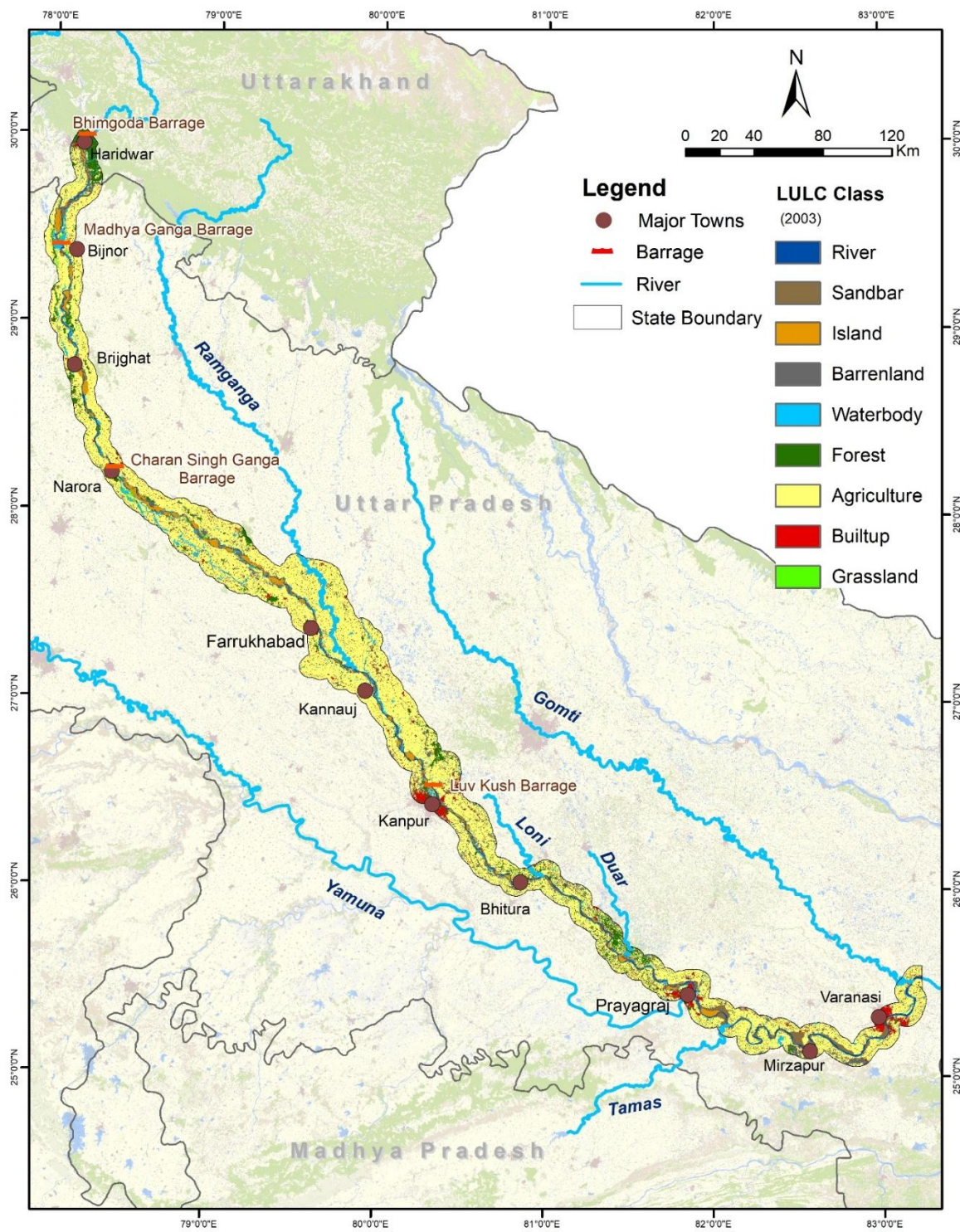


Figure 3.2. Land Use Land Cover 2003

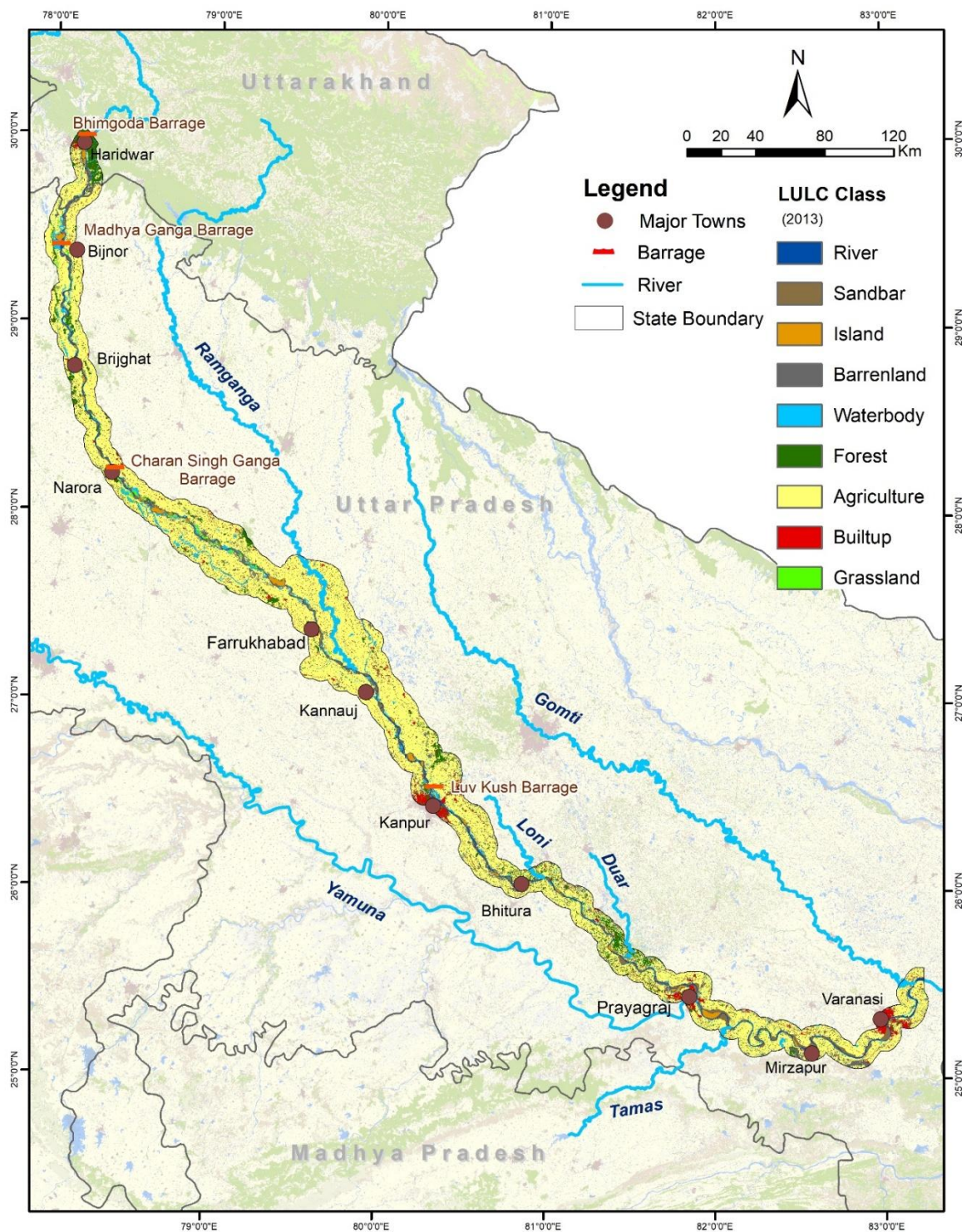


Figure 3.3. Land Use Land Cover 2013

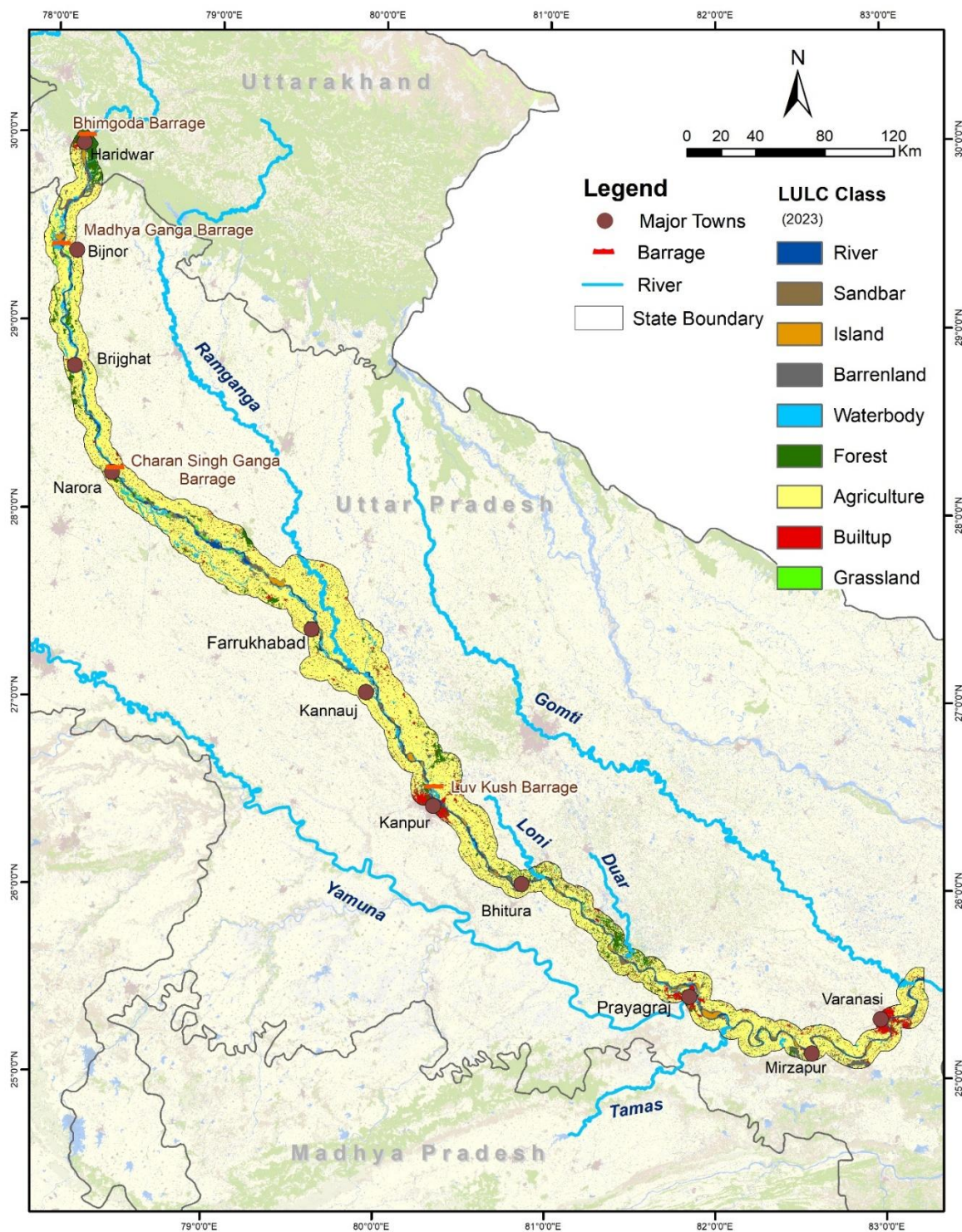


Figure 3.4. Land Use Land Cover 2023

3.3.2. Accuracy assessment

Accuracy assessment is carried out in the LULC of 2023. The confusion matrix is prepared using ground truth points and Google Earth reference data. A total of 135 random points were generated to assess the accuracy of image classification. The confusion matrix, individual class accuracy, overall accuracy and kappa coefficient were computed (Congalton, 1991). The overall accuracy and kappa coefficient of 2023 LULC map is 90.00% and 80.84, respectively (Table 3.6). The accuracy of the other two decades was assumed to be of the same order for LULC maps considering the mapping procedures followed in preparing decadal LULC maps (Roy et al., 2015). After the refinement of LULC maps and accuracy assessment, the change area matrices are prepared for three periods, i.e., 2003-2013, 2013-2023 and 2003-2023. These matrices were used to analyse the transition of one LULC class to another LULC class.

Table 3.6. Accuracy assessment of Land Use Land Cover, 2023

		Reference data										
Classified data	LULC Class	RI	SB	IS	BL	WB	FR	AG	BU	GL	Total	User Accuracy
	RI	11	1	0	0	0	0	0	0	0	12	0.92
	SB	1	1	0	0	0	0	0	0	0	2	0.50
	IS	0	0	1	0	0	0	0	0	0	1	1
	BL	0	0	0	5	0	0	0	0	0	5	1
	WB	0	0	0	0	6	0	1	0	0	7	1
	FR	1	0	0	0	0	7	1	0	0	9	0.78
	AG	0	0	0	5	1	0	85	1	0	92	1
	BU	0	0	0	1	1	0	0	3	0	5	1
	GL	0	0	0	0	0	0	0	0	2	2	1
Total	13	2	1	11	8	7	87	4	2	135		
Producer Accuracy	0.85	0.50	1	0.45	0.75	1	0.98	0.75	1			
Overall Accuracy (OA) = 0.90, Kappa Coefficient (κ) = 80.84 %												

Where,

RI = River, SB = Sandbar, IS = Island, BL = Barrenland, WB = Waterbody, FR = Forest, AG = Agriculture, BU = Builtup, GL = Grassland

3.3.3. Decadal change matrix of Land Use Land Cover

The transition of one LULC class to another LULC class is summarized from 2003 to 2013 (Tables 3.7a), 2013 to 2023 (3.7b) and 2003 to 2023 (3.7c), respectively. The result indicates that a major area of the river has transitioned into sandbar and agriculture between 2003 and 2013. The low base flow in the rivers triggers the formation of sandbars in the river channels (Ashworth et al., 2000), many of the sandbars and islands converted into agriculture areas, whereas the rate of conversion of rivers into sand bars and agricultural areas has decreased because of maintaining adequate water leading to increased river channels in the Ganga River system (Raj & Singh, 2021, Pal et al., 2022). The geomorphological attributes of river as well as the LULC classes have transitioned into builtup also, which indicates the river channel has shifted overtime and builtup areas sprawled on the dry river channels and lateral sandbars. The agricultural areas are also converted into the builtup areas over decades.

Rate of change in LULC classes were calculated by difference in multiple classes at temporal scale with interval of each 10 years i.e., 2003 to 2013, 2013 to 2023 and 2003 to 2023 (Table 3.8). The sand bars and islands have decreased from 3.60% to 2.69% and 1.18% to 1.06% respectively. Overall, Agriculture and builtup increased at a rate of 74.50 km²/year and 18.11 km²/year whereas, barrenland decreased at a rate of 67.16 km²/year in the floodplain from 2003 to 2023. River channel area increased at a rate of 8.18 km²/year whereas, sandbars and islands decreased at a rate of 9.60 km²/year and 35.80 km²/year respectively in the river channel from 2003 to 2023 (Figure 3.5).

Table 3.7. Change area matrix of Land Use Land Cover classes

(3.7a) 2003 to 2013

		2013									
	LULC Class	RI	SB	IS	BL	WB	FR	AG	BU	GL	Total (2013)
2003	River	264.61	166.98	35.96	23.17	68.00	2.20	40.17	1.54	4.16	606.79
	Sandbar	82.25	242.45	25.42	49.34	50.53	2.89	122.67	1.70	4.99	582.24
	Island	71.46	101.10	132.76	61.80	40.52	3.29	110.59	0.99	27.61	550.12
	Barrenland	27.04	26.62	4.74	961.48	17.04	17.03	402.49	7.16	1.15	1464.75
	Waterbody	56.66	78.72	4.76	18.49	413.90	7.37	67.72	5.40	1.01	654.03
	Forest	2.30	0.65	0.02	16.16	6.13	982.89	139.39	2.75	0.18	1150.47
	Agriculture	30.61	30.99	5.57	252.60	64.61	145.49	11572.64	5.96	3.06	12111.53
	Builtup	0	0	0	0	0	0	0	921.87	0	921.87
	Grassland	1.60	3.46	4.42	1.15	1.09	0.35	2.68	0.05	37.48	52.28
	Total (2003)	536.53	650.97	213.65	1384.19	661.82	1161.51	12458.35	947.42	79.64	18094.08

Where,

RI = River, SB = Sandbar, IS = Island, BL = Barrenland, WB = Waterbody, FR = Forest, AG = Agriculture, BU = Builtup, GL = Grassland

(3.7b) 2013 to 2023

		2023									
2013	LULC Class	RI	SB	IS	BL	WB	FR	AG	BU	GL	Total (2023)
	River	443.76	0.8	0.03	2.05	78.38	0.62	7.62	0.39	2.88	536.53
	Sandbar	74.46	320.13	23.81	16.53	114.09	1.71	89.11	7.71	3.42	650.97
	Island	14.06	3.14	168.09	1.42	15.55	0.03	10.15	0	1.21	213.65
	Barrenland	40.66	40.83	0.01	541.78	53.22	23.37	648.30	33.88	2.14	1384.19
	Waterbody	46.09	49.15	0.06	22.37	354.30	15.11	163.38	8.47	2.89	661.82
	Forest	3.64	4.40	0	19.47	10.16	866.57	222.35	34.32	0.6	1161.51
	Agriculture	59.09	54.78	0.13	187.72	120.16	253.46	11705.11	70.67	7.23	12458.35
	Builtup	0	0	0	0	0	0	0	947.42	0	947.42
	Grassland	6.85	12.99	0	1.86	3.50	1.05	10.47	0.14	42.78	79.64
Total (2013)	688.61	486.22	192.13	793.20	749.36	1161.92	12856.49	1103.00	63.15	18094.08	

Where,

RI = River, SB = Sandbar, IS = Island, BL = Barrenland, WB = Waterbody, FR = Forest, AG = Agriculture, BU = Builtup, GL = Grassland

(3.7c) 2003 to 2023

		2023									
	LULC class	RI	SB	IS	BL	WB	FR	AG	BU	GL	Total (2023)
2003	River	294.05	122.99	28.7	12.13	99.44	1.42	43.81	1.19	3.06	606.79
	Sandbar	104.84	134.95	38.04	35.57	76.64	2.82	177.79	8.56	3.03	582.24
	Island	117.42	94.85	102.99	26	62.6	2.97	125.48	0.75	17.06	550.12
	Barrenland	37.84	32.94	3	504.34	52.14	30.7	751.64	50.7	1.45	1464.75
	Waterbody	76.85	43	9.02	17.07	329.16	16.93	149.83	10.67	1.5	654.03
	Forest	2.73	3.36	0.02	22.42	12.83	805.02	262.74	40.7	0.65	1150.47
	Agriculture	52.93	50.11	4.61	174.59	114.3	300.93	11337.46	68.41	8.19	12111.53
	Builtup	0	0	0	0	0	0	0	921.87	0	921.87
	Grassland	1.95	4.02	5.75	1.08	2.25	1.13	7.74	0.15	28.21	52.28
	Total (2003)	688.61	486.22	192.13	793.20	749.36	1161.92	12856.49	1103	63.15	18094.08

Where,

RI = River, SB = Sandbar, IS = Island, BL = Barrenland, WB = Waterbody, FR = Forest, AG = Agriculture, BU = Builtup, GL = Grassland

Table 3.8. Change in area (km²) and Rate of change of Land Use Land Cover of 2003, 2013 and 2023

Serial No.	LULC Class	Change area (km ²)			Rate of change in area (km ² / Year)		
		2003-2013	2013-2023	2003-2023	2003-2013	2013-2023	2003-2023
1	River	-70.26	152.08	81.82	-7.03	15.21	8.18
2	Sandbar	68.73	-164.75	-96.02	6.87	-16.48	-9.60
3	Island	-336.47	-21.52	-357.99	-33.65	-2.15	-35.80
4	Barrenland	-80.56	-590.99	-671.55	-8.06	-59.10	-67.16
5	Waterbody	7.79	87.54	95.33	0.78	8.75	9.53
6	Forest	11.04	0.41	11.45	1.10	0.04	1.15
7	Agriculture	346.82	398.14	744.96	34.68	39.81	74.50
8	Builtup	25.55	155.58	181.13	2.56	15.56	18.11
9	Grassland	27.36	-16.49	10.87	2.74	-1.65	1.09

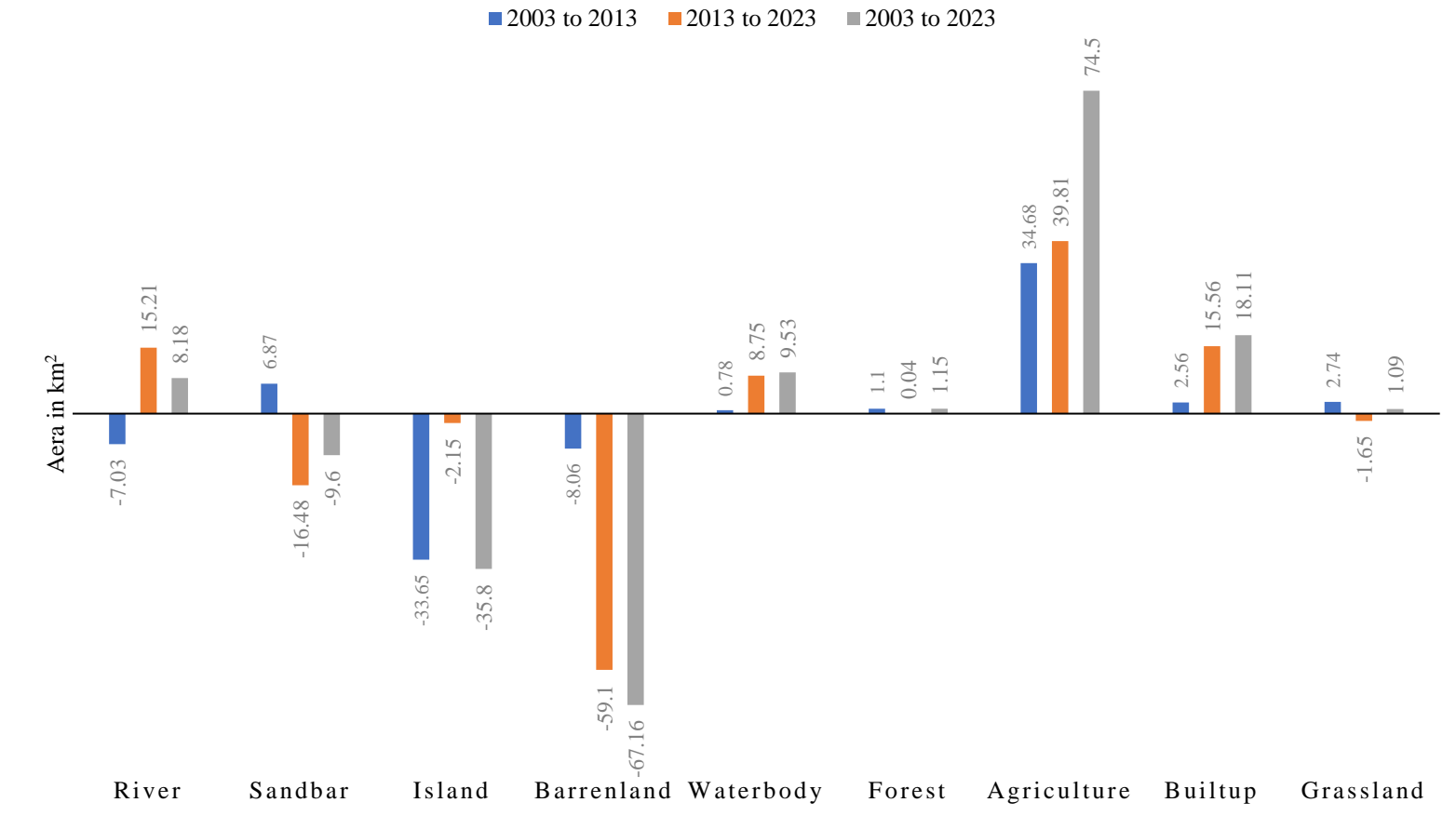


Table. Rate of change (km²/year) in Land Use Land Cover classes

3.4. Discussion

The patterns of land use and the temporal alterations of fluvial dynamics, particularly in terms of shifting river channels, are important criteria in sustainable river management. These factors are intricately linked to the types of habitats in the river ecosystem (Vasudeva et al, 2020), which, in turn are analogous to the river's hydromorphology. The natural morphology of rivers, like the shape, course, and flow has historically changed at different stretches, which have influenced the habitat for freshwater biodiversity along the Ganga River (Sarkar et al., 2011; Sonkar & Gaurav, 2020). These changes stem from various factors, including land use alterations and modifications in the river's flow regime, often due to anthropogenic pressures (Ashwini et al., 2020). The flow regime of a river refers to the variability in water flow, including seasonal changes in flow intensity, volume, and timing, which has significant implications for the biological and ecological functioning of river systems. The relationship between hydromorphology and biodiversity is key to understand the formation of river systems and habitat criteria by various species in the river (Hamilton et al., 2007; De Castro-Català et al., 2020; De Mendonça et al., 2021). A comprehensive approach to assess river habitats requires examining the linkages between hydraulic units like braided channels, sandbars, islands and the broader geomorphic units of the river system. Hydraulic geomorphic river units provide a framework for classifying and understanding different sections of the river based on characteristics like flow velocity, substrate type, and channel morphology. It is established that there is an essential connection between geomorphology and aquatic ecology (Grabowski et al, 2014). The shifting of river channels and the changes in habitat

distribution, whether caused by natural forces or human intervention significantly affects the biodiversity of the Ganga River (Sinha et al., 2019) as well as in other rivers globally (Hohensinner et al., 2011). The study of these linkages provides important insights into the processes within river systems and allows for better management strategies that balance the needs of human development with the requirements of aquatic ecosystems. Hierarchical segment of river course allows habitat characterization at multiple scales and facilitates understanding of processes and linkages between geomorphology and aquatic ecology (Thomson et al, 2001).

This study focuses on the floodplain of the Ganga River, which has experienced significant changes in land use and hydromorphology over the past two decades. Between 2003 and 2023, the land use pattern in this region has been altered primarily due to anthropogenic pressures and the construction of physical barriers, such as dams and barrages on the river. These interventions have a profound effect on the river's natural flow regime. Dams and barrages in the river reduce the natural flow variability of the main water channel, affecting both high and low flows and disrupts the functioning of the riverine ecosystem (Mittal et al, 2015). Dams tend to reduce the variability in the natural flow of the river, disrupting both high and low flow periods that are crucial for the functioning of the riverine ecosystem. This reduction in flow variability negatively impacts the hydrological processes that maintain the natural dynamics of the Ganga River (Swarnkar et al., 2021; Sinha et al., 2022), leading to alterations in sediment transport, channel morphology, and habitat availability for aquatic species (Kumar et al., 2023). The MGR, which is one of the most important and ecologically diverse river segments in India,

has four major dams. These dams have altered the natural flow patterns of the river's main stem, leading to significant changes in its hydromorphology (Khan et al., 2018; Pandey et al., 2020). As the flow has been regulated by the dams, the river's physical structure has transformed, leading to changes in habitat availability and quality. The altered flow regimes affect not only the river's channel morphology but also the ecological conditions. These changes are exacerbated by the land use changes that have occurred in the floodplain, which include increased agricultural activities, urbanization, and water extraction for irrigation purposes (Ara et al., 2023). The increased agricultural activities and water extraction have further stressed the Ganga River system, leading to a shift from deep, flowing channels to shallower, braided river channels (Jin et al., 2015; Anand et al., 2017; Bowes et al., 2020). Braided channels are formed when sediment accumulation, such as sandbars and islands, causes the river to split into multiple smaller, interconnected channels. These changes in channel morphology have significant ecological implications, as they lead to habitat loss for species that depend on uninterrupted, deep, slow-moving water like the Gangetic dolphin (*Platanista gangetica*), as the species requires deep, slow-moving water as its habitat (Bordoloi & Saharia, 2021; Nayak & Ibrahimi, 2023). The changes in river forms meanders where the Gangetic dolphin restricts themselves due to presence of eddy currents (Mazumder et al., 2014). Many other species in the Ganga River are affected by these changes in habitat also. The Ganga River is home to a variety of fish species that depend on specific hydraulic conditions for breeding and feeding. The loss of deep-water habitats, which are replaced by shallow, braided channels, disrupts the life cycles of these species, leading to a decline in biodiversity (Singh & Singh, 2020; Jain &

Singh, 2020; Prasad et al., 2021). In particular, the changes in flow regime and channel morphology have created challenges for large-ranging aquatic fauna, as their preferred habitats have become fragmented or disappeared entirely. The altered flow regimes and channel morphology also affected the sandbars and islands within the Ganga River (Singh et al., 2019; Pal & Pani, 2019). These features are critical habitats for a variety of species, including mammals such as the smooth-coated otter (*Lutrogale perspicillata*), reptiles like gharial (*Gavialis gangeticus*) and the mugger crocodile (*Crocodylus palustris*), as well as numerous bird species (Hussain, 2009; Vashistha et al., 2021; Bhat et al., 2023). Sandbars and islands provide critical breeding and basking sites for these species. However, the seasonal fluctuations in water flow, particularly during the monsoon season when water is released from the dams, can flood these habitats, making them highly vulnerable (Sarda & Pal, 2022). In some cases, the sandbars are entirely submerged, leading to a loss of habitat for the species that depend on them. The importance of maintaining adequate water flow downstream of the barrages, especially during the lean season when water levels are naturally low, is crucial for the survival of these habitats (Sonkar et al., 2022; Kumar et al., 2023). A sustainable flow regime, which mimics the natural variability of the river's hydrology, is necessary to ensure that the river's ecosystems remain functional and capable of supporting the biodiversity that has evolved to depend on them. Without such a flow regime, the ability of the river to support a diverse range of species is greatly diminished.

The study underscores the importance of the relationship between land use changes, fluvial geomorphology, and the management of water resources in sustaining the

biological integrity of the Ganga River. The shifting land use patterns, driven by agricultural expansion, urbanization, and water extraction, have a direct impact on the Ganga River's hydromorphology and consequently its biodiversity. To address these challenges, it is necessary for policymakers and river managers to take a holistic approach to river management that incorporates both ecological and hydrological considerations (Hussain et al., 2020; Singh & Singh, 2020). This study is relevant for the ongoing efforts to rejuvenate the Ganga River and restore its ecological health. The Ganga is not only a vital water source for millions of people but also a river of immense cultural and ecological significance. The preservation of its biodiversity and the restoration of its natural flow regime are essential to maintaining the river's ecological integrity. Policymakers must prioritize the protection and restoration of river habitats, including the maintenance of natural flow variability and the protection of critical habitats like sandbars, islands, and deep-water channels.

CHAPTER 4

ASSESSMENT OF HYDROGEOMORPHOLOGY

4.1. Introduction

The drainage pattern of river defines the arrangement of main stem river, tributaries, channels, and streams within the basin system influenced by variety of factors like geology, topography, climate, and flow dynamics. It addresses the flow characteristics, environmental health, and the long-term development of the river system (De Jalón et al., 2019). The study of drainage patterns is essential for understanding water movement, predicting flooding events, and assessing the ecological health of river ecosystems. There are several types of drainage patterns, including dendritic, radial, rectangular, and trellis, each of which forms under specific geological and hydrological conditions (Mejia & Niemann, 2008; Ghosh & Paul, 2019). These patterns describe about the underlying forces shaping the river basin, including tectonic activity, erosion processes, and sediment transport.

- **Dendritic drainage pattern**

Commonly observed drainage pattern is the dendritic pattern, which resembles the branching structure of a tree (Kumar, 2022). This pattern typically forms in regions with relatively uniform rock types and gentle slopes. When rivers flow through softer rock layers, tributaries develop in a branching, tree-like manner. This is because the river

erodes the softer material more easily, allowing the water to meander and form a network of smaller streams. The dendritic pattern is often found in flat or gently sloping areas (Pandey & Das, 2016), where the river and its tributaries flow without major geological constraints (Kumar et al, 2015).

- **Radial drainage pattern**

The radial drainage pattern forms when streams radiate outward from a central point, typically around a volcanic cone or dome. This type of drainage system occurs when the topography of the land is dominated by a central high point, with streams flowing away from it in all directions. Radial drainage patterns are often found around volcanic peaks or isolated mountains, where the landscape is shaped by volcanic or tectonic activity (Wan et al., 2022).

- **Rectangular drainage pattern**

Another drainage pattern commonly found is the rectangular pattern, which is characterized by streams that follow joint or fault lines, creating a grid like arrangement. This pattern forms in areas where the land is heavily fractured by fault lines or geological joints, causing the streams to follow the natural fractures in the earth's crust (Goren et al., 2021). The rectangular pattern is common in regions with hard rock formations that resist erosion, and where tectonic forces have caused significant displacement of the earth's surface. In these areas, streams follow the path of least resistance along the fractures, leading to the formation of right-angled stream segments that create a rectangular grid.

- **Trellis drainage pattern**

The trellis drainage pattern is commonly found in regions with alternating layers of hard and soft rocks (Kusák, 2022). In these areas, the harder rock layers resist erosion, while the softer rock layers are eroded more quickly, resulting in streams that flow parallel to the main river. This creates a pattern that resembles a garden trellis, with tributaries running parallel to the main river and intersecting at right angles. The trellis pattern is common in regions with a complex geological history, where the landscape is transformed by alternating layers of different rock types (Pazzaglia et al., 2007).

The study of drainage patterns emphasises into the underlying geology and tectonic activity of the river course (Jones, 2014; Różycka & Migoń, 2021). Areas that have undergone significant geological processes, such as folding, faulting, or volcanic activity exhibit unique drainage patterns. These patterns provide information about the topography, as well as the forces that have shaped it over time, additionally, the age and stage of development of a river influence its drainage pattern. Younger rivers tend to have more intricate and meandering drainage systems, while older river flows through less complex networks of tributaries.

4.1.1. Drainage network

The middle Ganga River (MGR) is one of the most densely populated regions in India, and its drainage network supports the livelihoods of millions of people. The river and its tributaries provide essential water resources for irrigation, drinking water, and sanitation. Fertile plains of the Ganga River are crucial for agricultural production, and the seasonal

flooding of the river enriches the soil, which is favourable for crop growth. The drainage system in this area ensures that water from various tributaries and channels is effectively distributed, maintaining a sustainable balance in the river system (Singh et al., 2018). The river's seasonal floods are also critical for sustaining the fertility of the floodplains, replenishing nutrients in the soil and supporting agricultural productivity. Understanding the hydrological dynamics and drainage system of MGR is essential for flood forecasting and mitigation. The region experiences regular seasonal flooding, particularly during the monsoon season, which leads to significant damage to infrastructure, loss of crops, and displacement of communities. A better understanding of the river's drainage system helps manage water resources, ensuring that water is distributed efficiently for irrigation, drinking, industrial use and to maintain the Environmental flow (E-flow) of the river for maintaining natural integrity of the river (Kaushal et al., 2019). Intricate drainage network of the Ganga River supports wetlands, forests, and aquatic life, which are vital for the overall ecological health of the region. The Ganga River is home to a wide variety of species, including several endangered and endemic species, and the health of its drainage system directly impacts these species' survival (Rai et al., 2024). Wetlands, in particular, are highly dependent on the seasonal flooding of the river, as they provide critical habitat for fish, amphibians, birds, and other aquatic biodiversity (Mukherjee, 2020). These ecosystems also contribute to water quality regulation, carbon sequestration, and flood mitigation that highlights the importance of preserving the river's drainage network. However, the drainage system of the MGR is under threat due to the anthropogenic pressures like urbanization, industrialization, and pollution (Whitehead et al., 2018;

Quadir, 2022). As cities expand and industrial activity increases, pollutants are contaminating the Ganga River system, affecting water quality and the health of aquatic biodiversity. Deforestation and changes in land use also alter the natural flow of water through the drainage network, leading to soil erosion, sedimentation, and habitat destruction. These changes disrupt the hydrological balance of the river system, leading to changes in the distribution of water and the health of wetland ecosystems (Mukherjee & Pal, 2021). Monitoring and preserving the drainage network is essential for maintaining water quality, preventing ecosystem degradation, and ensuring the long-term sustainability of the Ganga River. Previous studies on the drainage network of the MGR have provided significant insights into hydrological behaviour, sediment dynamics, and flood management strategies (Swarnkar et al., 2021). Those studies have focused on understanding the complex interactions between the river's tributaries, role of seasonal flooding, and the impact of human activities on the river's flow. Studies have also examined the geomorphological features of the basin, such as the presence of alluvial plains, river terraces, and floodplains, which are important for shaping river drainage pattern. These studies have been instrumental in identifying areas of the Ganga River basin that are most at risk of flooding or environmental degradation, and in developing strategies to protect vulnerable areas. Gregory (2006) emphasized the dynamic nature of the river's distributary system, with changes in river course due natural forces and human activity, such as channelization, dam construction, and land use alterations. Mishra (2011) highlighted that urbanization in the Ganga basin has disrupted surface water drainage due to infilling small natural channels. The use of remote sensing and GIS technologies has

been instrumental in mapping these changes (Pal & Pani, 2019), which provides updated cartographic data on the drainage patterns. Swarnkar et al, (2020) analysed morphometric diversity in river systems of the Himalayan foreland is influenced by hydrogeomorphic settings sediment flux in the Ganga basin. These previous studies underscore the complexity of the drainage network in MGR and highlight the need for further detailed studies for integrated water resource management.

4.1.2. Importance of riverine wetlands in drainage network

Riverine wetlands are vital ecosystems and integral part of river drainage network, that provides a wide array of ecological functions and ecosystem services in the river floodplains. These wetlands, often located along riverbanks and seasonally connected with the river, are central to a variety of environmental processes that support biodiversity and help mitigate the impacts of human activities on the natural world. According to Xu et al. (2020), riverine wetlands are increasingly recognized for their ecological importance, and their protection has become a priority in global conservation efforts. International frameworks such as the Ramsar Convention on wetlands highlight their significance, emphasizing the need for effective management and conservation strategies to preserve these ecosystems (Kingsford et al., 2021). One of the most important ecological functions of riverine wetlands are their ability to regulate water quality. Wetlands act as natural filters, absorbing and breaking down pollutants that enter the river system (Ma et al., 2019; Sileshi et al., 2020; Mpandeli et al., 2024). By trapping sediment, excess nutrients, and other contaminants, wetlands prevent these pollutants from reaching

downstream aquatic ecosystems, thus protecting water quality. Additionally, they provide habitats for a wide range of aquatic and semi-aquatic species, contributing to the maintenance of biodiversity in floodplain ecosystems (Mukherjee, 2020). Many species, including fish, amphibians, and reptiles, depend on these wetlands for breeding, feeding, and shelter. This biodiversity support is particularly important in the context of growing pressures from human activities, such as agriculture, urbanization, and industrialization, which threaten aquatic habitats. Riverine wetlands play a crucial role in flood mitigation by absorbing excess water during periods of high flow, such as during heavy rains or snowmelt (Wu et al., 2023). By acting as natural sponges, wetlands reduce the intensity and duration of floods, preventing damage to infrastructure and reducing the risk of loss of life. This flood control function is increasingly important in the context of climate change, as extreme weather events, including floods, are expected to become more frequent and severe. Wetlands also contribute to groundwater recharge, ensuring the sustained flow of water in rivers and maintaining hydrological balance (Dharpure et al., 2021). They help regulate the flow of water between surface and groundwater systems, which is particularly important during dry periods when rivers are at risk of drying up. Another critical function of riverine wetlands is their ability to sequester carbon, which makes them significant in the context of climate change mitigation (Dong, et al., 2020). Wetlands store large amounts of carbon in their soils and vegetation, helping to offset greenhouse gas emissions and contributing to global efforts to combat climate change. Wetlands support the achievement of Sustainable Development Goal (SDG) 13, which focuses on climate action, by contributing to climate change mitigation. Degradation of

riverine wetlands have serious consequences for both the environment and the communities that depend on them. The loss of wetland habitats leads to a decline in biodiversity, the deterioration of water quality, and the disruption of flood control services (Gulbin et al., 2019; Saha et al., 2022). As wetlands are drained for agricultural expansion, urban development, or industrial use, their ability to perform these vital ecological functions is diminished, leading to cascading environmental and social impacts. For this reason, protecting riverine wetlands is essential for maintaining environmental health and the sustainability of floodplain biodiversity. Efforts to protect and restore riverine wetlands require accurate mapping and monitoring of wetland areas, as this is crucial for effective conservation planning and ecological management. Mapping riverine wetlands enables policymakers to better understand the distribution, health, and role of these ecosystems within the riverscape. Jia et al. (2020) emphasize that mapping is not only essential for understanding wetland ecosystems but also for guiding policy development and the implementation of conservation strategies. Mapping riverine wetlands involves a combination of field surveys, remote sensing (RS), and Geographic Information Systems (GIS). Remote sensing technologies, including satellite imagery and aerial photography, provide high-resolution data that used to identify wetland boundaries, vegetation types, and changes over time. These technologies allow for the creation of detailed maps that is useful to monitor wetland conditions and assess the impact of environmental and anthropogenic factors. According to Ozesmi and Bauer (2002), RS and GIS are particularly valuable for mapping large-scale wetland areas, as they allow for efficient data collection and analysis over vast regions. One of the most widely used remote sensing

techniques for wetland mapping is the Modified Normalized Difference Water Index (MNDWI). This index is specifically designed to identify water bodies and distinguish between land and water, even in areas with complex land cover, such as vegetation or agricultural fields. MNDWI is particularly effective for detecting floodplain wetlands, where water levels fluctuate seasonally, inundating wetlands during high-flow events. Haider et al. (2023) noted, the MNDWI index allows for the accurate identification of surface water, which is crucial for mapping floodplain wetlands that are subject to seasonal inundation. By effectively distinguishing water from other land covers, MNDWI helps to create accurate wetland maps that can be used for monitoring wetland dynamics and identifying areas that may be at risk of environmental degradation (Singh et al., 2015; Kumar & Singh, 2020). Use of RS and GIS technologies are not limited to mapping wetland areas. It also supports the development of adaptive management strategies. Wetland maps provide valuable data for policymakers, to make informed decisions about land use, conservation, and restoration. These maps are used to delineate protected areas, enforce regulations, and guide land development decisions to minimize the adverse effects of human activities on wetlands. Effective mapping also supports the development of climate change adaptation strategies, as wetlands are among the most vulnerable ecosystems to the impacts of climate change, including rising temperatures, altered precipitation patterns, and shifting river channels. Riverine wetlands also maintain biodiversity in freshwater ecosystems (Bayen et al., 2021; Song et al., 2024). These wetlands provide essential habitat connectivity between rivers and floodplains, which is important for supporting a wide range of species. Continuous water supply in rivers is

necessary to maintain the natural integrity of riverine wetlands, ensuring that these seasonal habitats remain functional and provide suitable conditions for wildlife. The ecological consequences of riverine wetlands extend beyond the wetlands themselves, as they rejuvenate the surrounding riverscape, which is home to a variety of species, including aquatic fauna, water birds, amphibians, reptiles, and insects such as odonates (Arya et al., 2021; Joshi et al., 2021). The health of riverine wetlands is intimately connected to the health of surrounding ecosystems, they provide important resources and habitats for many species (Uzarski et al., 2009).

The riverine wetlands, streams of drainage network, tributaries of the river system form a distinct fluvial morphology of the main stem river, which is a key aspect in understanding rivers' physical characteristics and behaviour, including the changes in their planform, channel shapes, and the processes driving these changes over time (Uddin et al., 2011). It provides valuable insights into the way rivers evolve, interact with their surrounding environments, and how human activities impact them. It is a comprehensive examination of river systems' dynamic and ever-changing nature, the underlying processes that govern river development, and the consequences for the physical landscape, riverscape and the ecological systems they support. As described by Uddin et al. (2011), river morphology explores the physical form and structure of rivers, focusing on how the river planform, essentially the shape and layout of the river changes over time. One of the most important aspects of river morphology is the shape of the river channels themselves. These channels take on a variety of forms, such as meandering, braided, or straightened, each of which influences the flow of water, sediment transport, and deposition processes that occur

within the river system. The meandering pattern, for instance, is often seen in rivers with a lower gradient, where the flow of water is relatively slow, and the river bends in a curving pattern (Kumar et al., 2016). In contrast, braided rivers, characterized by multiple channels separated by sandbars or islands, are typically found in areas where sediment transport is high, and the flow of water is more dynamic. The interactions between the river channels and the flow of water are a key element in understanding river morphology (Han et al., 2024). Rivers are constantly shaped by water flow, which erodes the banks and bed of the river, moving sediment downstream. The ability of a river to transport sediment depends on factors such as the speed of the water, the amount of sediment in the river, and the physical characteristics of the riverbed (Zhou et al., 2022). These factors determine how sediment is deposited within the river system, which lead to the formation of sandbars, islands, and changes in the course of the river itself. Additionally, the process of sediment deposition in rivers varies, with the particles becoming coarser or finer depending on the water velocity and the nature of the sediment being transported.

One of the central themes in river morphology is the process of erosion and sediment deposition (Zarfl & Dunn, 2022). Erosion refers to the wearing away of the riverbanks and bed as the river transports material downstream. This process can occur through mechanical forces, such as the force of water acting on the bank, or through chemical processes, such as the dissolution of certain minerals in the riverbed. Erosion is an ongoing process that reshapes the river landscape, often leading to changes in the width and direction of the river channel (Eke et al., 2014). Sediment deposition, on the other hand, occurs when the river loses its ability to transport sediment, typically due to a

decrease in water velocity. This process leads to the formation of various fluvial features, such as sandbars, islands, and floodplains. The deposition of sediment is not uniform across the river, and the nature of the sediment can vary, from fine particles such as clay to coarser particles like gravel and sand. The process of sediment deposition is influenced by factors such as the discharge of the river, the slope of the riverbed, and the types of sediment available for transport (Sklar et al., 2017; Parker et al., 2024). The dynamics of river channels and their interactions with sediment transport are not static. They change over time in response to both natural forces and human interventions. The morphology of a river varies from one location to another, and the way a river channel responds to changes in flow and sediment supply alters the river's planform, width, and depth. For instance, a river may become wider or narrower, depending on the level of sediment deposition and the rate of erosion along its banks. Similarly, the river may meander or straighten, depending on the underlying geology and the dynamics of water flow within the system. Floodplains play a crucial role in shaping the morphology of rivers and the surrounding landscape (Pal & Pani, 2019). Floodplains are low lying areas adjacent to rivers that are prone to flooding during periods of high water flow. When a river floods, the floodwaters spread out over the floodplain, depositing sediments and reshaping the landscape. This process is essential for maintaining the ecological integrity of river systems, as floodplains provide critical habitat for a wide range of plant and animal species. The interaction between river flows and floodplains is especially important during flood events. During these events, the river's flow changes direction, leading to the creation of new channels and the deposition of sediments in different areas (Singh et al.,

2020). This dynamic process helps to maintain the diversity of habitats within the floodplain and ensures that nutrients are distributed throughout the landscape. Floodplain development is, therefore, a key aspect of river morphology, as it provides the necessary conditions for the growth and development of aquatic and riparian ecosystems. Riparian zones are the areas of land adjacent to rivers, that play an essential role in stabilizing riverbanks and providing ecological benefits (Gregory et al, 1991; Gurnell et al., 2005). These zones are often characterized by the presence of vegetation, which helps to prevent soil erosion and stabilize the riverbanks. Riparian vegetation also provides important habitat for wildlife, filtering pollutants from the water and contributing to the overall health of the river ecosystem (Dufour et al., 2019). The health of riparian zones is closely linked to the dynamics of the river itself, as the flow of water and the deposition of sediments can have significant impacts on the vegetation and wildlife in these areas.

Anthropogenic activities, such as dam construction, land development, and agriculture, have a profound impact on river morphology. These activities can alter the natural flow of water, disrupt sediment transport, and change the structure of river channels. Dams, for instance, blocks the natural flow of water, reducing the river's ability to transport sediment downstream (Brenna et al., 2020). This leads to the accumulation of sediment behind the dam, changing the shape of the river and impacting the ecosystems that depend on the natural flow of water. Similarly, land development and agriculture contribute to changes in river morphology by altering the amount of sediment entering the river. Construction activities, such as the building of roads and buildings, increases erosion in the surrounding landscape, leading to higher sediment loads in the river. Agricultural practices, such as

farming and grazing, can also contribute to erosion, as the removal of vegetation reduces the ability of the land to absorb water and prevent soil erosion (Jaiswal & Pandey, 2021). Understanding the impact of human activities on river morphology is crucial for effective water management, flood risk prediction, and environmental conservation. By studying the changes in river morphology caused by human interventions, it is possible to develop strategies for mitigating the negative effects of these activities and preserving the health of river ecosystems.

4.1.3. Interaction of hydrological and geomorphological processes

Hydrogeomorphology is a field that focuses on the interactions between hydrological and geomorphological processes and the interaction between water flow and sediment transport to form the riverscape in river channels and floodplains. The study of hydrogeomorphology is essential for understanding the dynamics of river systems, as it integrates both hydrological and geomorphological perspectives. One of the key aspects of hydrogeomorphology is the study of river channel dynamics, which involves shape, size, and behaviour, processes of erosion and sedimentation in the river channels (Orr et al, 2008). Formation of fluvial features, such as sandbars, islands, and meanders, are also important component of river channel dynamics. Floodplain development is another important aspect of hydrogeomorphology (Hudson et al., 2008). The interaction between floodwaters and floodplains is essential for maintaining the ecological integrity of river systems. During high-flow events, sediment deposition on floodplains forms new and enriched habitats for aquatic species, while also providing nutrients for the riverscape

(Jenkins & Boulton, 2003). The river incision, meandering, and sediment deposition processes contribute to the formation and evolution of landforms, shaping the physical landscape over time. The interactions between hydrological and geomorphological processes have significant implications for the functioning of ecosystem, including formation of habitats and the health of riparian areas, response of ecosystem to changes in water flow, sediment transport, and landform evolution by integrating hydrological and geomorphological perspectives. It is essential for managing river systems and preserving the biodiversity of aquatic and riparian ecosystems. Effective water management requires a thorough understanding of river morphology and hydrogeomorphology, as well as the factors that influence the dynamics of river.

The hydrogeomorphological processes in the Ganga River are dynamic and complex system that shapes the river morphology and influence its ecological functions. The Ganga River poses significant changes in flow regime due to seasonal monsoons, snowmelt from the Himalayas, and varying discharge in its course. These hydrological factors drive sediment transport, erosion, and deposition processes in the riverbed and floodplain, which is mainly governed by the major tributary system of the Ganga River particularly in the middle stretch (Azam et al., 2018). During high-flow events in monsoon season, the river velocity increases, resulting in riverbank erosion and transportation of sediments at downstream. These sediments are deposited on floodplains, forming natural levees, sandbars, and islands, which shifts the river constantly. Floodplain of the Ganga River is important habitat for sustaining biodiversity and provide fertile land for cultivation (Singh et al., 2018). Interaction between water flow and sediment dynamics is

essential for maintaining the river's ecological integrity. Understanding these processes helps in managing flood risks, water quality, and biodiversity conservation of the Ganga River.

4.2. Methodology

4.2.1. River basin and drainage network delineation

The basin of a river is delineated based on elevation (Palacios-Velez et al., 1986; Kumar et al., 2017). River basin delineation involves defining boundaries of river basin, which is essential for understanding water flow, managing water resources, and conducting environmental impact assessments. The Digital Elevation Model (DEM) is used to delineate the series of undulated earth surface to simulate the drainage course of river. The river orders are generated by the hydrological simulation. The total drainage channels are accumulated in a particular pour point as the main stem river channel termed as sink river. The entire area is known as river basin. In General, the larger river basin is subdivided into several smaller basins of tributary rivers termed as sub-basin (Yakubov, 2021). The sub-basins are further divided by several small basins of initial order rivers termed as catchment (Salami & Buehler, 2020). The total water of a catchment accumulates in a single water channel. The tributary basins are specified as the sub-basins and further small distributary systems are defined as catchments and stream networks of the Ganga River basin.

The Ganga River basin has been delineated using DEM of the Advanced Land Observing Satellite (ALOS) with 30-meter spatial resolution by Japan Aerospace Exploration

Agency (JAXA). The process involves several steps in ArcGIS software. First, the DEM data, obtained from JAXA, is imported into ArcGIS. Pre-processing is done by filling any sinks or depressions in the DEM using the "Fill" tool to ensure accurate flow modelling. Next, the 'Flow Direction' tool is applied to the DEM to create a raster that indicates the direction in which water flows from each cell, followed by the 'Flow Accumulation' tool to calculate the amount of upstream flow for each cell. This helps in identifying stream networks and significant drainage paths. The watershed boundaries are then delineated by selecting pour points (outlet locations) and using the 'Watershed' tool, which traces the contributing area for each pour point. Additionally, a stream network is created by defining a flow accumulation threshold, after which areas exceeding this threshold are considered streams. Finally, the Hydrology Tools in ArcGIS (within the Spatial Analyst toolbox) facilitated the detailed analysis and delineation of drainage basins and sub-basin boundaries (Figure 4.1). The sub-basins are the cross verified with reference hydroshed sub-basins (Lehner & Grill, 2013).

4.2.2. Delineation and mapping of riverine wetlands

The study was done by using Remote Sensing (RS) and Geographic Information System (GIS) technology. Modified Normalized Difference Water Index (MNDWI) is used for identification of wetlands in floodplain by distinguishing between water and land areas (Haider et al., 2023). MNDWI was derived from the Landsat 8 OLI satellite image with 30 m resolution (Table 4.1). The satellite images were derived from the United States Geological Survey (USGS) Earth explorer (<https://earthexplorer.usgs.gov>). The Landsat

image were processed through the digital image processing and stacked by multispectral bands of various wavelengths to achieve False Colour Composite (FCC) image. The FCC image was rectified by geometric and radiometric corrections to undergo MNDWI analysis. MNDWI utilizes the shortwave infrared (SWIR) and green bands to highlight water bodies while minimizing the influence of built-up areas, soil, and vegetation. Water has lower reflectance in the SWIR band, making MNDWI method effective at distinguishing water from vegetation and built-up areas, especially in urban or vegetated regions. The wetlands were identified and mapped using ArcGIS 10.6.1 software (Figure 4.1).

$$\text{MNDWI} = (\text{Green} - \text{SWIR}) / (\text{Green} + \text{SWIR})$$

Table 4.1. Satellite images used to derive Land Use Land Cover classes

Satellite	Path/Row	Date	Resolution	Source
Landsat 8 OLI	144/041	08.03.2023	30 m	https://earthexplorer.usgs.gov
	144/042	08.03.2023		
	146/039	06.03.2023		
	146/040	06.03.2023		
	142/042	02.03.2023		
	142/043	02.03.2023		
	143/042	01.03.2023		
	145/041	15.03.2023		

4.2.3. River classification based on of hydrogeomorphology

The Ganga River is classified based on the hydrology, physiography, and geomorphology into three major classes, i.e., 1. Upper Ganga River, 2. Middle Ganga River, and 3. Lower Ganga River.

- **Upper Ganga River**

The upper Ganga River originates from Gaumukh of Gangotri glacier (Longitude 79.081° N and Latitude 30.919° E) and flows upto the Bhimgoda barrage, Haridwar (Longitude 78.163° N and Latitude 29.943° E) in Uttarakhand. The Ganga River flows approximately 310 km from Gaumukh to Haridwar (WII-NMCG, 2019). The upper Ganga River flows on steep bed with high velocity and turbulent flow. Various hydroelectrical projects are located in this stretch which impact the substantial flow seasonally (Swarnkar et al., 2021). The hydroelectric project areas have decline in forest cover and results into landslides. River bed in this stretch is stony intercalated with pebbles and sand. Carps like Golden mahsheer (*Tor putitora*) and Snow trout (*Schizothorax richardsonii*), phytoplankton like Diatom followed by green algae and zooplankton like ciliates are major aquatic species in the Upper Ganga.

- **Middle Ganga River**

The middle Ganga River starts from the Bhimgoda, Haridwar in Uttarakhand (Longitude 78.163° N and Latitude 29.943° E) to the Gomti River confluence at Kaithi, Varanasi in Uttar Pradesh (Longitude 83.214° N and Latitude 25.530° E). Length of middle Ganga River is approximately 1000 km (WII-NMCG, 2019). The Ganga River enters into plain land in this segment. River bed sediment consists of boulder, gravel and finer sand

particles with gentle slope. Formation of riffles and pools due to meanders and channel braids are predominant in the middle Ganga River. Gangetic dolphin, Gharial, Crocodile, Turtles are dominant aquatic species in this stretch.

- **Lower Ganga River**

The lower Ganga River starts from the Gomti River confluence at Kaithi, Varanasi in Uttar Pradesh (Longitude 83.214° N and Latitude 25.530° E) to the Ganga Sagar in West Bengal (Longitude 87.926° N and Latitude 21.640° E). Length of lower Ganga River is approximately 1235 km (WII-NMCG, 2019). In this segment, the Ganga River flows through plain land with very gentle slope with very high surface flow due to massive silt inflow through the Ganga main stem and its major tributaries. Encroachment of river bed, riverbed farming, sand mining is major threats to the Ganga River. Gangetic dolphin, Gharial, Crocodile, turtles, Fishes and waterbirds are common along this stretch.

Classification of the middle Ganga River

The middle Ganga River (MGR) starts from the Bhimgoda barrage, Haridwar in Uttarakhand (Longitude 78.163° N and Latitude 29.943° E) to the Gomti River confluence at Kaithi, Varanasi in Uttar Pradesh (Longitude 83.214° N and Latitude 25.530° E). Four barrages are located in the MGR i.e., Bhimgoda barrage at Haridwar, Madhya Ganga barrage at Bijnor, Charan Singh Ganga barrage at Narora and Luvkush barrage at Kanpur (Table 4.2). Depending upon the physical barriers located on the Ganga River, the MGR is classified in four (4) primary segments (Table 4.3). The first segment extends from downstream Bhimgoda barrage, Haridwar to upstream Madhya Ganga barrage, Bijnor

having length of 70 km. The second segment extends from downstream Madhya Ganga barrage, Bijnor to upstream Charan Singh Ganga barrage, Narora having length of 155 km. The third segment extends from downstream Charan Singh Ganga barrage, Narora to upstream of Luv Kush barrage, Kanpur having length of 300 km and the fourth segment extends from downstream Luv Kush barrage, Kanpur to the Gomti River confluence with the Ganga River at Kaithi, Varanasi having length of 475 km. We have segmented the length of MGR in every 5 km interval and considered each 5 km segment as Basic Ecological Unit (BEU).

Table 4.2. List of barrages in the middle Ganga River

Barrage	Place	Functional year
Bhimgoda barrage	Haridwar	1854
Madhya Ganga barrage	Bijnor	1984
Charan Singh Ganga barrage	Narora	1967
Luv Kush barrage	Kanpur	2000

Table 4.3. Primary segments in the middle Ganga River

Segment	From	To	Remark	BEU Start	BEU End	Total BEU	Length (km)
1	Haridwar	Bijnor	Barrage	58	71	14	70 km
2	Bijnor	Narora	Barrage	72	102	31	155 km
3	Narora	Kanpur	Barrage	103	162	60	300 km
4	Kanpur	Varanasi	Gomti confluence	163	257	95	475 km

The primary segments are further classified into sub-segments depending upon hydrogeomorphology and landforms, based on which the major tributaries meet the main stem Ganga River during its course in the MGR (Figure 4.1).

The major eastward curvature in the Ganga River is due to the western Indian Aravalli craton (Figure 4.2), Aravali-Delhi fold belt (Figure 4.3) and central Indian Bundelkhand craton. In this region, the Ganga River flows in an eastern direction until Chunar in Uttar Pradesh. The upward movement of the Ganga River takes place at Chunar because of the Vindhya hills in the central Indian landscape. The left bank area of the Ganga River is divided into Rohilkhand plains and Awadh Plains. Whereas, the right bank area of the Ganga River is divided into Ganga-Yamuna doab, Bundelkhand upland and Vindhyan scarpland (Figure 4.4).

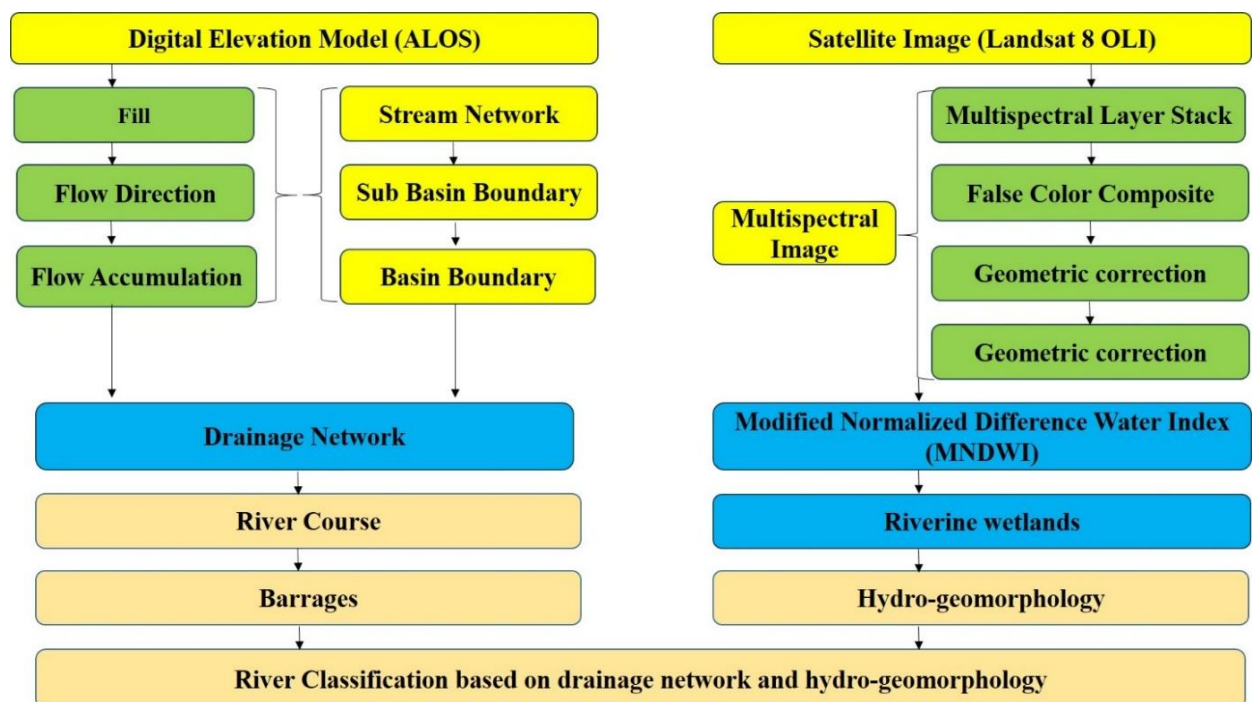


Figure 4.1. Methodology flow chart for river classification

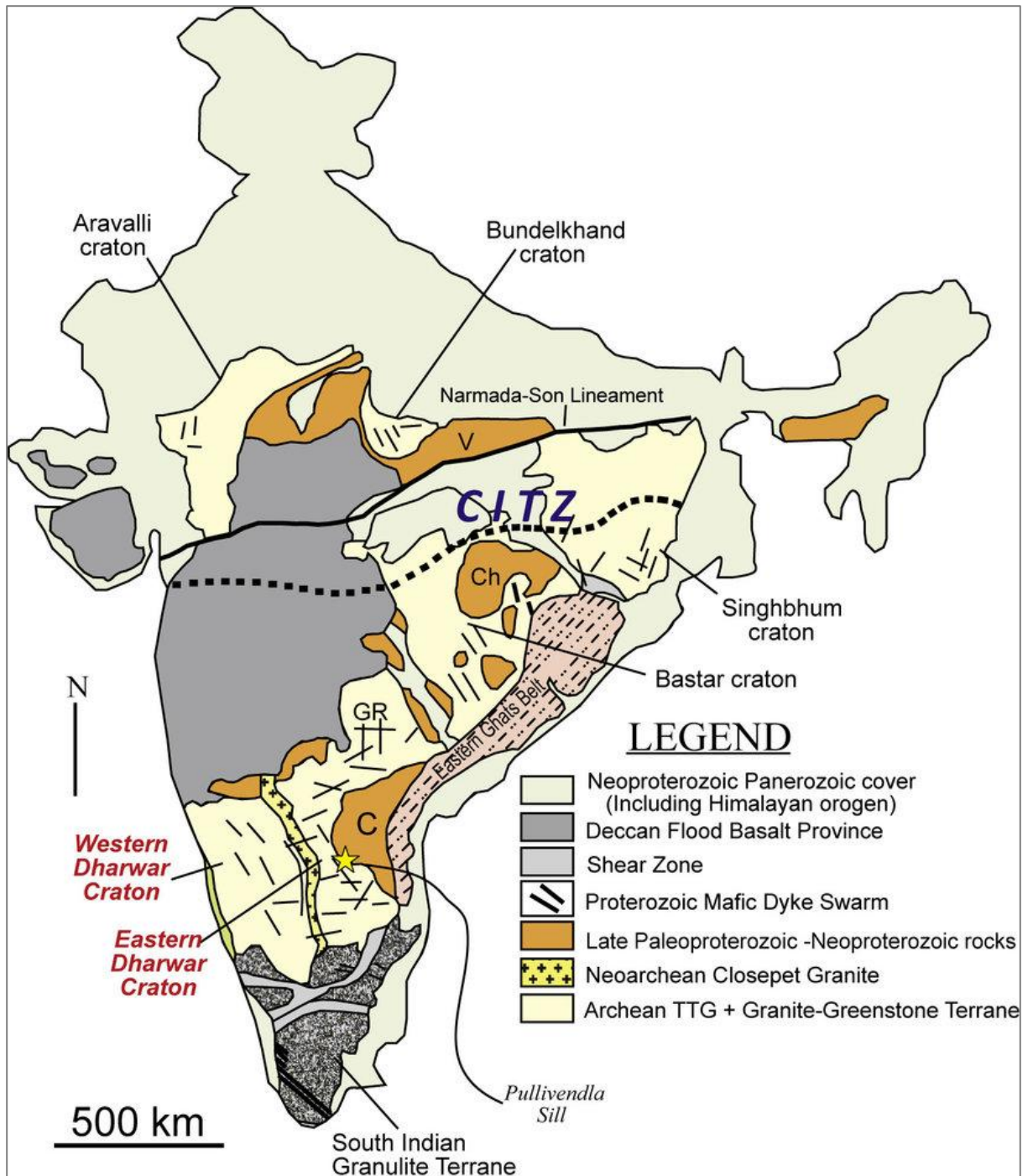


Figure 4.2. Generalized geologic map of major cratons in India (Belica et al, 2013)

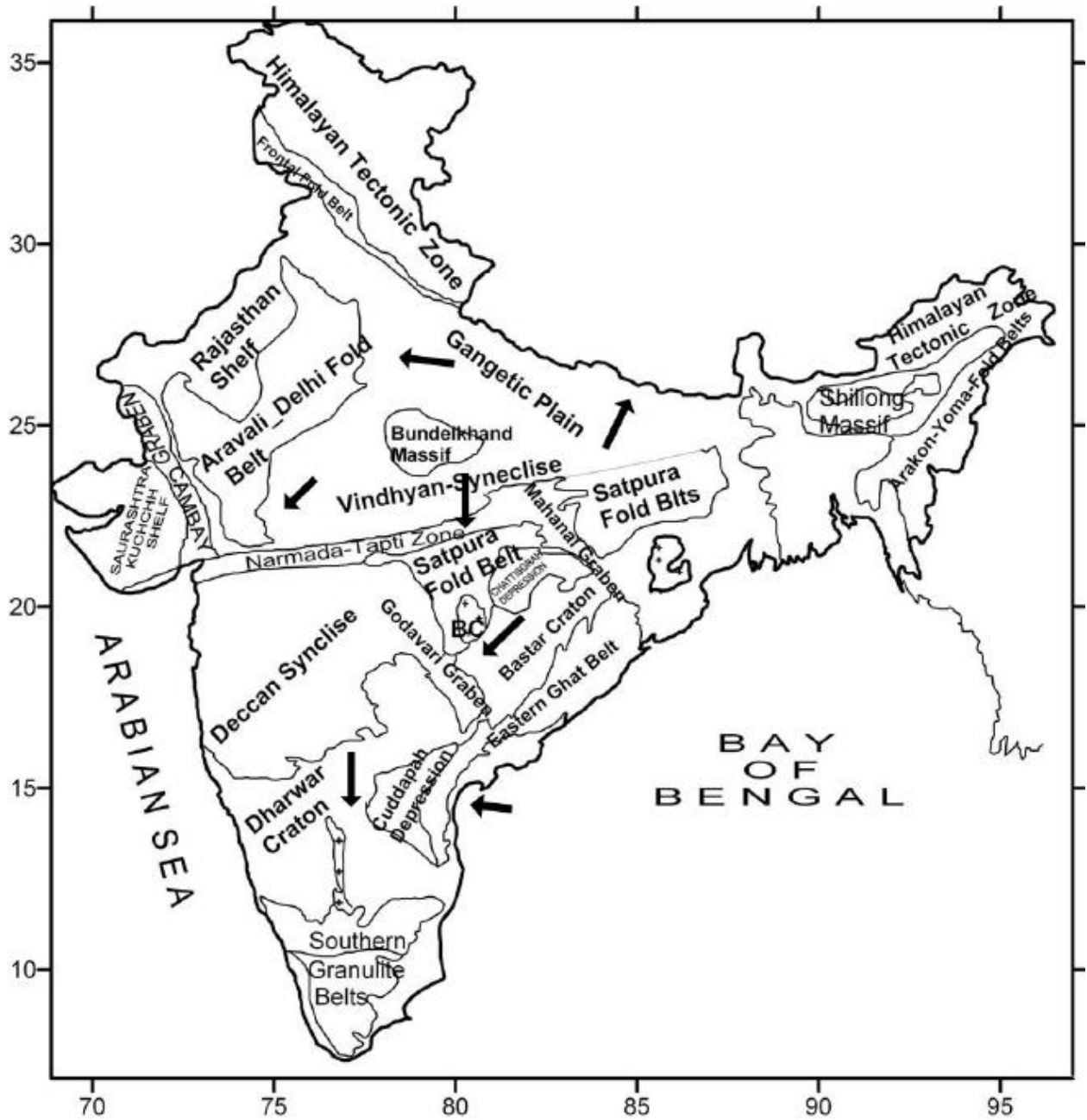


Figure 4.3. Tectonic map of India

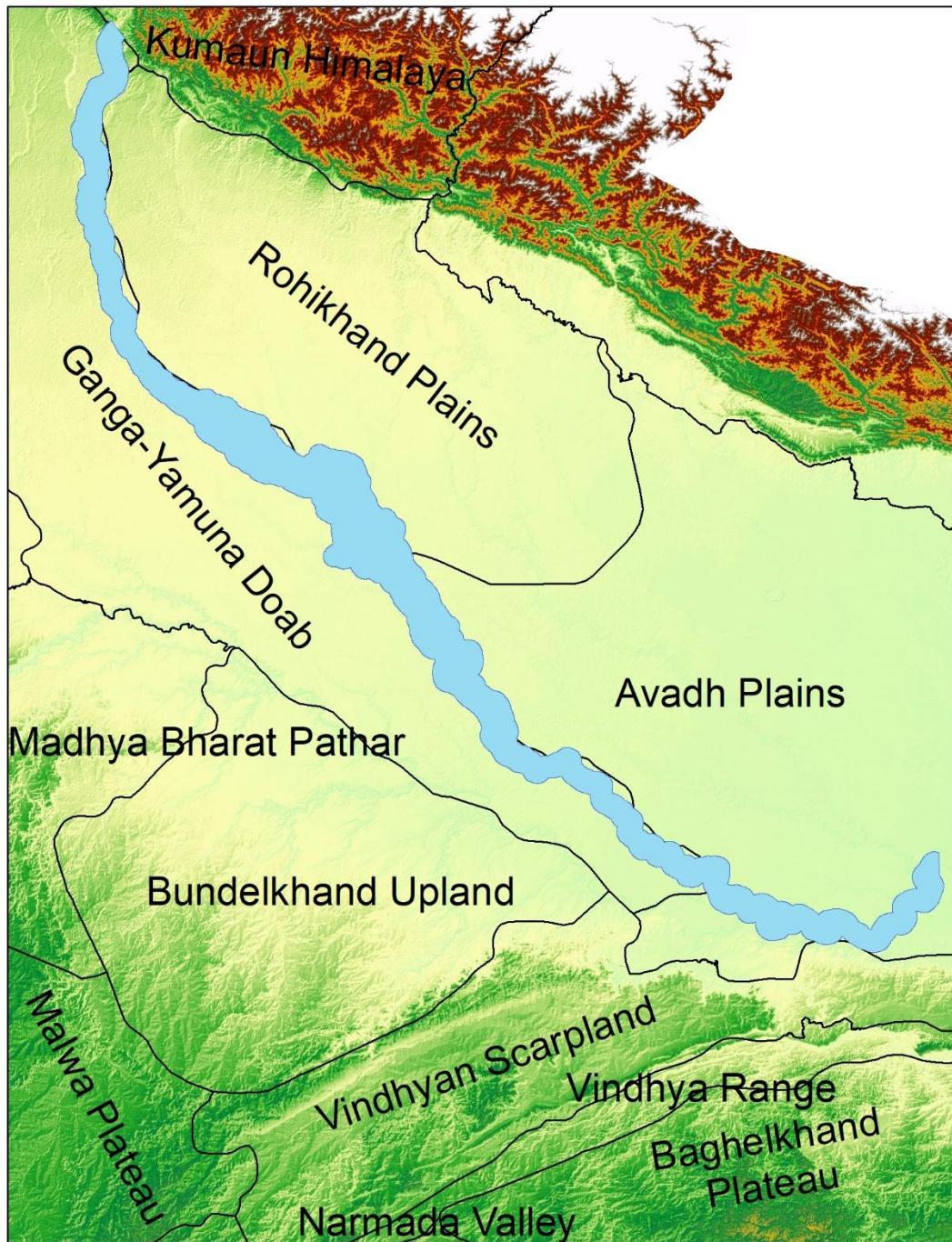


Figure 4.4. Physiographic map of the middle Ganga River

The river bed is essentially flat and the river channel exhibits meanders, bifurcates into several channels in some parts and consists of dynamic system of pools and riffles. Substantial portion of the river flow is diverted to support agricultural activities through canal system (Khan et al., 2018) referred as Upper Ganga Canal (from Bhimgoda Barrage, Haridwar), Madhya Ganga Canal (from Bijnor Barrage), and Lower Ganga Canal (from Charan Singh barrage, Narora). The confluence of Ramganga at Kusumkhor, Kali at Kannauj and Yamuna at Prayagraj augment water discharge in the Ganga River. However, these rivers, particularly Ramganga and Kali bring in a lot of domestic and industrial pollution. In addition, several towns, industries and agricultural activities contribute to the point and non-point pollution load in this segment. Thus, river flow and water quality are the key concerns in this segment in addition to general degradation of river system and encroachment of river bed, gravel, sand mining, riverbed farming, active fishing net, open defecation, etc. In many places dumping of solid wastes and other materials used for anthropogenic purposes.

4.3. Result

4.3.1. River basin and drainage network

The Ganga River basin, which spans approximately 8,61,404 km² (Table 4.4), is one of the largest river basins in the world, serving as a critical water resource for millions of people in India. The basin is divided into several sub-basins, each contributing to the overall flow of the river. Among these, the MGR stretch, which extends from Haridwar

to Varanasi, is an important segment, with distinct sub-basins that drain into the Ganga River. This stretch includes four key sub-basins - Ramganga basin, Garra basin, Gomti basin, Yamuna basin, Chambal basin and Tamas basin along with the Main Stem Ganga basin (Figure 4.4).

The Ramganga basin is located in the northern part of the middle Ganga region and drains an area primarily consisting of the hills and plains of Uttar Pradesh. This basin is characterized by a relatively short, fast-flowing river that contributes significant seasonal runoff to the Ganga River, particularly during the monsoon season (Khan et al., 2016). The Garra basin, situated to the east of the Ramganga basin, also lies within Uttar Pradesh. The Garra River is a smaller tributary, but its contribution to the Ganga is vital, especially during periods of heavy rainfall in the catchment area (Khan et al., 2016; Khan & Wen, 2020). The Gomti basin, another important sub-basin in the middle Ganga stretch, drains an area around the city of Lucknow in Uttar Pradesh. The Gomti River is an essential tributary, providing water to many agricultural regions, and its flow is affected by both seasonal monsoonal rains and the varying demands of urban and rural water usage (Sarkar et al., 2010). The Yamuna basin, one of the largest sub-basins in the middle Ganga region, originates from the Yamunotri Glacier in the Himalaya and flows through the plains of northern India. The Yamuna River is the longest tributary of the Ganga and plays a crucial role in contributing to the river's overall flow (Nishant & Singh, 2018). The Chambal basin (Hussain et al., 2013 and Tamas basin (Jha et al., 2022; Das et al., 2022) contributes in the Ganga River after originating from the central Indian highlands. In addition to these sub-basins, the Main Stem Ganga basin represents the central and most significant portion

of the river, stretching across the plains from Haridwar to Varanasi. This section carries the combined flow of all the tributaries. This is the focal point of water resource management, flood control, and agricultural irrigation in the region.

Table 4.4. Sub-basins in the Ganga River basin

S. No.	River basin	Area in km²	Area in %	Sub-basins contributing in Study Area
1	Ganga Main Stem (Upper and Middle)	74470	8.65	Yes
2	Ramganga	25698	2.98	Yes
3	Garra	6795	0.79	Yes
4	Gomti	30435	3.53	Yes
5	Yamuna	221482	25.72	Yes
6	Chambal	141600	16.44	Yes
7	Tamas	16860	1.96	Yes
8	Ganga Main Stem (Lower)	138004	16.02	No
9	Ghaghra	57647	6.69	No
10	Gandak	7620	0.88	No
11	Kosi	20370	2.36	No
12	Son	71259	8.27	No
13	Ajay	6050	0.70	No
14	Damodar	25820	3.00	No
15	Rupnarayan	17294	2.01	No
Total		861404	100	

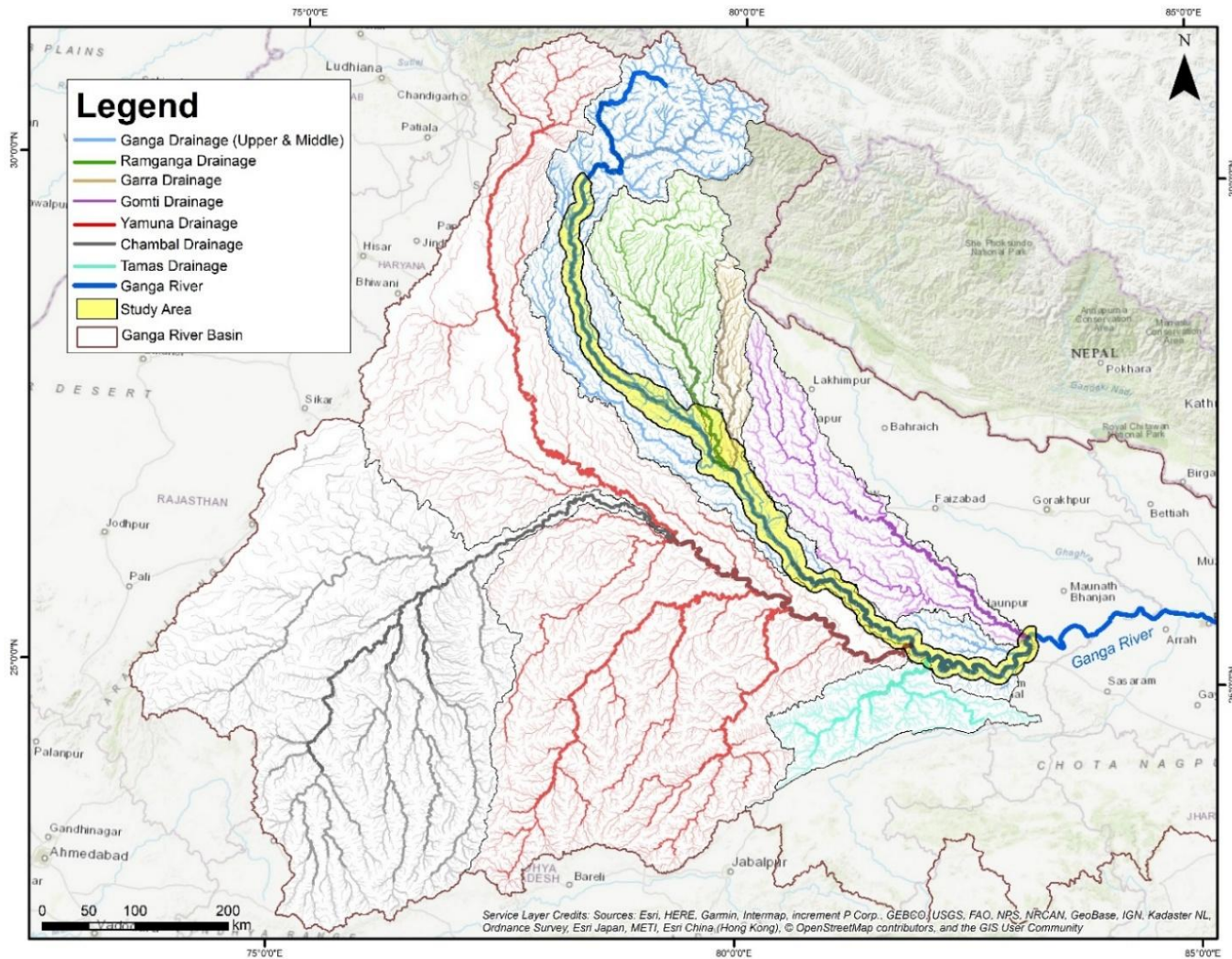


Figure 4.5. Sub-basins in the middle Ganga River basin

4.3.2. Mapping of riverine wetlands

The multispectral layer stacking method was applied on 11 spectral bands of the Landsat 8 OLI image and the MNDWI analysis was performed in resulting multispectral image. The water pixels were extracted by mask analysis and river areas were eliminated to extract specifically the wetlands (N=788) in the floodplain area. The district wise clusters of riverine wetlands in floodplain of the Ganga River are prepared. The Space Application Centre (SAC), Govt. of India and Ministry of Environment Forests and Climate Change (MoEFCC), Govt. of India mapped wetlands of India as a part of the project on National Wetland Inventory and Assessment (NWIA) and listed district wise wetlands (National Wetland Atlas, 2011). As per the Gazette of India, MoEFCC notification dated 26th September, 2017 “wetland” was defined as *‘an area of marsh, fen, peatland or water; whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters, but does not include river channels, paddy fields, human-made water bodies/tanks specifically constructed for drinking water purposes and structures specifically constructed for aquaculture, salt production, recreation and irrigation purposes’*. After extraction of the waterbodies, we have only considered the waterbodies which is defined as wetlands by the above guideline. The result of our study reveals that approximately 12.57 % of the district wise wetlands are present in floodplain of the middle Ganga River (Table 4.5).

Table 4.5. District wise clusters of riverine wetlands in floodplain

State	District	Wetlands in floodplain of middle Ganga River	Wetlands in district (National Wetland Atlas, 2011)
Uttarakhand	Dehradun	3	8
	Haridwar	37	46
	Pauri Garhwal	2	1
Uttar Pradesh	Aligarh	6	160
	Prayagraj	60	387
	Bijnor	19	219
	Budaun	5	177
	Bulandshahr	1	223
	Chandauli	22	162
	Etah	4	125
	Farrukhabad	36	236
	Fatehpur	35	288
	Ghazipur	8	148
	Hapur	7	74
	Hardoi	88	864
	Amroha	28	70
	Kannauj	17	132
	Kanpur Nagar	27	207
	Kanshiram Nagar	57	105
	Kaushambi	7	127
	Meerut	19	151
	Mirzapur	50	414
	Muzaffarnagar	10	148
Pratapgarh	41	277	
Rae Bareli	46	569	

Sambhal	7	89
Bhadohi	22	36
Shahjahanpur	25	329
Unnao	73	476
Varanasi	26	19
Total	788 (12.57%)	6267

The Figure 4.6. shows district wise floodplain area and presence of wetlands in the MGR. The result shows that Unnao district in Uttar Pradesh has maximum area of floodplain followed by Hardoi, though Hardoi district has maximum number of riverine wetlands. The Pauri Garhwal district in Uttarakhand and Etah district in Uttar Pradesh has minimum floodplain area of the middle Ganga River. Bulandshahr district in Uttar Pradesh has minimum number of riverine wetlands (Figure 4.7).

Riverine wetlands are important to maintain ecological balance and biodiversity conservation. Wetlands provide ecosystem services like water filtration, flood control, and carbon sequestration (Grazie & Gill, 2022). Various aquatic and water associated species are present in wetlands along the middle Ganga River. Wetland mapping, particularly in riverine areas, helps in the assessment, management, and conservation of ecosystems. Wetlands act as natural filters, removing excess nutrients and pollutants from the river water (Mpandeli et al., 2024). They also play an essential role in regulating water flow and controlling flooding by absorbing excess water during heavy rainfall or seasonal floods (Kadykalo & Findlay 2016).

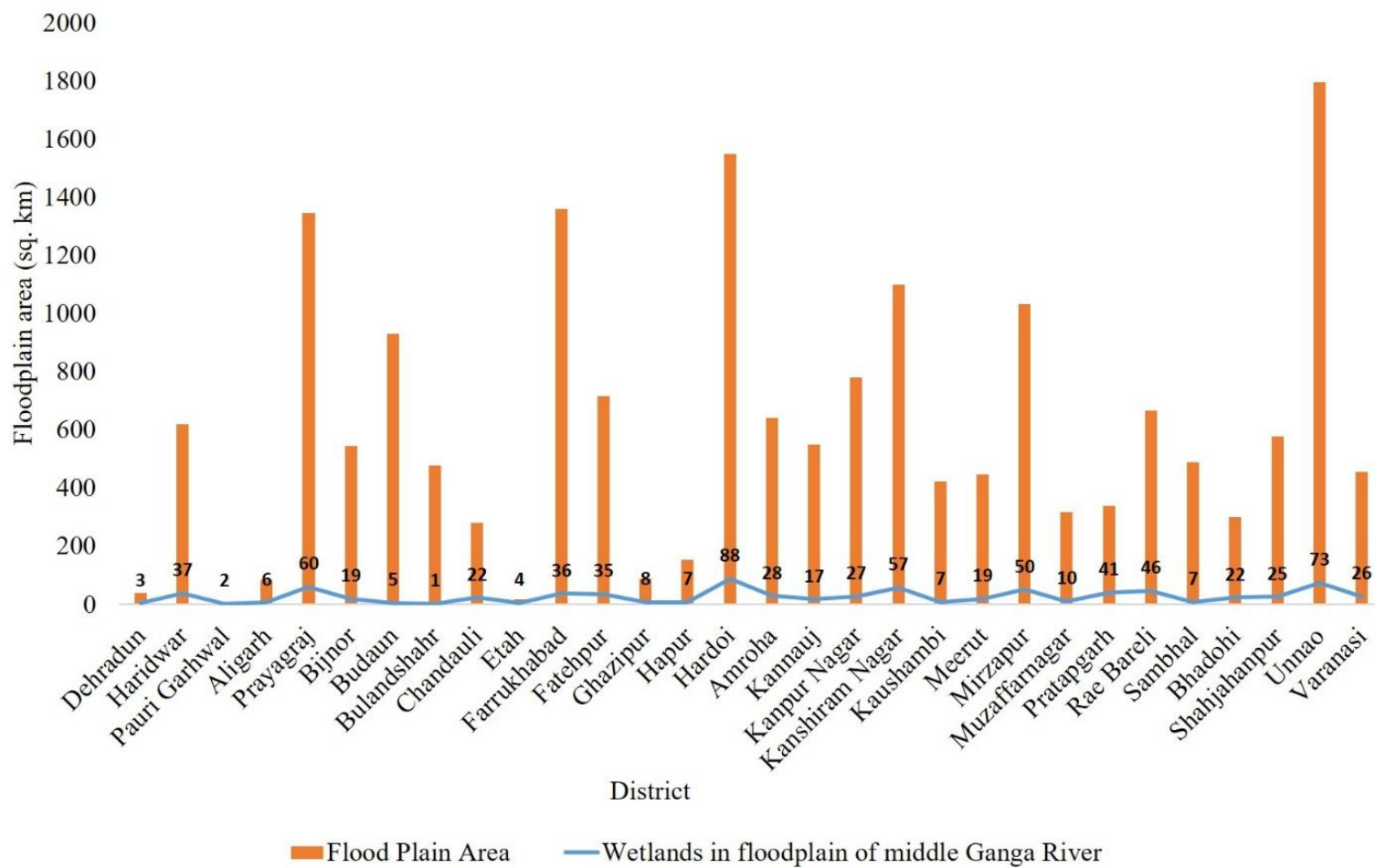


Figure 4.6. District wise floodplain area and presence of wetlands

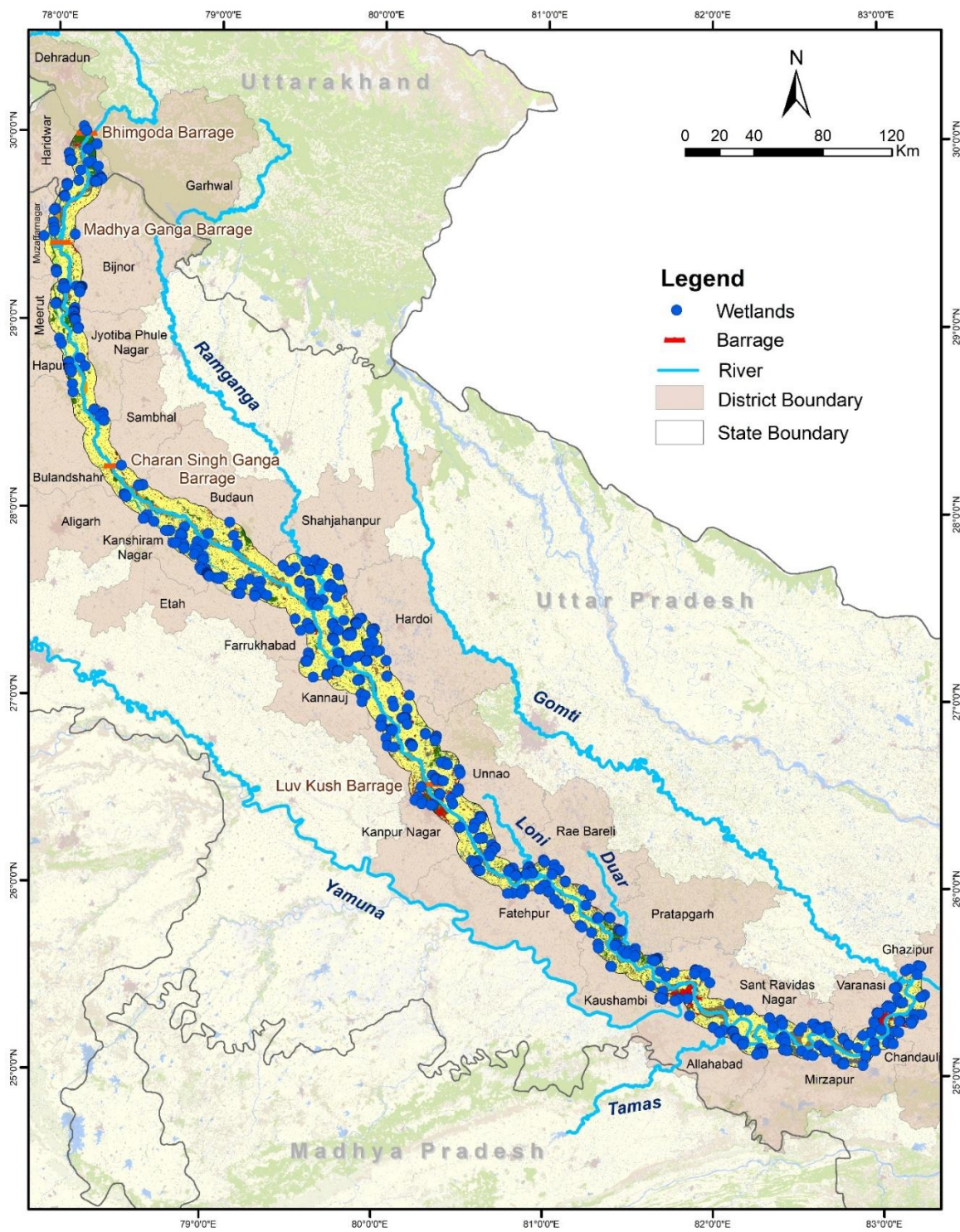


Figure 4.7. Distribution of riverine wetlands

Wetlands along the Ganga River are subject to seasonal changes, such as flooding and drying of the river (Mukherjee 2020). The riverine wetlands are formed due to surface depression and erosion of river bank and surrounding area. With due course of time and shifting nature of the Ganga River in middle course. The Ganga River's floodplain changes regularly, with meandering channels, islands, and braided streams creating dynamic wetland environments. Anthropogenic activities such as urbanization, industrialization, dam construction, and agricultural expansion have significantly altered the riverscape and impacted the wetlands along Ganga River (Kumar et al., 2023). Wetlands along Ganga River floodplain are increasingly encroached upon for development, agriculture, or human settlement, leading to habitat loss and degradation. Many riverine wetlands along the Ganga River have degraded due to pollution, water diversion, and encroachment (Singh 2022). These wetlands are interconnected with the broader Ganga River ecosystem, and their health is influenced by upstream and downstream activities. Integrated river basin management involves coordinating the management of water resources, wetlands, agriculture, and urban development within the entire Ganga basin to ensure that wetland ecosystems are protected and restored. Districts namely Mirzapur, Kansiram Nagar, Prayagraj, Farukhabad, Bulandshahr and Bijnor in Uttar Pradesh and Haridwar in Uttarakhand has larger floodplain along the Ganga River but the riverine wetlands are comparatively less in number. Smaller wetlands of these areas need to be restored in long term. The conservation measure of the riverine wetlands needs to be taken in gradual proximity along the bank of Ganga River. The wetlands located within one and two kilometer from river bank need to be protected from

encroachment and agricultural activity as these wetlands are more connected for infiltration and seasonal replenishment with the Ganga River, which makes the wetland a suitable habitat for aquatic flora and fauna. Restoration projects that involve reforestation, water quality improvement, and the removal of invasive species are essential for reviving these wetlands. The Government of India has enacted various policies and laws for wetland conservation, including the National Wetland Conservation Programme (NWCP). However, stronger enforcement of existing laws and the creation of specific regulations for riverine wetland protection along the Ganga River is necessary for ensuring the long-term sustainability of wetlands and inhabited biodiversity.

4.3.3. River classes based on hydrogeomorphology

The middle Ganga River is classified into sub-segments (Table 4.6) depending upon hydrogeomorphology and landforms (Figure 4.8). Various drainage forms due to fault-system related tectonic dynamics and the elevation gradient in the Gangetic plain, as a result of these land forms major tributaries meet the main stem Ganga River (Singh et al., 2019). The area forms an arc structure between the Himalayan arc at Terai region (Adilakshmi et al., 2021) and the Vindhyan escarpment at the central Indian landscape, which is located at the southern end of the Malwa plateau (Tang et al., 2017). The Ganga River flows at south-east direction in the middle course starting from Haridwar by following the Terai arc structure in the north and Vindyan scarpland at the south which is divided into Panna plateau, Bundelkhand plateau, Rewa plateau and Rohtas plateau.

Table 4.6. Sub-segments in the middle Ganga River

Sub-segment	From	To	Remark	BEU Start	BEU End	Total BEU	Length (km)
1	Haridwar	Bijnor	Barrage	58	71	14	70 km
2	Bijnor	Narora	Barrage	72	102	31	155 km
3A	Narora	Fatehgarh	U/s of Ramganga confluence	103	136	34	170 km
3B	Fatehgarh	Kusumkhor	Ramganga confluence	137	143	7	35 km
3C	Kusumkhor	Kanpur	Barrage	144	162	19	95 km
4A	Kanpur	Fatehpur	Loni confluence at Bhitura	163	178	16	80 km
4B	Fatehpur	Sirathu	Duar confluence at Kunda	179	194	16	80 km
4C	Sirathu	Prayagraj	Yamuna confluence	195	210	16	80 km
4D	Prayagraj	Gopiganj Mirzapur	Karnabati confluence	211	230	20	100 km
4E	Gopiganj Mirzapur	Chunar	Vindhya hills	231	242	12	60 km
4F	Chunar	Kaithi Varanasi	Gomti Confluence	243	257	15	75 km

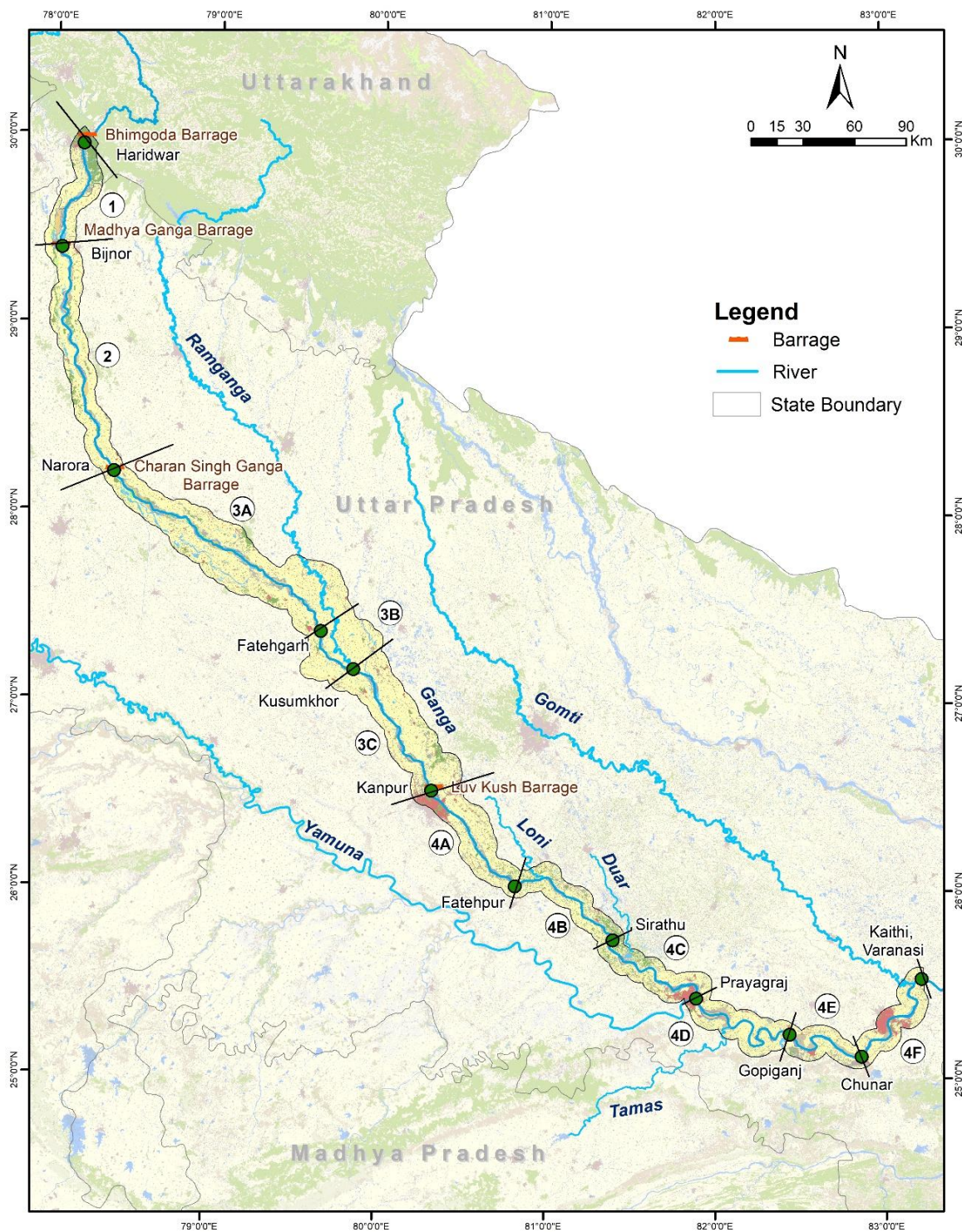


Figure 4.8. River classes based on hydrogeomorphology

- **Sub-segment 1 (Haridwar to Bijnor)**

River patterns and processes are crucial for their management and conservation (Lovric and Tasic 2016). Besides, hydrogeomorphic studies guide the rehabilitation, conservation and management post commissioning of large-scale river projects such as construction of reservoirs, barrages and even irrigation canals (Langat et al. 2019). The river stretch is less sinuous, suggesting that the river has not meandered much and remained more or less straight. This is attributed to the gradual decrease in the elevation from the Gangetic Plain at Haridwar (29° 57' N, 78° 10' E) to Bijnor (29°22' N, 78°02' E). Erosion and deposition in the river are highly dependent on flow, volume and sediment load (Mondal & Mandal, 2018). Bank erosion and deposition influence changes in the river morphology. The dynamic changes arise due the process of erosion and deposition. The landscape exhibits piedmont made up of unconsolidated sand, silt and clay. The river is highly braided in this segment. The stretch is situated between Haridwar to Bijnor is 70 km in length. This stretch is characterised by transition of Himalayan bedrock to the confined channel and the Ganga enters within the alluvial plains at the downstream of the Haridwar (Dimri et al., 2019). The landscape of this stretch exhibits piedmont zones and sub-Himalayan ranges which consists of sandstone, shale, conglomerate whereas the alluvial plains consist of unconsolidated sand, silt and occasionally with clay. The upper portion of the stretch shows development of narrow and fairly continuous floodplain along either side of the river channel, large alluvial plains and mid channels are the most prominent geomorphic feature in this section (Prasad et al, 2021). Downstream of the Haridwar is characterised by highly braided river and development of the small and large mid channel

bars and large alluvial island which is dissected by a number of chute and dry channel (Pandey et al., 2020). River channel and floodplains are partly confined, river flow is also highly asymmetric in this area (Sinha et al, 2017). At Haridwar river flow diverted through Upper Ganga canal near Bhimgoda barrage. Characteristic features of the alluvial plains situated at this area is very densely vegetated, mid channel bars are slightly vegetated and side bars or lateral bars are barren in nature. A large number of paleochannels on the western side of the main channel suggest an eastward migration of the river in recent times.

- **Sub-segment 2 (Bijnor to Narora)**

This stretch is located between Bijnor (29°22' N, 78°02' E) to Narora (28° 11' N, 78° 23' E) which is 155 km in length. This stretch is characterized by central alluvial plain, valley interfluvial, partially confined floodplain and braided channels (Sinha et al., 2017). River valley width narrow down considerably at Bijnor, the river valley widens downstream of Bijnor and also maintain its width upto Garhmukteshwar (Singh et al., 2019). Downstream of the Garhmukteshwar, the Ganga River is characteristically flowing along the western edge to Narora. The channel is asymmetric to the valley, river is highly braided, side bar, point bar and mid channel bars are most common features in this stretch. In places this mid channel bars and side bars are vegetated. These bars are also highly cultivated during lean season. Abandoned braid bars, meandering cut offs and ox-bow lakes are most prominent features in the active floodplains (Sinha et al., 2017). Downstream of Bijnor the floodplain is wider, whereas near Garhmukteswar the river

flows along the western edge of the river valley thus a wide valley is formed along the eastern side of the Ganga River. This stretch is an example of narrow floodplains compared to the valley.

- **Sub-segment 3A (Narora to Fatehgarh)**

This stretch extends from Narora (28° 11' N, 78° 23' E) to Fatehgarh (27°22 N; 79°38' E), covers a distance about 170 km. This stretch exhibits a North West-South East trending valley with wide valley margins on both sides of the river. Near upstream of Fatehgarh, the river turns to the western edge of the valley and a wide valley are formed on the eastern side (Sinha et al., 2017). Major geomorphic characteristics near Narora is absence of cliff line along left bank which resultant unconfined channel and flood plains for entire stretch. The river is symmetric and braided in nature, valley is interfluvial, floodplain is unconfined. The valley margin is highly irregular and abandoned braid bars and alluvial islands are most common geomorphic features in along this stretch (Prasad et al., 2021). The transition from segment 2 to 3A is characterized by the disappearance of cliff line along the left bank, which makes the channel and floodplain unconfined (Sinha et al., 2017). Braided channel, sand bars and alluvial islands are dominated in this stretch. Bed material varies from very fine sand to coarse sand and the bank comprises an alternate succession of mud and fine sand. Sandy bars are more frequent in the channel belt downstream of the Narora barrage, formed due to low flow reduction in the lean season.

- **Sub-segment 3B (Fatehgarh to Kusumkhor)**

This stretch is located between Fatehgarh (27°22' N; 79°38' E) to Kusumkhor (27°10' N, 79°50' E) which is 35 km in length. The Ramganga River meets the Ganga River from northern side near Kusumkhor. This stretch is characterized by Ramganga alluvial plain, flat terrain, partially confined floodplain and braided channels (Roy & Sinha, 2007; Khan & Chakrapani, 2016). River valley width widens at Fatehgarh. The Ganga River flows along the southern margin of the valley. A wide floodplain traverses along the northern bank and narrow floodplain formed along the southern bank. The river is asymmetric and braided, river valley is interfluvial in nature, and river channel is partly confined. Large mid channel bar and lateral bar are most characteristic geomorphic features of this stretch. The river channel is intersected by multiple frequently occurring mid channel bars and some lateral bars. The northern side of the river valley, meandering cut-offs, oxbow lakes are common geomorphological features within the active floodplain which suggest the river has gradually migrated towards the south.

- **Sub-segment 3C (Kusumkhor to Kanpur)**

This stretch is located between Kusumkhor (27°10' N, 79°50' E) to Kanpur (26°30' N, 80° 19' E) which is 95 km in length. The Luv Kush barrage is located at Kanpur. This stretch is characterized by the Ramganga alluvial plain, flat terrain, partially confined floodplain and braided channels (Mukherjee et al, 2017). Sediments of the Ramganga River form clay soil structures in this segment. Kali River meets the Ganga River in this sub-segment

from the southern direction. This stretch extends till the upstream of Luv Kush barrage at Kanpur.

- **Sub-segment 4A (Kanpur to Fatehpur)**

This stretch is located between Kanpur (26°30' N, 80° 19' E) to Fatehpur (26°01' N; 80°49' E) which is 80 km in length. Downstream of the Kanpur the river continuously flows along the western edge of the valley and further downstream the valley narrows down considerably (Santy et al., 2020). The river is swinging to the northern and western edge within limited space and produce a narrow floodplain alternate on both sides. Approximately 70 km downstream of the Kanpur the Ganga River flows east west direction then it flows towards NW-SE direction till the confluence of Loni River at Bhitura.

- **Sub-segment 4B (Fatehpur to Sirathu)**

This stretch is located between Fatehpur (26°01' N; 80°49' E) to Sirathu (25°44' N, 81°23' E) which is 80 km in length. This stretch is characterized by an incised channel and very narrow, floodplain. The channel is partly confined by valley margin, and it is highly asymmetric to the valley. The narrow floodplain is located at one side of the river due to the meandering characteristics. River channel is highly braided near Fatehpur where sand bars are dominant feature but the Ganga River is braided gradually leading to increasing sinuosity towards Sirathu, where patches of alluvial island are the prominent. Medium grained sand is the composition of bed material in this stretch (Sinha et al., 2017).

- **Sub-segment 4C (Sirathu to Prayagraj)**

This stretch is located between Sirathu (25°44' N, 81°23' E) to Prayagraj (25°25' N; 81°53' E) which is 80 km in length. This stretch is characterized by unconfined channel and floodplain. Braided channel, sand bars and alluvial islands. Bed material varies from very fine sand to coarse sand and the bank comprises an alternate succession of mud and fine sand. Sandy mid-channel bars are present in the channel belt downstream of the Sirathu (Sinha et al., 2017). This stretch more sinuous. Meander scars and abandoned braid bars are very frequent and sharp changes in the morphology of the Ganga River around the confluence is present (Pati et al., 2008).

- **Sub-segment 4D (Prayagraj to Gopiganj Mirzapur)**

This stretch is located between Prayagraj (25°25' N; 81°53' E) to Gopiganj Mirzapur (25°14' N, 82°26' E) which is, 100 km in length and located at the downstream of Ganga-Yamuna confluence. This is very unique stretch of the Ganga River, as it reaches to peninsular shield and exhibits a strong tectonic control with a maximum sinistral shift. Geomorphic features such as sand bars locate at mid river channel, along the river bank, alluvial island, meander scrolls, vegetation patches are prevalent in this stretch. This stretch initiates with a sharp transition from valley interfluvial setting to alluvial setting. Sinuosity of the Ganga River is high in this stretch. The channel is unconfined with wide floodplain with high dominance of sandbars. Meander scars and and ox-bow lakes are also present in the floodplain. Fine-grained sand is the dominant channel bed material in this stretch (Sinha et al., 2017).

- **Sub-segment 4E (Gopiganj Mirzapur to Chunar)**

This stretch is located between Gopiganj Mirzapur (25°14' N, 82°26' E) to Chunar (25°07' N, 82°51' E) which is 60 km in length. A major characteristic of this river class is the partial confinement of the channel and floodplain by the cratonic margin. The floodplains are wide, asymmetrical and unconfined at left bank but it is confined at the right bank as a result of the peninsular part and upper thrust generated due to the Vindhya hills. Large patches of abandoned meander belt with meander scrolls are most prominent geomorphic feature of this segment (Sinha et al., 2017). The Ganga River is highly braided in this stretch. The composition of bed material is medium to fine grained sand with clayey.

- **Sub-segment 4F (Chunar to Varanasi)**

This stretch is located between Chunar (25°07' N, 82°51' E) to Kaithi Varanasi (25°30' N, 83°10' E) which is 75 km in length. The river channel in this stretch is unconfined with wide floodplain with high dominance of sandbars. Meander scars and ox-bow lakes are present in the floodplain. Fine-grained sand is the dominant channel bed material in this class (Sinha et al., 2017). Alluvial islands are very common in this stretch. Large abandoned meander belt with numerous meander scrolls are located in this stretch demarcates significant migration of Ganga River to north.

4.4. Discussion

The drainage pattern and basin structure of the Ganga River are fundamental to understanding the river's hydrology, geomorphology, and environmental significance. The patterns, shaped by both natural forces and human activities, impact water flow, sediment transport, land use, and biodiversity in the Ganga River basin. The drainage pattern refers to the arrangement of tributaries, channels, and streams, influenced by geology, topography, and climate of the area. In its middle course, the Ganga River exhibits a complex drainage network, featuring meandering, braided, and anastomosing channels. The basin has numerous sub-basins responsible for draining water from tributaries and smaller rivers. These sub-basins include the main stem Ganga, Yamuna, Chambal, Ramganga, Garra, Gomti, and Tamas Rivers, each contributing significantly to the Ganga River's water volume. The sub-basins, characterised by topographical and climatic variations, affect water flow and sediment characteristics. The Yamuna sub-basin, which drains Uttarakhand, Haryana, Uttar Pradesh, and Delhi, is heavily influenced by human activities, such as agricultural runoff and urban pollution, affecting water quality. Sub-basins like the Ramganga, Garra, and Gomti, draining through terai region of northern India, are impacted by mountainous terrain and monsoon rains, leading to flash floods and sediment transport. The Tamas sub-basin brings enriched nutrients and minerals from central India, contributing to water quality and sediment load of the Ganga River. The MGR experiences seasonal flooding due to monsoonal rains, which increase water flow in the river and its tributaries. The vast alluvial floodplain of the Ganga River is fertile and supports extensive agriculture, but is also vulnerable to inundation during

peak monsoon events. The movement of water through the river system carries significant loads of sediments, including fine particles and nutrients, deposited across the floodplain and riverbanks. This sediment transport influences soil fertility, groundwater recharge, and the stability of riverbanks. Sediment deposition is also important for agriculture, replenishing soil nutrients, but also presents challenges, such as sedimentation in river channels reducing flow capacity and increasing flood risk.

The drainage patterns and sub-basins are also important in distribution of habitats and biodiversity within the MGR. Wetlands, river islands, oxbow lakes, and floodplain forests are essential ecosystems that support a wide range of species. The spatial distribution of these habitats is determined by the drainage system and seasonal water flow variation. Wetlands and floodplains serve as breeding grounds for aquatic species, and the interaction between drainage patterns, water flow, and biodiversity is crucial for maintaining ecological integrity. The drainage patterns and sub-basins are integral to land use planning, agricultural practices, and water resource management. Human interventions, such as dams, reservoirs, and canals, alter natural drainage patterns, impacting water availability, sediment transport, and flood regulation. Balancing agricultural needs with environmental sustainability requires understanding the interactions between drainage patterns and the river system. The drainage patterns and sub-basins of the MGR are essential for climate change adaptation. Climate change is expected to increase the frequency and intensity of extreme weather events, such as floods and droughts, putting additional stress on the drainage system. By studying the drainage

patterns and sub-basins, policy makers and water resource managers better understand the pattern of river system respond to changing climatic conditions.

Riverine wetlands along the Ganga River are vital to maintain the ecological balance and biodiversity conservation, offering invaluable ecosystem services such as water filtration, flood control, and carbon sequestration (Grazie & Gill, 2022). These wetlands act as natural filters that remove excess nutrients and pollutants from river water, thus improving water quality and supporting a wide array of aquatic and water-associated species (Mpandeli et al., 2024). In addition, they help regulate water flow, absorbing excess water during heavy rainfall or seasonal flooding, which contributes to the prevention of floods and overall water management (Kadykalo & Findlay, 2016). Wetlands along the MGR are influenced by the river's seasonal fluctuations, including periods of flooding and drying, which affect the ecosystem and hydrological processes within these areas (Mukherjee, 2020). These wetlands are primarily formed due to surface depressions, erosion of the riverbanks, and shifting hydrological patterns over time. The river's floodplain continuously changes due to meandering channels, islands, and braided streams, creating highly dynamic environments for wetland formation. The physical characteristics of the Ganga River, in addition to its seasonal behaviours, result in shifting wetland habitats that are difficult to assess, requiring continuous mapping for effective conservation and management. Anthropogenic activities have significantly altered the landscape along the Ganga River and impacted its wetlands. Urbanization, industrialization, dam construction, and agricultural expansion have all played a role in changing the natural flow of the river and disrupting the wetlands. These activities,

particularly the increasing encroachment of wetland areas for development, agriculture, and human settlement, have led to habitat loss, degradation, and a decline in wetland quality (Kumar et al., 2023). In many areas, wetlands are being drained for agricultural purposes or urban expansion, diminishing their capacity to perform crucial ecosystem functions such as nutrient cycling and water purification. Pollution, water diversion, and physical encroachment further threaten the wetlands, leading to the degradation of these valuable habitats (Singh, 2022).

Wetlands along the Ganga River floodplain supports local biodiversity and interconnected with the broader riverine ecosystem. Health of these wetlands depends on the activities occurring upstream and downstream within the river basin. Integrated river basin management, which involves coordinated management of water resources, agriculture, wetlands, and urban development across the entire Ganga basin, is essential to the long-term health of these ecosystems. In the Ganga River basin districts namely, Mirzapur, Kansiram Nagar, Prayagraj, Farukhabad, Bulandshahr, and Bijnor in Uttar Pradesh, and Haridwar in Uttarakhand, have large floodplains. Despite this, the riverine wetlands in these regions are comparatively few in number, and many of them are smaller and increasingly vulnerable to degradation. These wetlands, especially those located within one to two kilometers of the riverbank, are important for seasonal replenishment of water and are intimately connected to the Ganga River itself. As such, they need to be protected from encroachment and agricultural activity to ensure their continued functionality. Wetlands near the riverbanks serve as vital areas for infiltration, filtration, and the replenishment of groundwater, which supports diverse aquatic flora and fauna.

Restoration projects targeting these wetlands are essential for ensuring the long-term health and sustainability of the Ganga River ecosystem. These projects involve various strategies like reforestation, removal of invasive species, and improvement of water quality. Reforestation helps to restore the vegetation surrounding wetlands, which is important for stabilizing soil, preventing erosion, and providing habitat for wildlife. The removal of invasive species, which irradiate native flora and fauna, is another key aspect of wetland restoration efforts.

In response to the growing need for wetland conservation, the Government of India has enacted various policies and laws to protect these ecosystems. One such initiative is the National Wetland Conservation Programme (NWCP), which aims to conserve wetlands across the country, including those along the Ganga River. While these efforts have been beneficial, stronger enforcement of existing laws is necessary to ensure that wetland protection is taken seriously by local communities, industries, and government agencies. Additionally, creating specific regulations for the protection of riverine wetlands along the Ganga River could provide more focused and effective conservation measures. The challenges of wetland conservation along the Ganga River are compounded by ongoing human activities, such as agricultural expansion, industrial growth, and the construction of dams and other infrastructure. These activities change the natural dynamics of the river, contributing to habitat degradation and the loss of biodiversity. The shifting hydrological conditions of the river and the changing land use patterns make it difficult to establish clear boundaries for wetland areas, and ongoing development pressures threaten to further encroach upon these vital ecosystems. To address these challenges, a comprehensive

approach to wetland conservation is required. Integrated river basin management, which accounts for the interdependence of water resources, wetlands, agriculture, and urban development, is essential in mitigating the negative effects of anthropogenic activities. This holistic approach encourages cooperation between different stakeholders, including government agencies, local communities, industries, and conservation organizations, to promote sustainable development while protecting the environment.

Rivers are vital ecosystems that support a remarkable diversity of aquatic life, providing essential habitats for species ranging from microorganisms to large mammals. The intricate physical and ecological structure of river systems, characterized by various geomorphic zones, plays a central role in determining the distribution and composition of species throughout the waterway. A foundational concept in understanding these processes is the River Continuum Concept (RCC) proposed by Vannote et al. in 1980, which emphasizes the importance of geomorphic features, water flow, and other environmental variables in shaping the aquatic communities found along a river's course. According to the RCC, rivers can be seen as a continuum, with environmental conditions varying longitudinally from the headwaters to the river mouth, creating distinct habitats that support different species at various points along the river. The bathymetry or underwater topography of a river is a crucial factor in the formation of these habitats. Rivers typically consist of different features, including riffles, pools, and falls, each of which provides unique ecological conditions. Riffles, characterized by shallow, fast-moving water with rocky or gravelly substrates, are oxygen-rich environments that support a variety of species, particularly fish and invertebrates that thrive in turbulent

waters. Pools, in contrast, are deeper, slower-moving areas that provide shelter, feeding, and breeding grounds for many aquatic organisms, including species like Gangetic dolphin (*Platanista gangetica*) and a variety of fish species. Deeper areas which are often found in sections of rivers, can also play an important role by either acting as barriers to species movement or creating unique hydrodynamic conditions that favour certain species adapted to these high-energy environments.

An interesting feature of river ecosystems is their ability to form temporary habitats during periods of low water. When water levels recede, features like sandbars become exposed. These areas, which are typically submerged during high-flow conditions, serve as critical habitats for various species, including reptiles and birds. During the lean periods, sandbars created by sediment deposition provide ideal basking sites for reptiles like Gharial (*Gavialis gangeticus*) and several species of turtles. These sandbars also serve as nesting sites for aquatic birds, such as Indian skimmer (*Rynchops albicollis*), which prefer these open, sandy spaces for laying their eggs. The temporary nature of these habitats highlights the dynamic relationship between river systems and the species they support. The ability of river ecosystems to create new habitats through seasonal changes is crucial for maintaining biodiversity, especially for species that rely on such sites for reproduction, thermoregulation, and feeding.

In MGR, the Ganga River exhibits a combination of physical features that influence species distribution. The river has gentle slope and deep pools in the river thalweg provides stable habitats for species that prefer deeper waters. The presence of riffles in the mid-channel, along with the formation of mid-channel bars, further diversifies the

habitat structure, offering oxygen-rich, fast-flowing environments that support different species. Additionally, the moderate flow in this part of the river contributes to the formation of meanders i.e., curves in the river's path that create lateral sandbars, particularly in 3B (Fatehgarh to Kusumkhor) and 4B (Fatehpur to Sirathu). These sandbars, often associated with the bends in the river, are critical habitats for several species that thrive in these specific hydrodynamic conditions. However, the ecological suitability of these bars is not uniform across the river. Lateral bars, which are connected to the riverbank, are often less desirable for aquatic species due to the increased risk of predation from terrestrial animals. In contrast, mid-channel bars, being more isolated from the shoreline, tend to offer safer, more stable habitats for aquatic organisms.

Other important factor influencing the suitability of river habitats for various species is the depth and width of the river channel. Rivers with deeper, wider channels are generally more conducive to species like the Gangetic dolphin, which require spacious, stable environments to navigate and forage. In such river sections, the larger spatial volume and less turbulent flow provide more favourable conditions for these species. Conversely, rivers with shallow, narrow channels may not offer the same level of protection or resources for such species, which rely on deeper, more stable areas for feeding and shelter. The substrate composition of the riverbed is critical factor in determining the suitability of habitats for aquatic life. The riverbed made up of variety of materials, including sand, clay, silt, and minerals, each of which supports different species of organisms. For example, certain fish species, birds, invertebrates require specific types of substrates for nesting, feeding, or growing. Rivers with sandy or clay-based beds, for instance, may

support different species compared to those with rocky or gravelly substrates. This variation in substrate types influences species distribution and behaviour, making it an important consideration when designing conservation strategies or assessing the health of a river ecosystem (Gorman & Karr, 1978; Wilhelm et al., 2005; Dauwalter et al., 2007; Moir & Pasternack, 2008, Sinha et al, 2017).

The floodplain areas surrounding rivers are also essential habitats, especially for water-associated birds. These areas are periodically inundated by the river's floodwaters, which deposit nutrients and create a variety of habitats. The floodplain acts as a dynamic, nutrient-rich landscape that supports a range of aquatic and terrestrial species. In the case of the Ganga River, its floodplain is particularly fertile, providing ample resources for agricultural activities.

Human activities, particularly the construction of physical barriers like dams and barrages, have a profound impact on river ecosystems. In the middle stretch of the Ganga River, for instance, four major barrages regulate water flow, significantly altering the river's natural dynamics. These barrages have confined the river's flow, disrupted the sediment transport processes and changed both the morphology and environmental conditions of the river. Upstream of the barrages, water flow has been altered, leading to the deposition and storage of sediments within the river channel. Downstream, the reduced water flow has resulted in the formation of braided channels and sandbars. These changes in river morphology have far-reaching implications for aquatic life, as they reduce the availability of suitable habitats and disrupt the natural flow regime that species depend on for survival.

The Ganga River's braided-meandering system (Sinha et al., 2017). The degree of meandering in the river is an important factor influencing the distribution and behaviour of species. Meanders create eddy currents—localized, circular water movements—that form calm areas where species can find food, shelter, and breeding grounds. These areas foster healthy predator-prey relationships, which are essential for maintaining the balance of the ecosystem. However, when the river's natural flow is altered due to human interventions such as water diversion and dam construction, the extent of meanders and eddy currents may be diminished, reducing the availability of these critical habitats.

Determining the appropriate environmental flow criteria for rivers is an ongoing challenge for ecologists and water resource managers. Environmental flow refers to the quantity, quality, and timing of water required to sustain the river's natural ecological functions. These needs vary depending on the species present in the river and their specific habitat requirements. For instance, different species of fish, mammals, and invertebrates have distinct needs for water depth, flow velocity, temperature, and substrate type. Maintaining these conditions is crucial for preserving biodiversity and ecosystem function. Additionally, the hydro-morphological features of the river, such as its shape, size, and flow characteristics, play a key role in determining the availability of suitable habitats for various species. Longitudinal connectivity, the ability of species to move freely along the river is another critical aspect of maintaining ecological integrity. For aquatic species, this connectivity must be maintained throughout the year, especially during periods of low flow, when the availability of water and suitable habitats may be limited. To ensure the

long-term sustainability of these vital ecosystems, it is essential to adopt a holistic approach to river management.

CHAPTER 5

ASSESSMENT OF RIVER DISCHARGE AND FLOW

5.1. Introduction

River discharge and flow are essential aspects of hydrology, defining the movement and volume of water through river systems. These components significantly influence the ecology, geography, and socio-economic conditions of riverine regions (Jin et al., 2018). The assessment of river discharge and flow is important for understanding the interaction of rivers with environment and human activities (Anderson et al., 2019). Among the world's major rivers, the Ganga River stands out because of its immense significance in the Indian subcontinent and dynamic patterns of discharge and flow. With its large drainage basin, unique geographical features, and socio-cultural significance, the Ganga River is ideal for studying river dynamics and hydrological systems. By understanding the discharge and flow characteristics of the Ganga River, we gain insights into broader themes of water resource management, flood mitigation, pollution control, and climate change adaptation.

River Discharge refers to the volume of water flowing through a river at a given point over a specific time. It is measured in cubic meters per second (m^3/s) or cumec (Gleason & Smith, 2014). Discharge is a key indicator of the river's capacity to transport water and sediment from its source to its mouth (Zakwan et al., 2021). This phenomenon is

influenced by various factors, including precipitation, snowmelt, groundwater inflow, evaporation, and human activities. Flow, on the other hand, refers to the movement of water within the river system. River flow is driven by the gradient of the riverbed or slope, volume of water, and channel characteristics (Reaney et al., 2014). Flow velocity, channel morphology, and cross-sectional area of the river also influence the speed and behaviour of water moving through the river system. These two aspects i.e., discharge and flow are intimately connected. Discharge is essentially a measure of the water moving through the river over time, while flow refers to how that water moves through the system (McCabe, 2011; Zeiringer et al., 2018). Together, they provide a comprehensive picture of a river's behaviour and its capacity to sustain aquatic ecosystems, provide water for human use, and contribute to various ecosystem services. Several natural and anthropogenic factors determine the discharge and flow patterns of rivers (Masharif et al., 2023).

- **Precipitation**

The amount, timing, and precipitation type play a major role in determining river discharge (Zeng et al., 2020; Ebode et al., 2022). Heavy rainfall during the monsoon season dramatically increases the discharge, causing rivers to swell and flood their banks. In dry seasons with minimal rainfall result in lower discharge, leading to reduced flow and potential drought conditions.

- **Snowmelt**

In mountainous regions, snow and ice serve as significant sources of water for rivers. As snow melts in warmer months, it adds to river discharge, particularly in rivers with

headwaters in glaciers (Singh et al., 2021), like the Ganga River. Snowmelt driven discharge is important in the early spring and summer months, when other sources of water remain low.

- **Groundwater contributions**

Groundwater acts as a steady, though often hidden, source of water to rivers, especially during lean period. This flow from underground aquifers is known as base flow (Pauwels et al., 2002; Pratama et al., 2020). In regions where groundwater is abundant, it helps to maintain flow in rivers even when surface runoff from rainfall is minimal.

- **Topography and River Basin Characteristics**

The topography of region surrounding a river affects both its flow and discharge. Steep mountain slopes lead to fast flowing rivers with higher velocities (Carrillo et al., 2021), while flatter landscapes tend to produce slower, meandering rivers. The catchment area or drainage basin, which refers to the area of land that collects precipitation and funnels it into the river, also plays a critical role in determining the volume of water flowing into the river.

- **Human Activity**

Human activities significantly alter both river discharge and flow. Dams, barrages, and other water storage structures regulates river flow by controlling the amount of water released downstream (Ghosh & Guchhait, 2014). Furthermore, the extraction of water for irrigation, industrial use, and urban water supply decreases river discharge, especially

during periods of high water demand (McKay & King, 2006). Additionally, pollution negatively affects water quality and flow characteristics, leading to changes in the ecosystem.

The fluvial system is important for water supply in river channels to maintain natural integrity of rivers. The impact assessment of flowing water on the riverbed, surrounding environment and the sustenance of habitat for aquatic biodiversity is important in eco-hydrology and geomorphology. The spatial distribution of geomorphological characteristics of river system governs the structure and composition of aquatic biodiversity (Belmar et al., 2019). The stress factors are forces exerted by flowing water on the river bed and bank as well. These forces are important for shaping river channels, and sediment transport. It also alters the morphology and ecology of fluvial environment. The stressors are influenced by variables, like flow which results in greater stress on the river bed, banks, depth, and parent material which differs from genesis, type and size of the sediment. The fluvial stressor dynamics is a key factor in ensuring water availability and sustainable management for addressing the Sustainable Development Goal (SDG). The alteration in fluvial attributes can modify stream habitats (Jacobson et al., 2001; Mandal et al., 2024). River flow, changes in climatic conditions, and anthropogenic pressure on rivers are major causes of Land Use Land Cover (LULC) change, which alters the river hydro-geomorphology and leads towards habitat loss for aquatic biodiversity (Dudgeon et al., 2006). Due to environmental factors, freshwater scarcity, soil structure and parent material, assessing potential habitat is a significant concern globally (Rai et al., 2022; Mishra et al., 2021).

5.1.1. Geographical and hydrological overview of the Ganga River

The Ganga River originating from the Gaumukh of Gangotri Glacier in the Himalayas, flows through the biogeographic zone namely Gangetic plain (7) and meets the Bay of Bengal at Ganga Sagar. The river flows approximately 2525 km. The Ganga River Basin is one of the largest and most densely populated river basins in the world, covering an area of approximately 8,61,404 km². It is home to more than 500 million people, making it the lifeline for a significant portion of South Asia. The basin receives water from a combination of snowmelt from the Himalayas, monsoon rainfall, and tributaries such as the Ramganga, Gomti, Gandak, Ghaghra, Kosi, Yamuna, Tamas, Sone etc. The Ganga River's flow is influenced by several factors, including its geographical features, the monsoon climate, and the snowmelt from the Himalayan glaciers. The flow regime is highly variable, showing significant fluctuations from season to season and across its length. The discharge and flow of the Ganga River are highly influenced by the seasonal variability that characterizes the climate of its basin area (Whitehead et al., 2018). The main seasons affecting river discharge are the monsoon, winter, and pre-monsoon seasons. The monsoon has a profound effect on the discharge of the Ganga River (Whitehead et al., 2018; Khan et al., 2018). During monsoon, the Ganga River receives substantial amounts of water from heavy rainfall. The monsoon rains over the Gangetic plain and snowmelt from the Himalayas lead to a marked increase in river discharge (Siderius et al., 2013). This period is marked by high flow, which results in flooding along the riverbanks. Flood during the monsoon season is a recurring phenomenon, often causing significant damage to agriculture, infrastructure, and livelihoods. However, it also

plays a natural role in replenishing groundwater reserves, nourishing floodplain ecosystems, and providing nutrients to the soil, which are essential for agricultural productivity. During the winter months and in the pre-monsoon months, the discharge of the Ganga River generally decreases (Somisetty et al., 2022). Rainfall is minimal, and the flow is sustained mainly by groundwater contributions and the melting of snow and ice from the Himalayan region. Although the discharge is lower than during the monsoon, this period is vital for agricultural activities as the river continues to provide water for irrigation. The reduced flow during this time also exposes some of the challenges posed by water scarcity in certain regions of the Ganga basin.

Human activities have significantly altered the natural flow and discharge patterns of the Ganga River (Swarnkar et al., 2021). Construction of dams, barrages, and hydroelectric power plants along the Ganga River and its tributaries has regulated river discharge, making it more predictable but also less dynamic (Sonkar & Gaurav, 2020). The dams and barrages serve important purposes such as flood control, irrigation, and power generation, they also disrupt the natural ecological balance of the river, affecting sediment transport, aquatic habitats, and biodiversity. The over-extraction of water for agriculture and industrial use has led to lower water levels in the river, particularly in areas downstream of major cities like Varanasi and Kanpur (Kumar, 2011; Maheswaran et al., 2016; Vat et al., 2019). Water scarcity is becoming an increasingly serious issue in the Ganga basin, as the demand for water grows while the river's natural discharge is altered by human intervention (Anand et al., 2018). Pollution is another significant challenge. The Ganga River has long been subjected to high levels of industrial pollution, sewage

discharge, and chemical contaminants (Chakraborty et al., 2021). While efforts have been made to clean the river under initiatives such as the Namami Gange Programme, pollution continues to pose a severe threat to water quality and public health. Contaminants from industrial effluents, untreated sewage, and agricultural runoff have degraded the river's water quality, especially in urban centres along its banks.

River discharge and flow are critical components of hydrology, influencing a river's ecological, social, and economic functions. The Ganga River provides a vivid example of how natural and human factors interact to shape the discharge and flow patterns of a major river system. The Ganga River's seasonal fluctuations, driven by monsoon rainfall, snowmelt, and groundwater contributions, underscore the complex dynamics that govern river behaviour (Sinha & Sinha, 2020). However, human activities such as dam construction, water extraction, and pollution have altered the natural discharge and flow regimes, presenting new challenges for water management, environmental protection, and the sustainable use of the river. Assessment of the discharge and flow of the Ganga River is essential for addressing the critical issues of water scarcity, flood management, pollution control and environmental flow to sustain the Ganga River and its aquatic biodiversity in the region. Given the river's central role in the lives of millions of people, a comprehensive approach to preserving its health and ensuring equitable access to its waters is essential for future generations.

5.1.2. Fluvial stressors and riverine habitat criteria

The changes in climatic conditions, deforestation, and land use changes significantly

affect river hydrology leading to alterations in river discharge, water availability, and the timing of peak flows (Hoang et al., 2020). The riparian areas experience more extreme weather events, including heavy rainfall followed by long droughts because of rising temperatures and decreased precipitation (Filho et al., 2022). Trees and vegetation regulate water flow by intercepting rainfall, promoting groundwater recharge, and reducing soil erosion. Loss of vegetation cover leads to increased surface runoff, greater sediment transport, and higher rates of soil erosion resulting in the siltation of rivers, where sediments are deposited on the riverbed altering flow patterns and ecological integrity of the river system (Zhang et al., 2014). The urbanisation along rivers and embankments also increases surface runoff which results in reduced base flows and prolonged low-water periods and flash floods. Altered snowmelt regimes in mountainous regions change the timing and volume of runoff introduced to the sink rivers, which impacts water storage, seasonal flow. The warming of glaciers has led to changes in river discharge patterns at headwaters in the Himalaya (Hasnain, 2002). The reducing flow regime increases sediment loads at the river bed which alters the shape of the river channel, water discharge, erosion rates, and floodplain dynamics. The river bed mining activity is also detrimental; uncontrolled mining leads to deeper channel, lower water tables, and loss of riparian habitat (Kondolf, 2018). The alteration of fluvial dynamics disrupts the ecosystem of conservation concerned species (Juracek & Fitzpatrick, 2022). The rapid, concentrated influx of water triggers the river systems to swell unpredictably, leading to increased flood risks and changes in river channel morphology that affect the habitats of aquatic biodiversity. Irrigation for agricultural practices along the river diverts

water from the mainstem to the canal system, which reduces the available water to downstream of barrages, lowering river discharge and altering flow patterns. Dams control flow, and regulate the discharge which alters the natural hydrological cycle. The natural flow pattern maintains longitudinal connectivity and Environmental flow (E-flow) in riverine habitat to sustain aquatic biodiversity in river system (Bower et al., 2021). The dams and barrages reduce the flow variability of rivers by regulating the seasonal peaks and troughs, which have significant ecological consequences. Aquatic biodiversity like fish, Gangetic dolphin (*Platanista gangetica*), and Gharial (*Gavialis gangeticus*) rely on seasonal flow fluctuations for migration, and habitat availability (Paudel et. al., 2020; Vashistha et al., 2021, Alam et al., 2021). The release of water from dam controls in a way that is detrimental to downstream ecosystems. Riparian vegetation and wetlands along rivers stabilize the soil, reduce erosion, and help in groundwater recharge. Wetlands act as natural buffers, filtering pollutants and absorbing excess nutrients from water (Walton et. al., 2020). Loss of riparian vegetation and wetlands due to land development, and agricultural expansion in river bed impact river systems by increasing runoff, sedimentation, and pollutant load leading to more erratic flow regimes and habitat loss for aquatic biodiversity. The Ganga River basin has an extensive alluvial plain (Sinha et al., 2017) and carries a sediment load of 356 million tonnes per year (Khan et al., 2018). The sediment remains less transported as a result of lower flow in the river and decrease in stressors like dams and barrages, closed drainage systems and changing climate, which changes the river morphology and reduces the water supply, particularly in the lean season (Zarfl & Dunn, 2022).

5.1.3. Geospatial model for multi criteria decision making

The study was carried out using Geographic Information System (GIS) and Analytical Hierarchical Process (AHP) techniques (Satty, 1980). The study assigns weights and scoring to variables based on their ecological significance leading to river zones by evaluating the model through Multi Criteria Decision Making (MCDM) analysis. Various studies use AHP for river-related decision-making scenarios like hydropower planning, water quality management and river basin restoration. Das (2025) assessed river zones for water quality management by considering pollution levels, land use, and water flow characteristics using AHP method. Ahmad & Verma (2018) identified suitable water storage sites based on GIS, and MCDM using AHP method. Achu et al., (2020) used the AHP and Remote Sensing and GIS for identifying groundwater zones with varying hydrological characteristics of river systems by considering rainfall, water flow, geological features, and land use as factors. Betz et al., (2018) delineated riparian zones in data scarce regions and indicated connectivity within riverscape. The Ganga River has been studied to understand impact of stressors in fluvial dynamics, geomorphic diversity and potential habitat of aquatic biodiversity (Rao, 2001; Sinha et al., 2017). This study is significant to monitor the impact of fluvial stress factors on river eco-hydrology and a framework for sustainable management of stressors and restore the resilience of river systems by adopting integrated approaches that account for environmental, social, and economic factors towards aquatic biodiversity conservation.

5.2. Methodology

5.2.1. Assessment of river discharge

The assessment of river discharge is important in understanding the hydrology of river systems, managing water resources, and ensuring effective flood control. River discharge, also known as streamflow, represents the volume of water flowing through a river channel over time. It is measured in cubic meters per second (m^3/s) or cumec. Accurate discharge measurements are necessary for a wide range of applications, including flood forecasting, environmental protection, hydropower generation, and water quality monitoring (Depetris, 2021). Traditionally, river discharge has been measured using methods such as flow rating curves, stream gauges, and velocity-area techniques. However, advancements in technology have led to the development of more sophisticated instruments, such as the Acoustic Doppler Current Profiler (ADCP), which offers high precision, reliability, and flexibility in assessing river discharge (Sperandelli & Gireli, 2022).

ADCP is an advanced tool that uses the principles of doppler shift to measure the velocity of water flow at various depths and locations within a river (Klema et al., 2020). ADCPs are employed to assess river discharge by providing continuous, real-time data on water velocity profiles (Coz et al., 2008). The device works by emitting sound waves that interact with suspended particles, such as sediment or bubbles, moving with the water current. These particles scatter the sound waves, and the Doppler shift in the frequency of the returned signal is used to calculate the velocity of the particles. By measuring the velocity at different depths and cross-sectional locations of the river, the ADCP

determines the flow rate or discharge across a river profile (Gordon, 1989; Sassi et al., 2011). A typical ADCP consists of multiple transducers arranged in a circular or linear configuration. The transducers emit high-frequency sound waves that travel through the water and reflect off moving particles (Dunn & Zedel, 2022). The frequency shift in the reflected sound waves is proportional to the velocity of the particles, which in turn represents the velocity of the water at specific depths. Most ADCPs operate at a frequency range of 1 to 2 MHz, with higher frequencies being more suitable for shallow rivers, while lower frequencies are better for deeper water bodies. One of the key advantages of using an ADCP to assess river discharge is its ability to measure water velocity profiles across a wide range of depths. Traditional methods such as electromagnetic sensors or velocity-area techniques are often limited to shallow depths and require time-consuming measurements of velocity at discrete points across the river channel. In contrast, ADCPs capture velocity data across the entire cross-section of the river in a single deployment, providing a comprehensive and continuous assessment of the river's flow dynamics (Dinehart & Burau, 2005).

To calculate river discharge using an ADCP, the device typically operates in a 'streamwise' or 'transversal' measurement mode. The ADCP is positioned perpendicular to the river's flow direction in streamwise mode. The transducers are placed either vertically or angled in the direction of the flow, allowing them to measure the water velocity at various depths and across different vertical layers. In transversal mode, the ADCP is deployed along the riverbank or across the river channel, providing velocity measurements across different sections of the river cross-profile. These measurements are

then integrated over the entire cross-sectional area to compute the total discharge. The accurate discharge estimation using an ADCP lies in the ability to measure the velocity at multiple depths (Kim et al., 2015). By dividing the river cross-section into a grid of small vertical segments, the velocity data gathered from the ADCP is integrated into a series of velocity-depth profiles, and multiplied by the cross-sectional area of each segment to estimate the total discharge. The formula for calculating discharge (Q) using ADCP data is as follows,

$$Q = \sum (V_i \times A_i)$$

Where:

Q is the river discharge,

V_i is the average velocity at depth segment

A_i is the cross-sectional area of the segment

This approach provides a more accurate representation of river flow dynamics compared to traditional methods, especially in areas with complex flow patterns, such as braided rivers, meandering streams, or channels with substantial turbulence. The flexibility of ADCP also allows for measurements in both open water and in environments with challenging access, such as under bridges, within culverts, or in remote river sections (Vermeulen et al., 2014). The ADCP's non-contact nature is another significant advantage. Moreover, the ability of ADCPs to provide real-time data is invaluable for continuous monitoring, enabling operators to respond promptly to changes in river discharge, such as those that occur during flood events. Despite these advantages, the use

of ADCPs to assess river discharge is not without its challenges. One limitation is the requirement for appropriate calibration and the consideration of environmental factors that can affect the accuracy of measurements. For instance, suspended sediment concentrations, water temperature, and salinity can influence the wave propagation and the Doppler shift, leading to potential errors in velocity measurements (Elci et al., 2009). In addition, the complexity of flow conditions, such as turbulent flows or areas with strong lateral shear, can make it more difficult to obtain accurate velocity profiles. To address these issues, it is essential to deploy ADCPs in conjunction with other complementary monitoring methods, such as stream gauging stations or remote sensing technologies, to validate and cross-check results. Additionally, while ADCPs provide highly detailed velocity measurements, they are less effective in very shallow or low-velocity areas where suspended particles may be scarce (Stansbury et al., 2002). In these instances, alternative methods, such as electromagnetic sensors or acoustic Doppler velocimeters (ADV), may be more appropriate. In very shallow rivers, the vertical range of the ADCP may also be limited, requiring the use of low-frequency transducers or different techniques to assess discharge (Stone & Hotchkiss, 2007). Another consideration is the cost and expertise required to deploy and interpret ADCP measurements. While ADCP technology has become more affordable in recent years. Despite these challenges, ADCPs remain a valuable tool for assessing river discharge, especially in large or complex river systems. The sampling was conducted at 21 selected sites depending on the upstream of barrages, downstream of barrages, tributaries, upstream of tributary confluences and downstream of tributary confluences (Table 5.1).

Table 5.1. Sampling sites of river discharge

State	Sampling Site	Sites	Site importance	Longitude	Latitude
Uttarakhand	1	Ghat No. 1, Haridwar	Upstream Bhimgoda barrage, Haridwar	78.1853	29.9719
	2	Haridwar-Bijnor bridge, Haridwar	Downstream Bhimgoda barrage, Haridwar	78.1618	29.9431
	3	Shimla Kalan, Bijnor	Upstream Madhya Ganga barrage, Bijnor	78.0571	29.5165
Uttar Pradesh	4	Jalalpur, Bijnor	Downstream Madhya Ganga barrage, Bijnor	78.0947	29.3261
	5	Tigri Ghat - Garhmukteshwar	Ramsar site	78.1530	28.8278
	6	Ghat No. 5, Narora	Upstream Charan Singh barrage, Narora	78.3738	28.2276
	7	Deramile, Narora	Downstream Charan Singh barrage, Narora	78.4036	28.1774
	8	Panchalghat, Farrukhabad	Upstream Ramganga River (Tributary) confluence	79.6291	27.3966
	9	Kusumkhor	Ramganga River (Tributary) confluence	79.8455	27.1773
	10	D/s Kusumkhor	Downstream Ramganga River (Tributary) confluence	79.8615	27.1701
	11	Kalasanpur, Kannauj	Downstream major town	79.9948	27.0017

12	Rautapur, Kanpur	Upstream Luv Kush barrage, Kanpur	80.3017	26.5696
13	Parmat Ghat, Kanpur	Downstream Luv Kush barrage, Kanpur	80.3443	26.4873
14	Phaphamau	Upstream Yamunaa River (Tributary) confluence	81.8804	25.5111
15	Prayagraj	Yamuna River (Tributary) confluence	81.8731	25.4297
16	D/s Prayagraj	Downstream Yamunaa River (Tributary) confluence and Upstream Tamas River (Tributary) confluence	82.0787	25.2849
17	Sirsa	Tamas River (Tributary) confluence	82.0757	25.2744
18	D/s Sirsa	Downstream Tamas River (Tributary) confluence	82.0992	25.2673
19	Rajghat, Varanasi	Major town and Upstream Gomti River (Tributary) confluence	83.0439	25.3289
20	Kaithi, Varanasi	Gomti River (Tributary) confluence	83.1655	25.5070
21	D/s Kaithi, Varanasi	Downstream Gomti River (Tributary) confluence	83.1719	25.5121

5.2.2. Interaction of physical barriers and river discharge

Simulation of river discharge is a critical aspect of hydrology and water resources management. It involves the use of mathematical models and computational tools to estimate the flow of water through a river system under varying conditions. The accurate simulation of river discharge is essential for managing water resources, predicting floods, designing hydraulic structures, monitoring environmental changes, and assessing the impact of land use changes (Rao et al., 2020; Iqbal et al., 2022; Yoon et al., 2023). Over the past few decades, advancements in computational technology, hydrological models, and data acquisition techniques have significantly improved the accuracy and reliability of river discharge simulations. These simulations use physical principles, empirical observations, and numerical methods to model the complex interactions between precipitation, land surface characteristics, river channels, and atmospheric conditions (Williams et al., 2013).

At its core, river discharge simulation is based on the principles of hydrology, which is the study of water movement within the Earth's atmosphere, rivers, and watersheds. To simulate discharge, it is essential to understand the hydrological processes involved, including precipitation, infiltration, evaporation, runoff, and channel flow (Fernández-Pato et al., 2016). Rainfall events, for example, generate surface runoff that flows over the land surface and eventually reaches the river. The river channel then conveys this runoff downstream, contributing to the river's discharge. Factors such as soil permeability, vegetation cover, and land use influence how much of the precipitation will

infiltrate into the soil or run off into the river (He et al., 2020). In addition, the river's flow characteristics, such as its width, depth, slope, and roughness, affect the discharge and its variation over time (Gaurav et al., 2017; Pelletier, 2010). The simulation of river discharge is typically carried out using hydrological and hydraulic models. These models vary in complexity, ranging from simple empirical equations to sophisticated, physically-based numerical models. Hydrological models are primarily concerned with the catchment or watershed scale, where rainfall and runoff processes are simulated to estimate how water flows from the land surface into the river system (Anand et al., 2018). Hydraulic models, on the other hand, focus on the river channel itself, simulating how water moves through the river and interacts with channel geometry, flow resistance, and boundary conditions. One of the simplest and most widely used approaches for river discharge simulation is the conceptual hydrological model, which approximates the hydrological processes using simplified representations. These models often divide the watershed into sub-catchments and estimate runoff based on rainfall, land use, and soil properties (Wen et al., 2021). Some commonly used conceptual models include the Rational Method, the SCS Curve Number method, and the Tank Model. These models are relatively easy to implement and provide quick estimates of river discharge for small to medium-sized catchments. However, they may not account for complex physical processes in large, heterogeneous watersheds or rivers with intricate flow dynamics. Physically-based distributed models, such as the SWAT (Soil and Water Assessment Tool) and HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System), are used in many studies. These models simulate water movement across a landscape,

dividing the watershed into smaller grid cells or sub-basins (Rathjens et al., 2015). By accounting for factors such as soil moisture, land cover, topography, and precipitation, these models provide more accurate and spatially distributed estimates of runoff and discharge. In addition, distributed models allow for the simulation of different types of land use and management practices, making them useful for assessing the impact of urbanization, agriculture, and climate change on river discharge. In contrast, hydraulic models are used to simulate how water moves through the river channel itself (Randle, 2020). These models typically solve the governing equations of fluid dynamics, such as the Saint-Venant equations, which describe the conservation of mass and momentum in an open channel flow (Roohi et al., 2020). Hydraulic models can be one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D), depending on the level of complexity required. One-dimensional models, such as HEC-RAS (Hydrologic Engineering Center's River Analysis System), are commonly used for simulating river discharge in relatively simple, straight river channels (Hodges, 2018). These models calculate the flow rate and water surface elevation at multiple cross-sections along the river, using flow continuity and energy equations. In more complex river systems with meanders, floodplains, or varying flow conditions, two-dimensional and three-dimensional hydraulic models are employed. These models provide a detailed representation of the river flow in both the horizontal and vertical directions (Tamiru & Dinka, 2021). 2D models simulate flow dynamics in the plane of the river cross-section, capturing lateral variations in velocity and discharge. 3D models, such as Delft3D, extend this approach by simulating flow dynamics in the vertical direction as well, allowing for

a more accurate representation of turbulent mixing and velocity distributions in complex river systems. These models are computationally demanding but are valuable for accurately simulating discharge in large rivers or areas with intricate flow patterns, such as river confluences, deltas, and coastal regions. The process of simulating river discharge is not only about modeling the flow of water but also requires the integration of various data sources (Zhang et al., 2024). Rainfall data, streamflow measurements, meteorological observations, and satellite imagery are commonly used to drive and validate river discharge simulations. Meteorological data, such as precipitation, temperature, and wind speed, are often used as inputs to hydrological models, while river discharge measurements at gauging stations are used to calibrate and validate the model outputs (Zakwan & Ahmad, 2021). Calibration involves adjusting model parameters to ensure that the simulation results match observed discharge values under historical or real-time conditions. Validation is the process of testing the model's accuracy by comparing its predictions against independent measurements of river discharge at different locations or times. In addition to using traditional hydrological and hydraulic models, river discharge simulation can also benefit from the incorporation of remote sensing technologies (Pôssa et al., 2020), such as radar, satellite-based measurements, and unmanned aerial vehicles (UAVs). These technologies provide real-time or near-real-time data on river surface elevation, velocity, and discharge, which can be integrated with model simulations to improve accuracy and resolution. For example, satellite altimetry can measure river surface elevation, while UAVs can capture high-resolution images of river channels, providing valuable information on cross-sectional geometry and flow

conditions. Remote sensing can also aid in monitoring changes in land use, vegetation cover, and watershed dynamics, providing additional data for model input and calibration. The simulation of river discharge is not only important for short-term applications, such as flood forecasting and water quality monitoring but also for long-term planning and management (Swarnkar et al., 2021). By simulating future scenarios, such as climate change, land use changes, or infrastructure development, hydrologists can assess the potential impact of these factors on river discharge patterns. For instance, simulations predict how changing precipitation patterns due to climate change might affect river flow, or how the construction of dams, levees, or reservoirs will alter discharge and flood regimes. These long-term simulations are essential for informing water resource management decisions, such as reservoir operation, flood control measures, and ecological conservation strategies (Nale et al., 2017; Singh & Singh, 2020). Despite significant advances in river discharge simulation, challenges remain in ensuring model accuracy and reliability. Many models still struggle with accurately representing complex hydrological processes, such as evapotranspiration, groundwater flow, and surface-water interactions. Additionally, the availability and quality of data can limit the effectiveness of simulations, especially in remote or under-monitored regions. Nonetheless, the continuous development of modelling techniques, improved data acquisition methods, and enhanced computational power promise to improve the accuracy and applicability of river discharge simulations in the future.

Dams and barrages are constructed on rivers for irrigation, hydropower, flood mitigation to achieve needs of growing human population, but assessment of flowing water on the

riverbed, surrounding environment and the sustenance of habitat for aquatic biodiversity is important in eco-hydrology and geomorphology (Palmer & Ruhí, 2019). Continuous water supply in river channels are important to maintain natural integrity and habitat connectivity of rivers for sustenance of aquatic biodiversity in river system. The immediate effects of barrages on river habitats is the alteration of the river morphology and natural flow regime by regulating the water passing through the river system, leading to a more artificial water scenario that often fails to mimic the river's natural variability. Aquatic species that depend on specific river conditions face disruptions in their life cycles, resulting to the population decline. The construction of barrage leads to creation of artificial reservoirs at upstream, which significantly alters the physical characteristics of the riverine habitat. This difference between upstream and downstream condition in the Ganga River have artificially formed sandbars, river islands and fragmented deep pools. In this study, the Acoustic Doppler Current Profiler (ADCP) is used to continuously characterize river width, depth and discharge to reciprocate the habitat availability for aquatic species in the Ganga River (Muste et al., 2004; Hoitink et al., 2009). Barrages restricts migration of aquatic biodiversity from upstream to downstream of barrages leading to population fragmentation and species loss in future. Barrage construction creates an impassable barrier, preventing species from reaching their breeding or feeding grounds. Though the presence of fish ladder in few barrages, these systems are often not entirely effective and cannot support large size species like Gangetic dolphin (*Platanista gangetica*), Gharial (*Gavialis gangeticus*). Sediment transport also have profound impact on river habitats. Rivers naturally carry sediment downstream, which helps maintain the

riverbed and creates diverse habitats such as sandbars, mudflats, and wetlands. The construction of a barrage traps sediment in the reservoir leading to riverbed erosion and loss of habitat for species. In the long term, the ecological consequences of barrages extend beyond the river itself, affecting the surrounding riverscape which is habitat for water associated avian fauna and odonates in surrounding floodplains, wetlands, and riparian zones. We conducted the study at the four barrages in middle Ganga River using geospatial techniques to monitor comparative river pattern at upstream and downstream of the barriers. Rolls et al., 2013 suggested that physical barriers alter the structure, size, and distribution of species populations, leading to impacts on aquatic biodiversity. In another study by Branco et al., 2014 it is suggested dam construction on the Tagus River led to a 484 - 544% reduction in fish connectivity. The barriers like dams disrupts macrophyte dispersal and compromise their distribution and persistence (Jones et al., 2020). This study is significant to monitor the impact of barrages and tributary confluences on aquatic habitat and a framework for sustainable management of natural connectivity in aquatic habitat towards conservation of aquatic biodiversity (Figure 5.1).

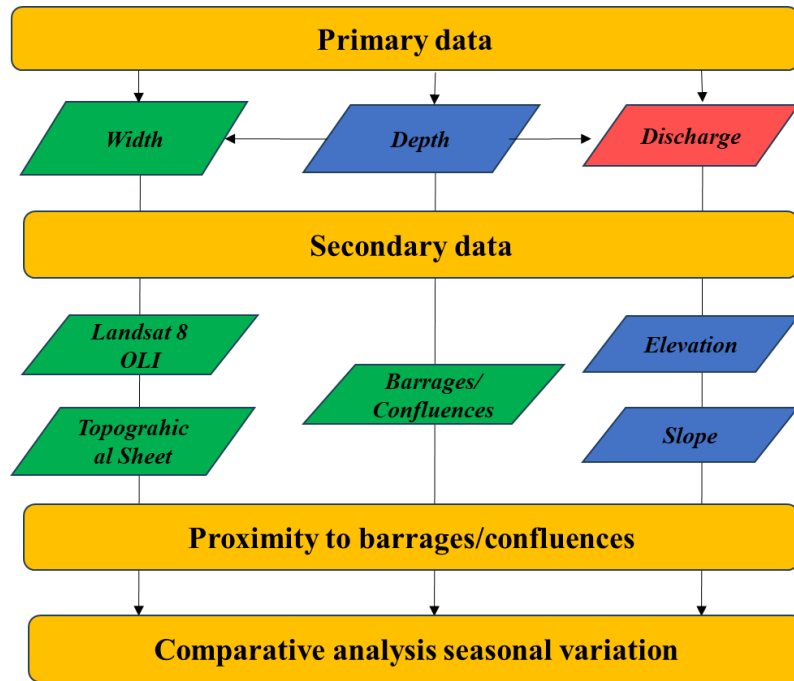


Figure 5.1. Methodology flow chart of river discharge

5.2.3. Assessment of fluvial stressors and potential habitat area

The study was carried out using the GIS and AHP to undergo MCDM analysis (Achu et al., 2020; Canco, 2021). The GIS technique was used for delineating the boundary of the river belt and the floodplain by channel width and proximity to river bank. Physical, environmental and anthropogenic factors governing as stressors to the fluvial system were derived from multiple sources and harmonised the factors to 30 m spatial resolution. AHP technique was used moreover relating with the MCDM process to classify the continuous variable and providing specific weight and rank (Figure 5.2).

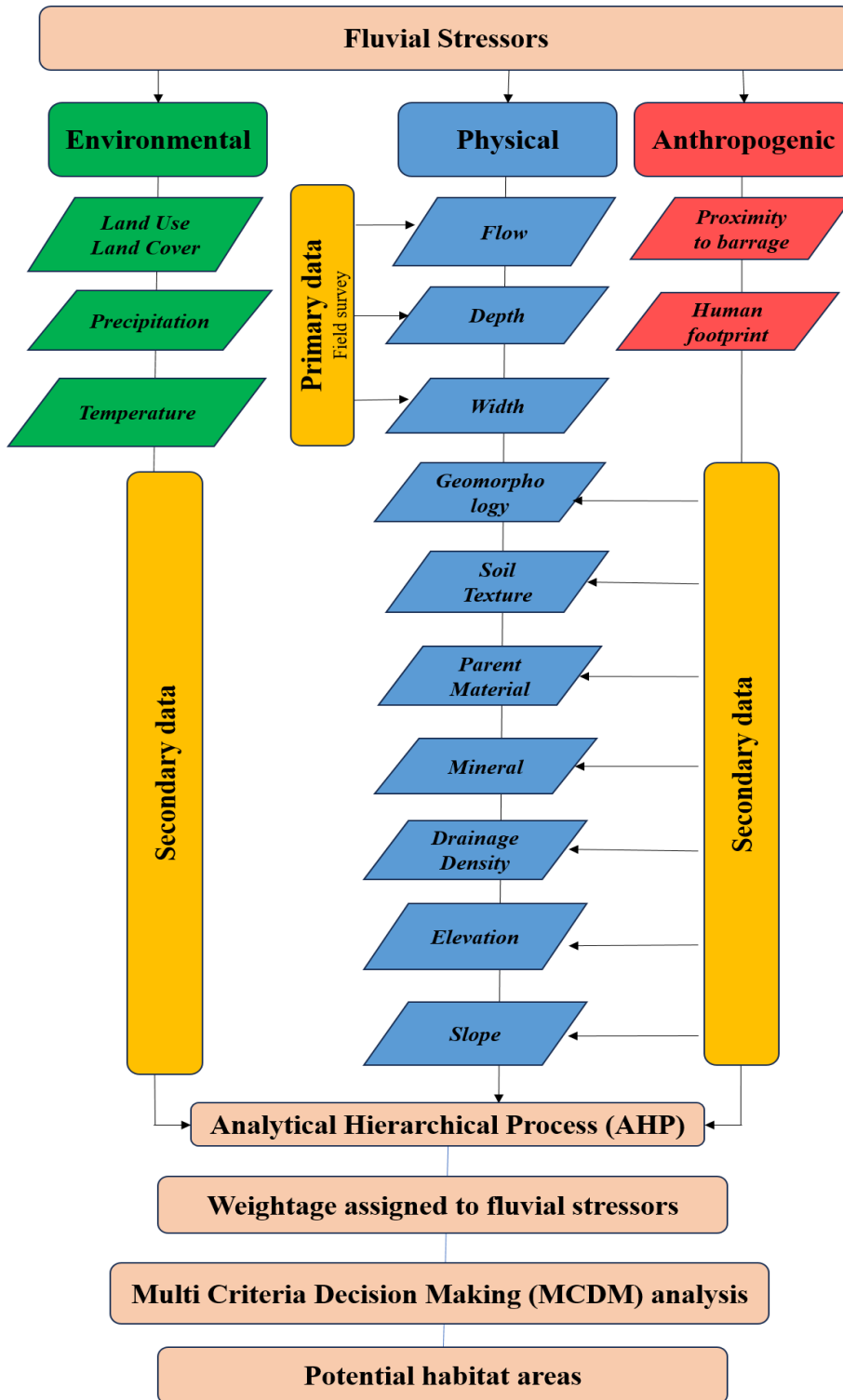


Figure 5.2. Methodology flow chart of potential habitat area

The Survey of India topographical sheets (Table 5.2) were used for study area delineation, Land Use Land Cover (LULC) was derived from the Landsat 8 OLI satellite image (Table 5.3), flow, depth, width and proximity to barrages were measured at field site which were further classified by reclassification method in ArcGIS 10.6.1 software. Physical earth features of geomorphology, soil texture, parent material and mineral were derived from the Bhoomi portal by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Government of India (GoI). Elevation, slope and drainage density were derived from the Advanced Land Observing Satellite (ALOS) Digital Elevation Model (DEM) by the Japan Aerospace Exploration Agency (JAXA). Precipitation and Temperature were derived from Worldclim, Human footprint were derived from Earthdata portal by the National Aeronautics and Space Administration (NASA) (Table 5.4).

Table 5.2. List of topographical sheets

Source	Topographical Sheet Number
Survey of India (SOI), Government of India	53J04 53K01 53K05 53G14 53K02 53K06 53G15 53K03 53G16 53K04 53H13 53L01 53L05 53L02 53L06 53L03 53L07 53L08 53L12 53L16 54I09 54I13 54M01 54M05 54M09 54I14 54M02 54M06 54M10 54M14 54M07 54M11 54M15 63A03 54M12 54M16 63A04 54N13 63B01 63B05 63B02 63B06 63B10 63B03 63B07 63B11 63B08 63B12 63B16 63F04 63F08 63C13 63G01 63G05 63O02 63G06 63G10 63G14 63O07 63O03 63K15 63K11 63G11 63K07 63G15 63K03 63O04 63K16 63K12 63K08 63K04

Table 5.3. Satellite images used to derive Land Use Land Cover classes

Satellite	Path/Row	Date	Resolution	Source
Landsat 8 OLI	144/041	08.03.2023	30 m	https://earthexplorer.usgs.gov
	144/042	08.03.2023		
	146/039	06.03.2023		
	146/040	06.03.2023		
	142/042	02.03.2023		
	142/043	02.03.2023		
	143/042	01.03.2023		
	145/041	15.03.2023		

Table 5.4. List of variables

Serial No.	Variables	Source
1	Flow (m ³ /s)	Measured at field site
2	Depth (m)	Measured at field site
3	Width (m)	Measured at field site
4	Precipitation (mm)	Derived from Worldclim (https://www.worldclim.org/data/monthlywth.html)
5	Land Use Land Cover	Derived from Landsat 8 OLI satellite image from Landsat 8 OLI (https://earthexplorer.usgs.gov)
6	Geomorphology	Derived from Bhoomi portal, NBSS&LUP, GoI (https://www.bhoomigeoportal-nbsslup.in/)
7	Soil texture	Derived from Bhoomi portal, NBSS&LUP, GoI (https://www.bhoomigeoportal-nbsslup.in/)
8	Parent material	Derived from Bhoomi portal, NBSS&LUP, GoI (https://www.bhoomigeoportal-nbsslup.in/)
9	Mineral	Derived from Bhoomi portal, NBSS&LUP, GoI (https://www.bhoomigeoportal-nbsslup.in/)

10	Drainage density (km/km ²)	Derived from ALOS DEM (https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm)
11	Elevation (m)	Derived from ALOS DEM (https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm)
12	Slope (degree)	Derived from ALOS DEM (https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm)
13	Proximity to barrage (km)	Measured at field site
14	Human footprint	Derived from Earthdata, NASA and Socioeconomic Data and Applications Center (SEDAC) (https://earthdata.nasa.gov/data/catalog/sedac-ciesin-sedac-lwp2-hf-geog-2.00)
15	Temperature (°C)	Derived from Worldclim (https://www.worldclim.org/data/monthlywth.html)

5.2.4. Multi Criteria Decision Making using Geographical Information System

Multi Criteria Decision Making (MCDM) using Analytical Hierarchical Process (AHP) in combination with Geographical Information Systems (GIS) is a widely used approach for delineating potential wildlife habitats (Sinha, 2020). Spatial decision support system, and evaluation of multi criteria factors to address aquatic systems is a globally accepted approach (Rousta & Araghinejad, 2015). MCDM is a Decision Support System (DSS) that integrates environmental, physical, anthropogenic and socioeconomic factors in a single framework. The DSS supports spatial visualization and analysis of these criteria to provide a comprehensive understanding about the geo-physical, hydrological and biological variables involved all together. GIS technique overlays multiple layers derived

from these factors enabling the spatial correlation and identification of suitable areas based on multiple objectives. This integrated approach is widely used in urban planning, environmental management, land suitability analysis, and resource allocation (Malczewski, 2006). Various thematic layers (n=15) were considered for this study. These thematic layers are the stress factors to maintain hydrological balance, natural flow, and storage of water in the MGR area. Combining these controlling factors are weighted according to their influence on fluvial morphology and biodiversity occurrence. A parameter with high weight and rank depicts its high control over the aquatic system, whereas parameters with low weight showcase the lesser impact on potential areas for species restoration. The weightages of each factor were assigned according to Saaty's scale (1–9) of relative importance value (Saaty, 1990) with consideration of reference studies and field experience. The Saaty's scale of relative importance value reveals that value of 9 indicates primary importance, 8 very strong, 7 very to extreme importance, 6 strong plus, 5 strong importance, 4 moderate plus, 3 moderate importance, 2 weak and 1 equal importance (Arulbalaji et. al., 2019). Every factor has been compared with each other in a pairwise comparison matrix (Table 5.5). The continuous parameters were reclassified using ArcGIS 10.6.1 software for assigning weight.

Table 5.5. Pairwise comparison matrix

Parameter	Assigned Weight	FL	DP	WD	PP	LU	GM	SL	PM	MN	DD	EV	SL	PB	HF	TM	Geometric Mean	Normalized Weight
FL	9	1.000	1.000	1.000	1.125	1.125	1.286	1.286	1.286	1.286	1.500	1.500	1.500	1.800	2.250	3.000	1.391	0.089
DP	9	1.000	1.000	1.000	1.125	1.125	1.286	1.286	1.286	1.286	1.500	1.500	1.500	1.800	2.250	3.000	1.391	0.089
WD	9	1.000	1.000	1.000	1.125	1.125	1.286	1.286	1.286	1.286	1.500	1.500	1.500	1.800	2.250	3.000	1.391	0.089
PP	8	0.889	0.889	0.889	1.000	1.000	1.143	1.143	1.143	1.143	1.333	1.333	1.333	1.600	2.000	2.667	1.237	0.079
LU	8	0.889	0.889	0.889	1.000	1.000	1.143	1.143	1.143	1.143	1.333	1.333	1.333	1.600	2.000	2.667	1.237	0.079
GM	7	0.778	0.778	0.778	0.875	0.875	1.000	1.000	1.000	1.000	1.167	1.167	1.167	1.400	1.750	2.333	1.082	0.069
SL	7	0.778	0.778	0.778	0.875	0.875	1.000	1.000	1.000	1.000	1.167	1.167	1.167	1.400	1.750	2.333	1.082	0.069
PM	7	0.778	0.778	0.778	0.875	0.875	1.000	1.000	1.000	1.000	1.167	1.167	1.167	1.400	1.750	2.333	1.082	0.069
MN	7	0.778	0.778	0.778	0.875	0.875	1.000	1.000	1.000	1.000	1.167	1.167	1.167	1.400	1.750	2.333	1.082	0.069
DD	6	0.667	0.667	0.667	0.750	0.750	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.200	1.500	2.000	0.928	0.059
EV	6	0.667	0.667	0.667	0.750	0.750	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.200	1.500	2.000	0.928	0.059
SL	6	0.667	0.667	0.667	0.750	0.750	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.200	1.500	2.000	0.928	0.059
PB	5	0.556	0.556	0.556	0.625	0.625	0.714	0.714	0.714	0.714	0.833	0.833	0.833	1.000	1.250	1.667	0.773	0.050
HF	4	0.444	0.444	0.444	0.500	0.500	0.571	0.571	0.571	0.571	0.667	0.667	0.667	0.800	1.000	1.333	0.618	0.040
TM	3	0.333	0.333	0.333	0.375	0.375	0.429	0.429	0.429	0.429	0.500	0.500	0.500	0.600	0.750	1.000	0.464	0.030

FL = Flow, DP = Depth, WD = Width, PP = Precipitation, LU = Land Use Land Cover, GM = Geomorphology, SL = Soil texture, PM = Parent material, MN = Mineral, DD = Drainage density, EV = Elevation, SL = Slope, PB = Proximity to barrage, HF = Human footprint, TM = Temperature.

The consistency ratio (CR) was calculated by computing, Principal Eigen value (λ) and Consistency Index (CI) (Equation 1 & Equation 2).

$$\lambda_{\max} = \Sigma_{\text{Geometric Mean}} = 15.614 \quad (1)$$

$$CI = (\lambda_{\max} - n) / (n - 1) \quad (2)$$

where n=15 is the number of factors used in the analysis.

$$CI = (15.614 - 15) / (15 - 1) = 0.0439$$

Consistency Ratio is defined as the ratio of the Consistency Index (CI) to the Random Consistency Index (RCI) (Equation 3).

$$CR = CI/RCI = 0.0439/1.59 = 0.0276 \quad (3)$$

RCI values were obtained from the Saaty's standard (Table 5.6)

Table 5.6. Saaty's standard

The consistency indices of randomly generated reciprocal matrices															
Order of the matrix															
N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RCI value	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

CR of 0.10 or less is acceptable to continue the analysis (Saaty, 1990). We obtained the CR value 0.0276. The CR value equal to 0 shows the perfect level of consistency in pairwise comparison. The threshold value has not exceeded 0.1, which means the judgment matrix is reasonably consistent. All the 15 layers of factors were integrated with the Weighted Overlay Analysis (WOL) method in ArcGIS 10.6.1 for potential habitat areas estimation (Equation 4).

The assigned rank and weights to the thematic layers are listed in Table 5.7.

$$\text{Potential Habitat Area} = \sum (X_i \times Y_i) \quad (4)$$

Table 5.7. Categorisation of factors influencing potential habitat areas

Weightage Category	Factor	Assigned weight (X)	Class Name	Rank (Y)
1	Flow (m ³ /s)	9	≤ 220	4
			221 to 300	6
			301 to 350	6
			351 to 400	7
			401 to 450	8
			451 to 500	9
			> 500	9
2	Depth (m)	9	≤ 4	3
			5 to 7	6
			8 to 10	7
			11 to 14	8
			15 to 17	8
			18 to 20	9
			> 20	9
3	Width (m)	9	≤ 200	5
			201 to 250	6
			251 to 300	7
			301 to 350	8
			351 to 400	9
			> 400	9

4	Precipitation (mm)	8	≤ 950	3
			951 to 1000	4
			1001 to 1200	6
			1201 to 1500	8
			> 1500	9
5	Land Use Land Cover	8	Sandbar	8
			Island	8
			River	9
			Barrenland	2
			Waterbody	8
			Agriculture	2
			Builtup	1
			Forest	7
			Grassland	7
6	Geomorphology	7	Flood Plain	8
			Waterbody	9
			Alluvial Plain	8
			River	9
			Pediment Pediplain Complex	7
			Dam and Reservoir	4
			Moderately Dissected Plateau	6
			Highly Dissected Hills and Valleys	5
			Moderately Dissected Hills and Valleys	5
7	Soil texture	7	Loamy Skeletal	5
			Loamy	7
			Sandy	9
			Clayey	8

8	Parent material	7	Colluvium	6
			Alluvium	9
			Sandstone	7
9	Mineral composition	7	Smectite Mixed Mineral	6
			Illite Mineral	8
			Montmorillonite	4
10	Drainage density (km/km ²)	6	≤ 0.8	6
			0.9 to 1.0	7
			1.1 to 1.2	7
			1.3 to 1.5	8
			> 1.5	9
11	Elevation (m)	6	≤ 50	9
			51 to 100	9
			101 to 150	8
			151 to 200	7
			201 to 250	7
			251 to 300	6
			301 to 400	5
			> 400	4
12	Slope (degree)	6	≤ 0.5	9
			0.6 to 1	8
			1.1 to 2	7
			2.1 to 3	7
			3.1 to 4	6
			4.1 to 5	6
			> 5	3
13	Proximity to barrage (km)	5	≤ 20	3
			21 to 50	5
			51 to 100	6

			101 to 200	8
			> 200	9
14	Human footprint	4	≤ 30	9
			31 to 40	7
			41 to 60	5
			61 to 80	3
			> 80	2
15	Temperature (°C)	3	≤ 24	5
			24.1 to 25	6
			25.1 to 26	7
			> 26	8

5.3. Result

5.3.1. Existing discharge

The existing discharge measured at the selected sampling sites at strategic locations in MGR. The river discharge and covariates like depth and width were measured for the year 2018, 2019 and 2020 with seasonal replicates. The discharge and covariates in year 2018 (May-June and November-December) is listed in Table 5.8. Discharge and covariates in year 2019 (January-February and March-April) is listed in Table 5.9 and 2019 (May-June and November-December) is listed in Table 5.10 and 2020 (January-February) is listed in Table 5.11. The season May-June 2018, March-April, 2019 and May-June 2019 are considered as the pre monsoon season, whereas, the November-December 2018, January-February 2019, November-December 2019, January-February 2020 are considered as the post monsoon season. The seasonally comparative mean discharge is listed in Table 5.12, mean depth is listed in Table 5.13, and mean width is listed in Table 5.14. The discharge is highly correlated factor with depth and width of the river (Eggleston et al., 2024). It is observed also from this study that the discharge of the MGR is in an increasing trend with increasing depth and width. The river morphology changes in the monsoon season with availability of water in river. The post monsoon scenario of the Ganga River changed the river hydro-geomorphological features (Anand et al., 2018). The sandbars, river braids, small islands were submerged due to high water volume and the fragmented river stretches were connected to a single channel. This phenomenon promotes the river to achieve its free-flowing characteristics and allows the aquatic biodiversity to forage in

their habitat freely. The dams and barrages play detrimental role in the water allocation at upstream and downstream of the barrages, which restricts the species movement.

Table 5.8. Discharge and covariates in May-June and November-December 2018

May- June 2018	Discharge (m³/s)	Depth (m)	Width (m)	November- December 2018	Discharge (m³/s)	Depth (m)	Width (m)
1	329.570	5.558	145.945	1	293.263	6.436	87.521
2	18.044	3.688	58.861	2	36.888	5.690	46.085
3	34.671	2.447	87.027	3	37.066	1.758	65.943
4	43.554	1.514	129.194	4	65.771	3.213	185.175
5	82.403	1.651	81.430	5	43.517	1.409	80.545
6	128.668	9.102	479.052	6	107.619	2.924	461.243
7	25.433	4.149	68.959	7	59.574	9.920	166.376
8	23.300	1.378	138.936	8	80.109	2.563	218.575
9	9.943	0.670	127.482	9	70.087	1.720	114.584
10	34.071	3.815	319.470	10	150.763	2.845	97.257
11	20.678	2.177	82.825	11	212.715	6.427	144.243
12	39.118	4.176	313.249	12	265.415	11.244	186.707
13	31.638	1.843	266.775	13	252.641	2.678	223.777
14	33.562	2.741	295.247	14	242.793	5.750	232.744
15	42.682	5.571	318.562	15	232.592	13.927	673.698
16	51.028	16.337	242.263	16	446.079	6.885	175.672
17	72.842	14.648	254.745	17	475.552	7.291	197.353
18	94.727	10.272	68.096	18	597.806	10.178	367.772
19	134.540	12.222	415.086	19	660.123	10.604	545.248
20	16.805	2.038	29.647	20	31.197	1.960	102.226
21	121.027	4.379	638.810	21	694.952	9.838	631.001

Table 5.9. Discharge and covariates in January-February and March-April 2019

January- February 2019	Discharge (m³/s)	Depth (m)	Width (m)	March- April 2019	Discharge (m³/s)	Depth (m)	Width (m)
1	291.603	7.458	171.195	1	418.209	8.022	155.140
2	109.976	2.313	125.963	2	71.759	5.010	67.137
3	141.870	3.391	201.654	3	116.405	2.473	108.968
4	218.216	3.006	198.764	4	142.427	2.542	176.131
5	242.658	4.374	227.854	5	132.310	2.663	314.065
z6	329.413	2.957	466.850	6	220.571	3.273	463.172
7	166.918	10.138	162.619	7	33.728	9.465	167.087
8	154.274	5.374	159.277	8	34.505	1.429	132.399
9	49.075	1.740	185.271	9	34.870	1.253	158.196
10	187.656	3.180	142.346	10	75.858	2.986	138.093
11	244.139	4.590	277.965	11	99.782	1.638	239.919
12	257.456	9.027	250.797	12	117.544	8.873	252.188
13	236.756	2.710	226.457	13	109.559	2.608	210.699
14	209.798	3.253	280.046	14	146.842	3.622	133.084
15	276.937	4.163	277.366	15	172.145	14.717	567.352
16	353.168	5.143	160.362	16	288.534	3.918	186.323
17	35.906	4.468	153.194	17	49.990	3.933	148.807
18	431.033	9.545	361.471	18	344.983	8.710	355.737
19	471.282	20.028	396.130	19	366.976	19.972	397.683
20	485.467	8.558	364.752	20	76.578	1.797	97.901
21	555.060	7.953	510.760	21	460.186	8.770	592.645

Table 5.10. Discharge and covariates in May-June and November-December 2019

May- June 2019	Discharge (m³/s)	Depth (m)	Width (m)	November- December 2019	Discharge (m³/s)	Depth (m)	Width (m)
1	550.191	7.833	161.529	1	358.242	8.220	161.573
2	88.119	1.865	93.593	2	30.540	2.197	191.569
3	173.437	2.849	89.497	3	95.193	1.776	209.678
4	162.562	2.400	203.472	4	107.274	1.610	213.121
5	109.590	2.578	214.490	5	128.439	2.217	141.309
6	230.544	3.147	463.585	6	179.343	5.822	565.317
7	29.837	9.052	162.656	7	129.846	5.048	186.249
8	45.175	2.687	85.597	8	122.514	3.055	167.239
9	6.070	2.434	117.775	9	39.613	1.031	106.463
10	52.704	2.359	71.264	10	158.731	4.381	214.160
11	72.335	3.165	126.912	11	224.729	6.875	109.203
12	87.169	7.130	337.563	12	245.826	7.251	336.959
13	80.669	2.595	203.971	13	210.237	3.148	288.651
14	116.620	5.756	121.316	14	222.373	3.323	140.915
15	87.568	13.215	579.175	15	617.957	19.870	538.963
16	213.043	4.329	158.323	16	814.967	13.779	575.238
17	84.005	3.894	157.586	17	116.767	4.315	181.874
18	290.104	3.315	338.668	18	943.265	10.352	454.830
19	346.664	19.479	397.199	19	1033.522	21.915	456.616
20	24.318	2.196	39.740	20	57.869	1.687	120.211
21	315.066	8.180	582.579	21	1065.591	8.633	670.255

Table 5.11. Discharge and covariates in January-February 2020

January- February 2020	Discharge (m³/s)	Depth (m)	Width (m)
1	475.520	8.953	186.556
2	0.034	0.758	7.824
3	203.473	3.170	171.521
4	163.711	2.903	169.250
5	299.989	2.516	238.981
6	318.486	11.173	376.461
7	112.012	5.526	223.114
8	167.893	2.749	152.199
9	75.697	2.286	84.834
10	234.214	8.180	248.854
11	260.393	4.400	634.031
12	257.880	5.948	363.838
13	292.573	38.684	286.355
14	307.288	3.354	155.456
15	324.783	10.854	569.993
16	569.597	5.829	483.991
17	117.875	4.185	170.033
18	745.798	13.069	467.987
19	735.275	21.270	455.007
20	115.971	2.315	116.629
21	830.596	7.943	728.647

Table 5.12. Mean Discharge (pre monsoon and post monsoon)

Sampling Site	Mean Discharge (pre monsoon)	Mean Discharge (post monsoon)
1	432.657	354.657
2	59.307	44.360
3	108.171	119.401
4	116.181	138.743
5	108.101	178.651
6	193.261	233.715
7	29.666	117.088
8	34.327	131.198
9	16.961	58.618
10	54.211	182.841
11	64.265	235.494
12	81.277	256.644
13	73.955	248.052
14	99.008	245.563
15	100.798	363.067
16	184.202	545.953
17	68.946	186.525
18	243.271	679.476
19	282.727	725.051
20	39.234	172.626
21	298.760	786.550

Table 5.13. Mean Depth (pre monsoon and post monsoon)

Sampling Site	Mean Depth (pre monsoon)	Mean Depth (post monsoon)
1	7.138	7.767
2	3.521	2.740
3	2.590	2.524
4	2.152	2.683
5	2.297	2.629
6	5.174	5.719
7	7.555	7.658
8	1.831	3.435
9	1.452	1.694
10	3.053	4.647
11	2.327	5.573
12	6.726	8.368
13	2.349	11.805
14	4.039	3.920
15	11.167	12.203
16	8.195	7.909
17	7.491	5.064
18	7.432	10.786
19	17.224	18.454
20	2.010	3.630
21	7.110	8.592

Table 5.14. Mean Width (pre monsoon and post monsoon)

Sampling Site	Mean Width (pre monsoon)	Mean Width (post monsoon)
1	154.205	151.711
2	73.197	92.860
3	95.164	162.199
4	169.599	191.578
5	203.328	171.172
6	468.603	467.468
7	132.901	184.590
8	118.977	174.322
9	134.484	122.788
10	176.276	175.654
11	149.885	291.361
12	301.000	284.575
13	227.148	256.310
14	183.215	202.290
15	488.363	515.005
16	195.636	348.816
17	187.046	175.613
18	254.167	413.015
19	403.323	463.250
20	55.763	175.954
21	604.678	635.166

The sampling sites are located continuously from upper to lower reach of the MGR. The discharge has increased from the upper to lower reach because of the gradient in river channel. The depth and width have also increased from upper to lower reach. The season May-June 2018, March-April, 2019 and May-June 2019 are considered as the pre monsoon season, whereas, the November-December 2018, January-February 2019, November-December 2019, January-February 2020 are considered as the post monsoon season. Result shows an increasing trend in the discharge from upper to lower reaches in the Ganga River according to its gradient. The depth and width of Ganga River also increased with discharge. Presence of dams and barrages has changed the scenario and the natural occurrence of discharge, depth and width were restricted at the upstream of barrages. The sampling site 2 (downstream of Bhimgoda barrage, Haridwar), 4 (downstream of Madhya Ganga barrage, Bijnor), 7 (downstream of Charan Singh barrage, Narora) and 13 (downstream of Luv Kush barrage, Kanpur) shows low discharge in pre monsoon season (Figure 5.3) and post monsoon season (Figure 5.4). However, the overall discharge in the MGR shows increasing trend from upper to lower reaches. The depth also shows increasing trend from upper to lower reaches in the Ganga River. Depth in pre monsoon shown in Figure 5.5 and post monsoon depth is shown in Figure 5.6. The width of MGR is also increasing from upper to lower reaches. The width in pre monsoon shown in Figure 5.7 and post monsoon width is shown in Figure 5.8.

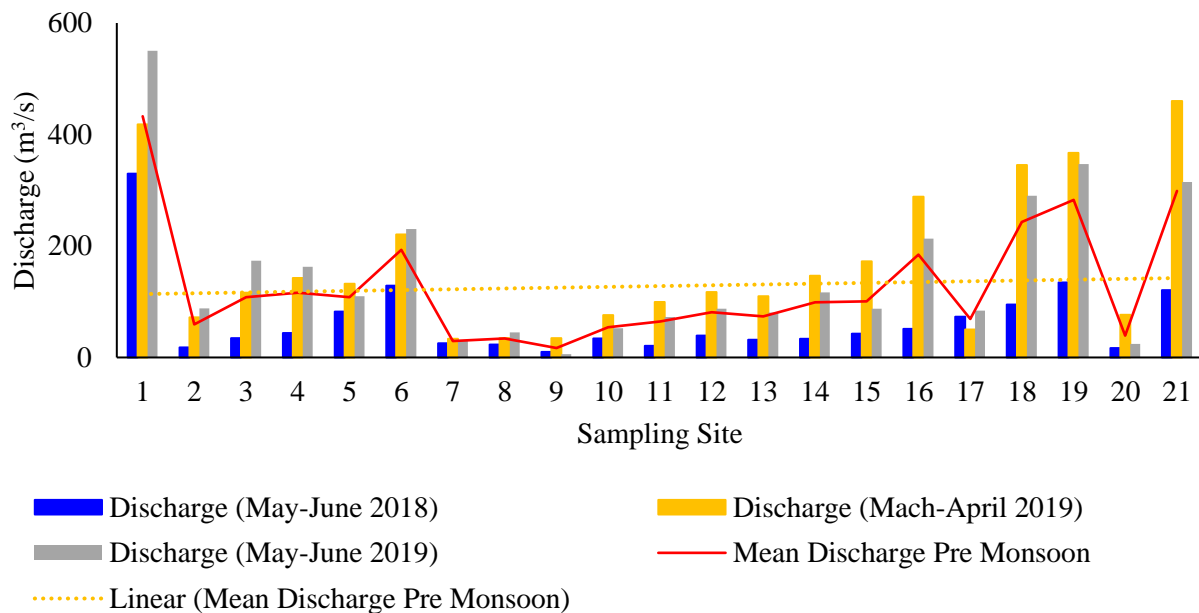


Figure 5.3. Comparative discharge in pre monsoon season

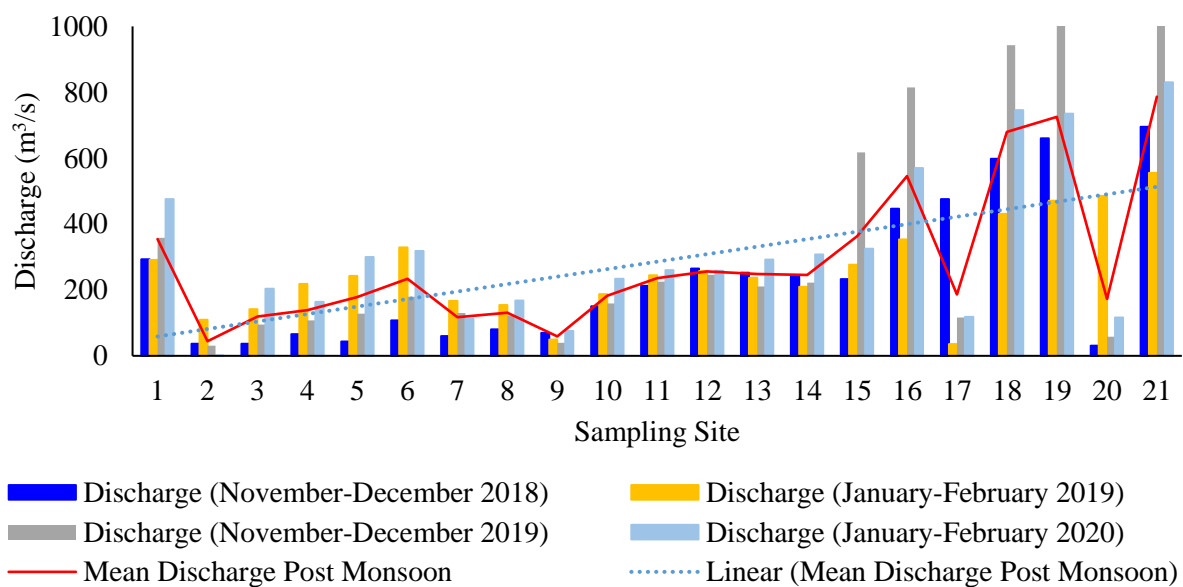


Figure 5.4. Comparative discharge in post monsoon season

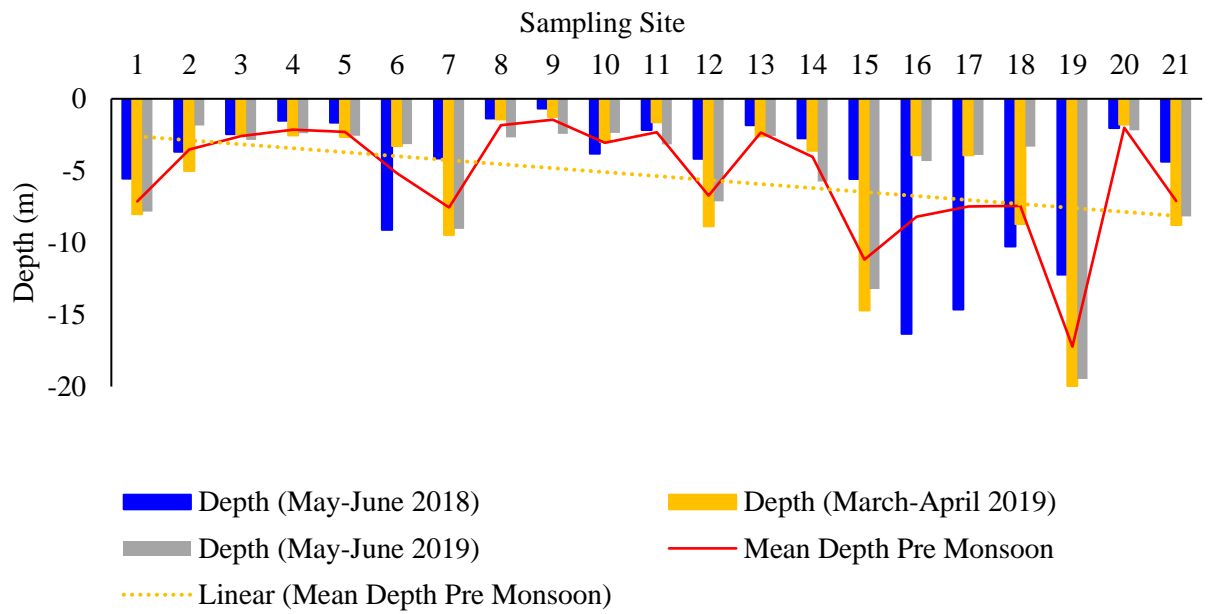


Figure 5.5. Comparative depth in pre monsoon season

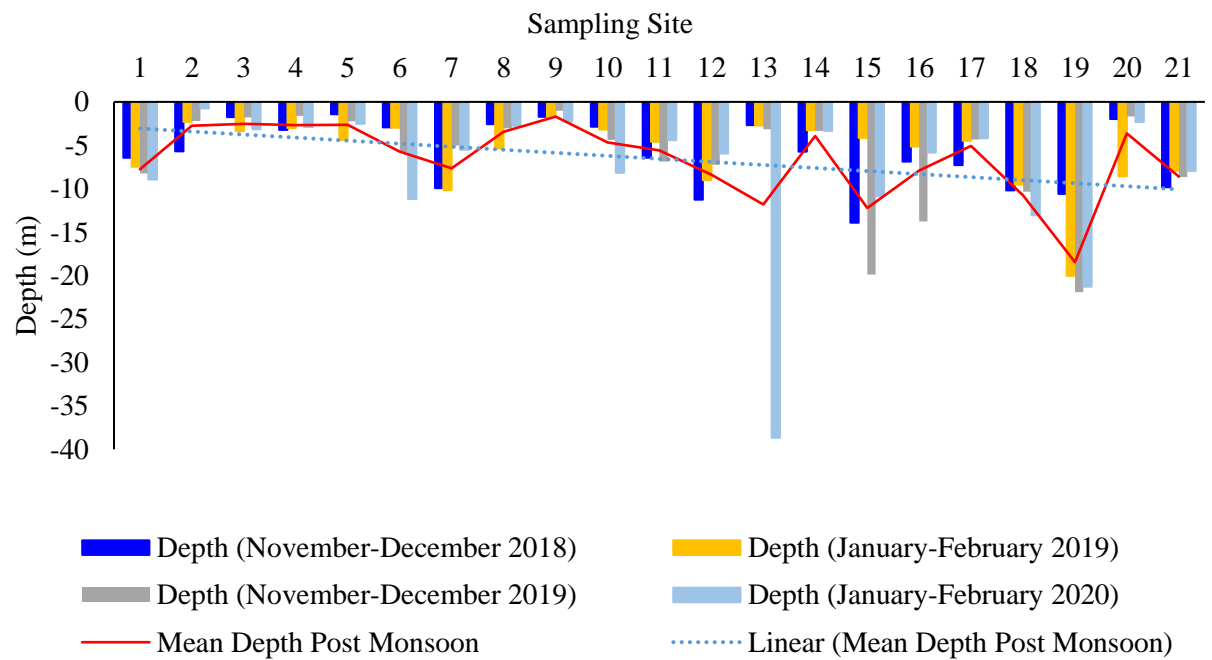


Figure 5.6. Comparative depth in post monsoon season

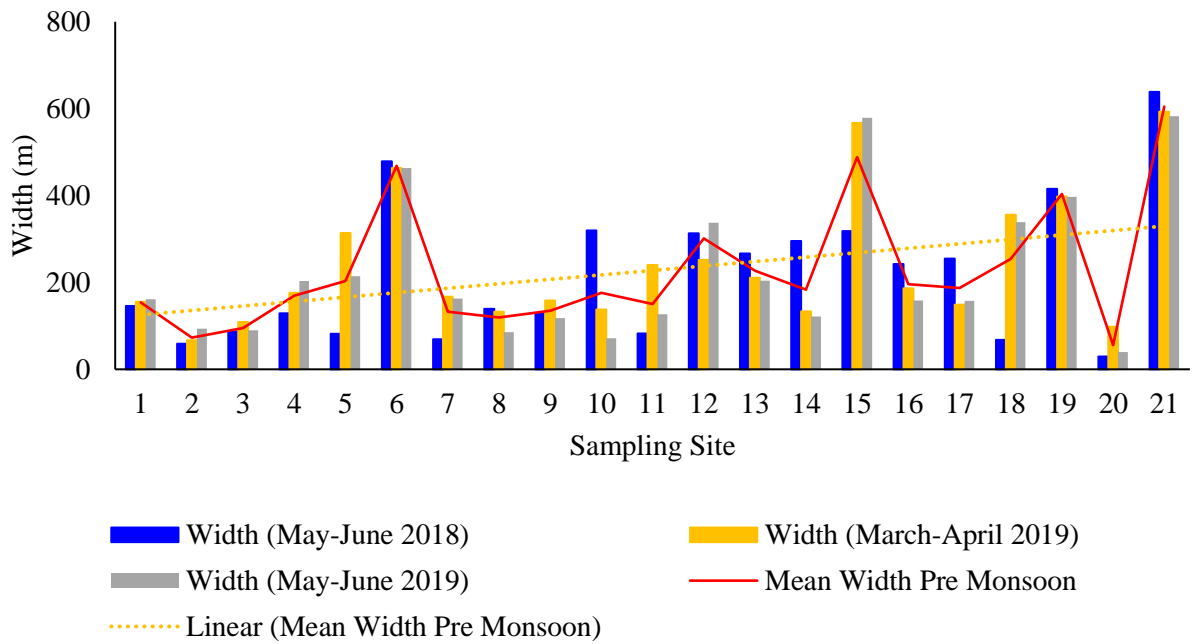


Figure 5.7. Comparative width in pre monsoon season

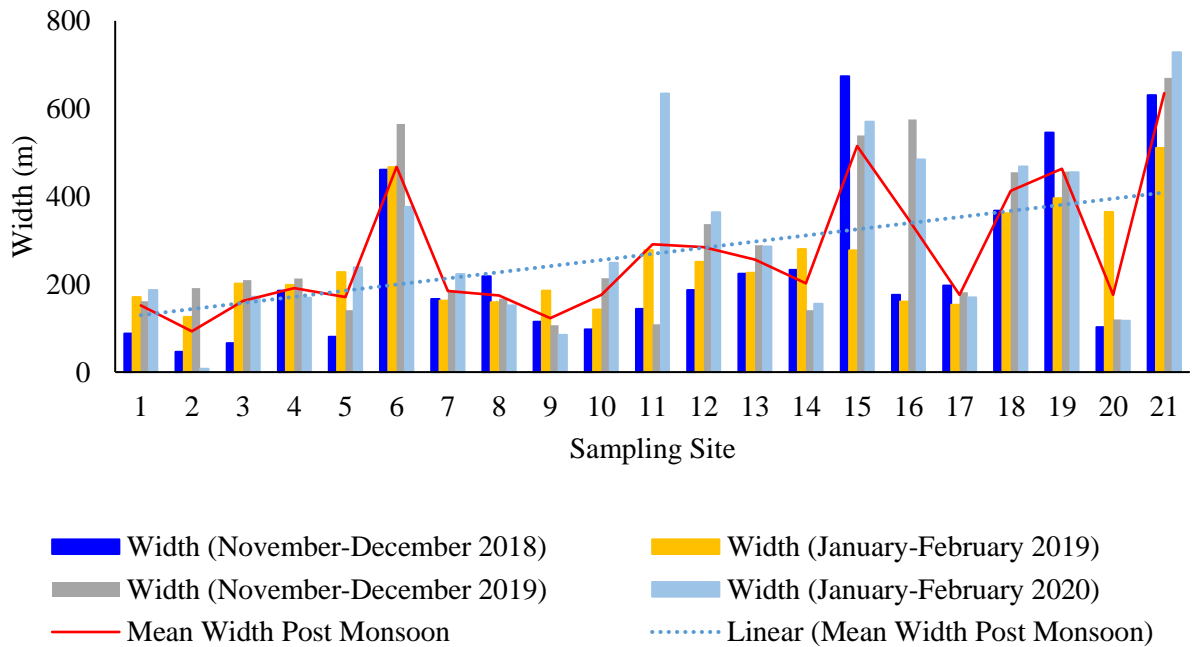


Figure 5.8. Comparative width in post monsoon season

5.3.2. Impact of barrages on river discharge

The river habitat conditions at the upstream and downstream of barrages in the Ganga River varies significantly due to alterations in water flow, sediment transport, and ecosystem dynamics caused by the construction of such structures. The construction of barrages usually leads to reduced water flow in the upstream area, particularly during dry seasons. This can result in a decrease in the natural flow variability, which affects aquatic species. Sediment load in the upstream region may increase as the barrage traps sediment, reducing downstream transport.

- **Width**

The width of the Ganga River varies significantly between the upstream and downstream of barrages, primarily due to changes in flow dynamics and sediment deposition. The middle course of rivers flows through wider channel and pose meanders when the river is free flowing but construction of barrages changes the scenario. The river experiences higher width in upstream areas due to presence of artificial reservoir. However, the downstream of barrages are narrow in comparison with the upstream areas. Dewan et al., 2017 suggested that width of the Ganga River changed from maximum of 5.36 to minimum of 3.23 km indicating the effect of upstream barrage of river. Singh et al., 2019 suggested that construction of Bijnor and Narora barrages has altered the planform geometry of the Ganga River, with natural and anthropogenic factors contributing to its oscillating nature. The result shows that the difference of width between upstream and

downstream is maximum at Charan Singh Ganga barrage at Narora followed by Luv Kush barrage at Kanpur (Figure 5.9).

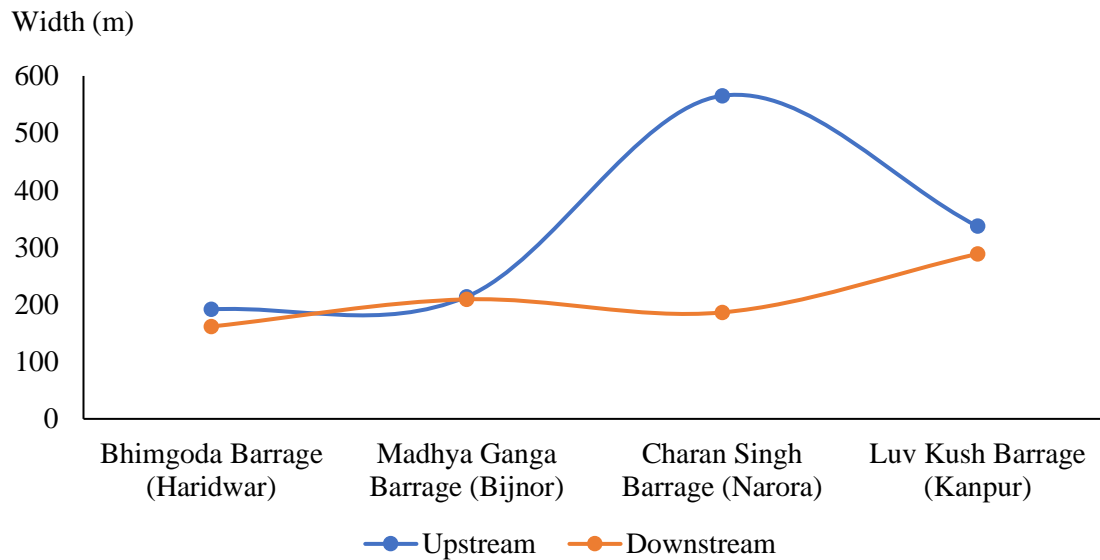


Figure 5.9. Width at upstream and downstream of barrages

- **Depth**

The depth of the Ganga River also varies between the upstream and downstream of barrages, primarily due to changes in water discharge at upstream and water scarcity in downstream in lean season (Zakwan et al., 2021). The river water gets restricted in the artificial reservoir at upper section of barrages which lead to form deeper areas. However, due to irrigation, municipal and hydropower generation purpose water to divers in canal system leading to water scarcity at downstream of barrages. Result shows, deeper areas present at upstream and shallow areas are present in downstream of river. Maximum depth

is present at upstream of Bhimgoda barrage at Haridwar followed by Luv Kush barrage at Kanpur. However, the depth at downstream of Charan Singh Ganga barrage at Narora has maximum depth. The Bhimgoda barrage at Haridwar followed by Madhya Ganga barrage at Bijnor has low depth areas at downstream of barrages (Figure 5.10).

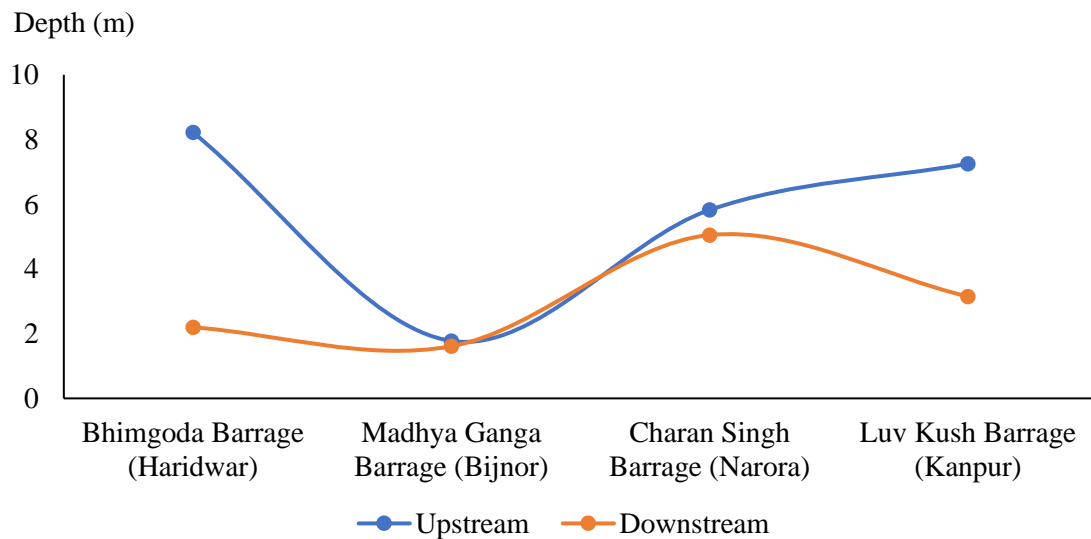


Figure 5.10. Depth at upstream and downstream of barrages

- **Discharge**

The discharge of water in the Ganga River differs between upstream and downstream of barrages, primarily due to manmade fragmentation. Barrages and human interventions in the Ganga River negatively impact its ecological integrity, causing water flow issues and restricting aquatic fauna migration (Kumar et al., 2023). The water discharge prepares the river to rejuvenate and maintain its natural flow. The discharge reduces in Ganga river

due to water diversion through canals and water extraction. As the release of water is very impulsive, the downstream areas However, due to irrigation, municipal and hydropower generation purpose water to divers in canal system leading to water scarcity at downstream of barrages. Result shows an increasing trend in water discharge at downstream of barrages due to joining of tributary rivers that contributes to the mainstem Ganga River (Figure 5.11).

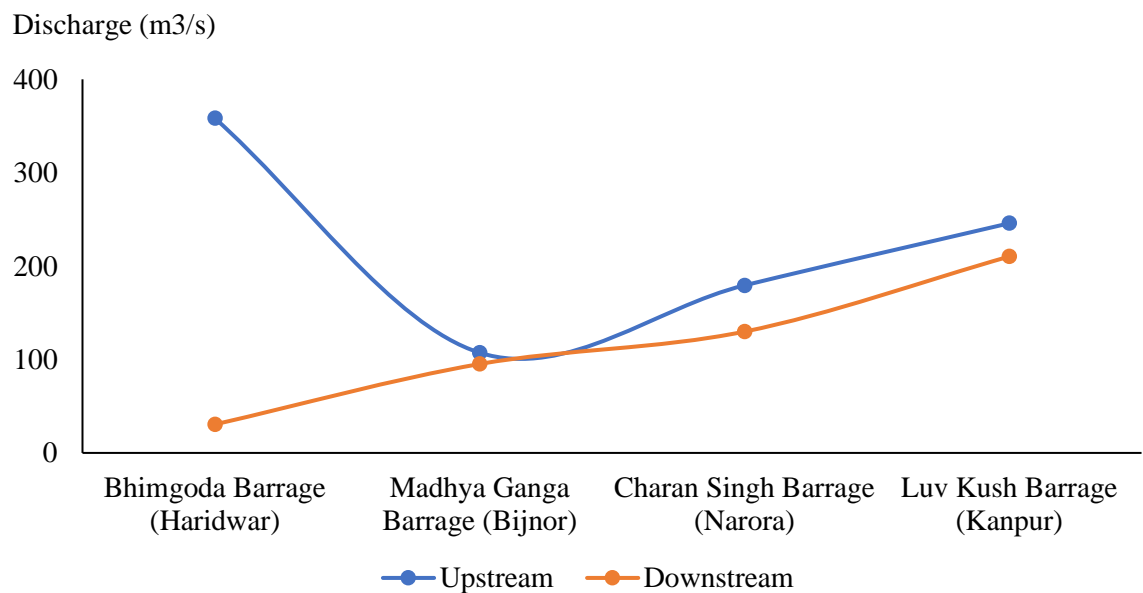










Figure 5.11. Discharge at upstream and downstream of barrages

The photographs of field work are listed in Figure 5.12.

Figure 5.12. Field sites at upstream and downstream of barrages

Middle Ganga River		
Barrage	Upstream	Downstream
Bhimgoda barrage, Haridwar		
Madhya Ganga barrage, Bijnor		
Charan Singh Ganga barrage, Narora		
Luv Kush barrage, Kanpur		

5.3.3. Fluvial stressors

The potential habitat area mapping is important for sustainable water resource management in view of conservation of aquatic biodiversity and their habitat in freshwater systems (Mcmanamay et al., 2017). Delineation and mapping potential habitat areas using GIS, and MCDM analysis through AHP methods are targeted. GIS is used as a spatial tool for data collection, analysis, and visualization of various factors. AHP is used as a decision-making methodology to assign relative weights to factors based on their importance in determining habitat suitability. MCDM applied to combine these factors into a single suitability index, generating maps of potential habitat areas. This multi-faceted approach allows for a holistic understanding of potential aquatic habitat, considering physical, environmental, ecological and anthropogenic factors. The classified layers of stressors are segmented based on the digital and visual interpretation techniques and verified with ground truth data (Pande & Moharir, 2017). In this study fifteen factors are used as thematic layers and ranks are assigned to the layer classes as per the hierarchical analytical process with the Satty's scale (Satty, 1990) for identification of potential habitat areas.

- **Flow**

Flow is an important factor for structure and function of river systems that influence the habitat availability. The flow was measured in field using ADCP in selected locations (Gao, 2023) and interpolated the result. The continuous layer was reclassified in seven thematic classes (Table 5.15). The Ganga River from downstream of Jilmil Conservation Reserve (CR) to downstream of Madhya Ganga barrage at Bijnor, and downstream of Charan Singh Ganga barrage at Narora to upstream of Ramganga River confluence at Kannauj is observed with less flow ($\leq 220 \text{ m}^3/\text{s}$) covering the largest area i.e. 7812.91 km^2 and 43.18% of the MGR. Whereas, from downstream of Tamas River confluence at Sirsa to Gomti River confluence at Kaithi is observed with maximum flow ($> 500 \text{ m}^3/\text{s}$) covering 1799.59 km^2 and 9.95% of the area (Figure 5.13).

Table 5.15. Flow classes

Serial No.	Flow (m^3/s)	Area (km^2)	Area (%)
1	≤ 220	7812.91	43.18
2	221 to 300	4906.32	27.12
3	301 to 350	1403.00	7.75
4	351 to 400	1165.36	6.44
5	401 to 450	381.02	2.11
6	451 to 500	625.86	3.46
7	> 500	1799.59	9.95

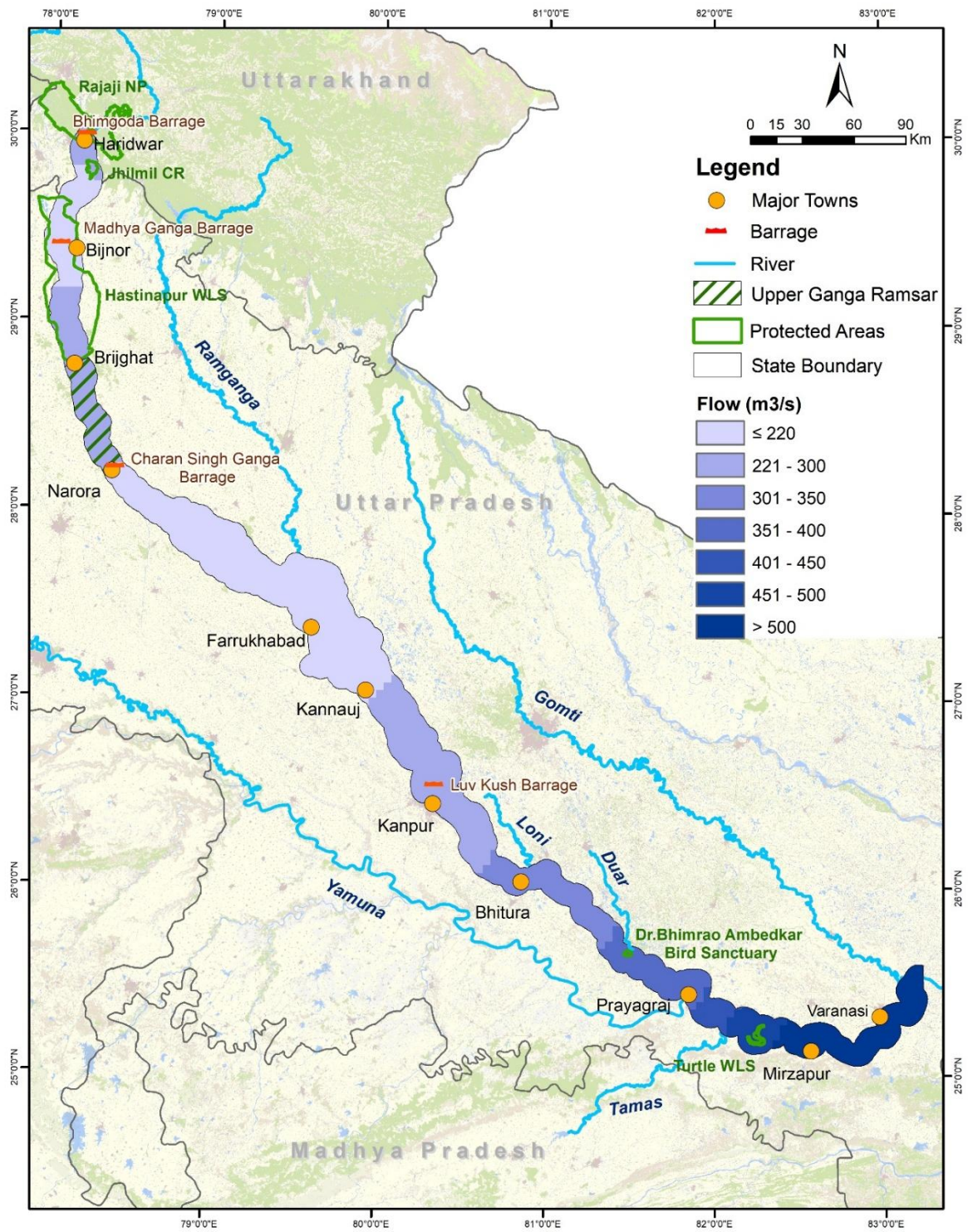


Figure 5.13. Flow

- **Depth**

Freshwater biodiversity is threatened by overexploitation, flow modification, habitat destruction, and invasion by exotic species (Dudgeon et al., 2006). Deeper stretches provide refuge for species during low flow conditions, whereas shallow areas are important for spawning and nutrient cycling. Change in depth in river impacts species survival and river ecosystem (Poff et al., 1997; Bunn & Arthington, 2002). Depth was measured in the field. The continuous layer was reclassified in seven thematic classes (Table 5.16). The Ganga River from downstream of Jilmil CR to Brijghat is observed with low depth (≤ 4 m) covering 1706.90 km² and 9.43% of the total area. Whereas, from downstream of Luv Kush barrage at Kanpur to Loni River confluence at Bhitura is observed with deeper channel (> 20 m) covering 468.33 km² and 2.59% of the area. The Ganga River downstream Brijghat and downstream Charan Singh Ganga barrage at Narora to Ramganga River confluence at Kannauj having channel depth 4 to 7 m, that covers maximum area of 6452.67 km² which is 35.66% of the MGR (Figure 5.14).

Table 5.16. Depth classes

Serial No.	Depth (m)	Area (km ²)	Area (%)
1	≤ 4	1706.90	9.43
2	5 to 7	6452.67	35.66
3	8 to 10	3577.89	19.77
4	11 to 14	3815.43	21.09
5	15 to 17	1234.45	6.82
6	18 to 20	838.40	4.63
7	> 20	468.33	2.59

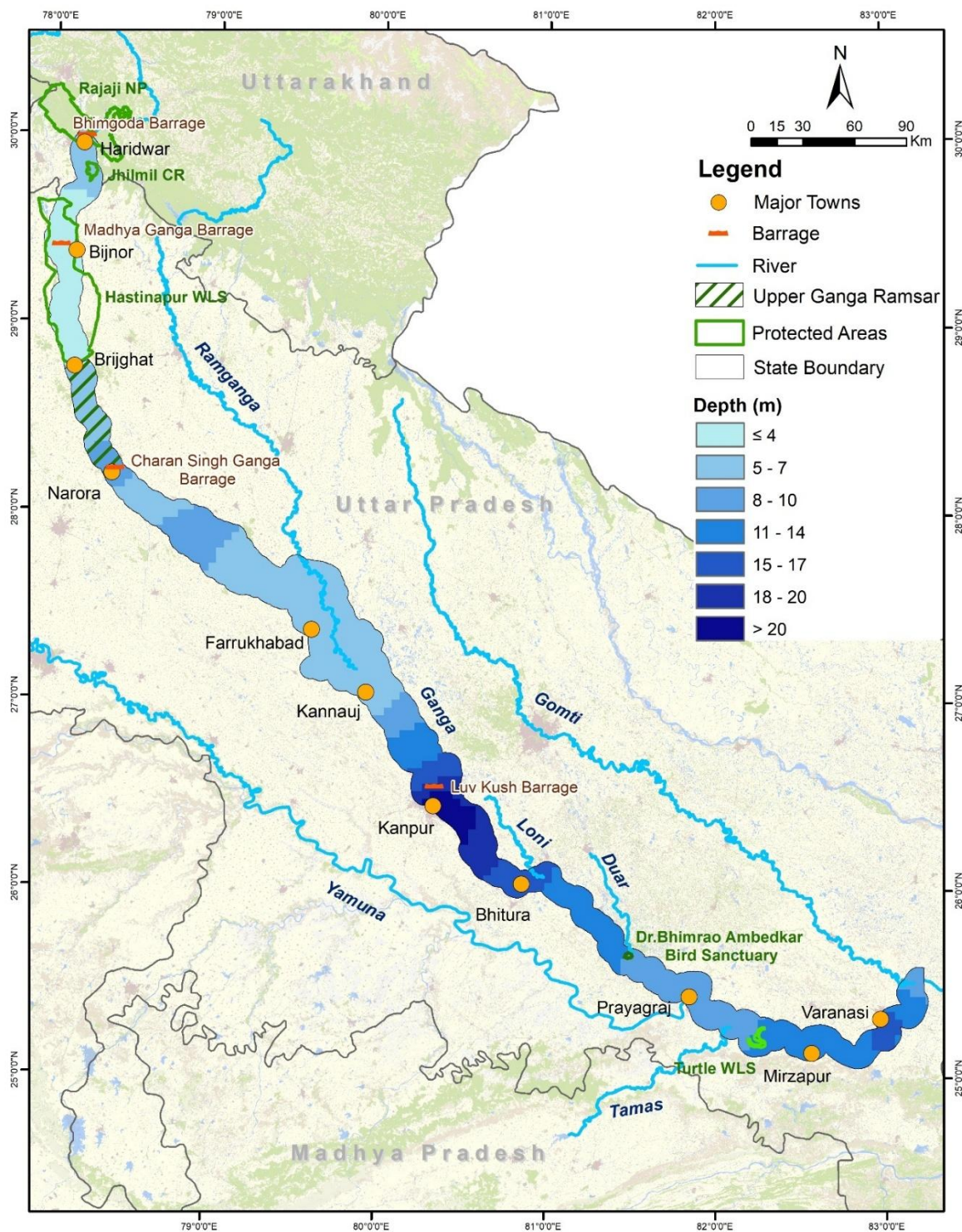


Figure 5.14. Depth

- **Width**

The width of river is important to maintain habitat structure and biodiversity in river system. Wider river channels create a greater variety of habitats, such as shallow water areas, lateral channels, and floodplains, which support a diverse range of aquatic species. Channelization of rivers reduces nutrient flow and macroinvertebrate diversity in the transition zone between the river and riparian floodplain (Kennedy & Turner, 2011). Width was measured in field. The continuous layer was reclassified in six thematic classes (Table 5.17). The Ganga River from downstream of Bhimgoda barrage at Haridwar to downstream of Madhya Ganga barrage at Bijnor is observed with less channel width (≤ 200 m) covering 1453.29 km² and 8.03% of the total area. Whereas, from Turtle (Kachua) Wildlife Sanctuary to Gomti River confluence near Kaithi is observed with highest channel width (> 400 m) covering 2463.98 km² and 13.62% of the area. The Ganga River downstream of Charan Singh Ganga barrage at Narora to upstream of Ranganga River confluence at Kannauj having channel width 250 to 300 m, that covers maximum area of 4715.16 km² which is 26.06% of the MGR (Figure 5.15).

Table 5.17. Width classes

Serial No.	Width (m)	Area (km ²)	Area (%)
1	≤ 200	1453.29	8.03
2	201 to 250	2706.77	14.96
3	251 to 300	4715.16	26.06
4	301 to 350	4330.66	23.93
5	351 to 400	2424.20	13.40
6	> 400	2463.98	13.62

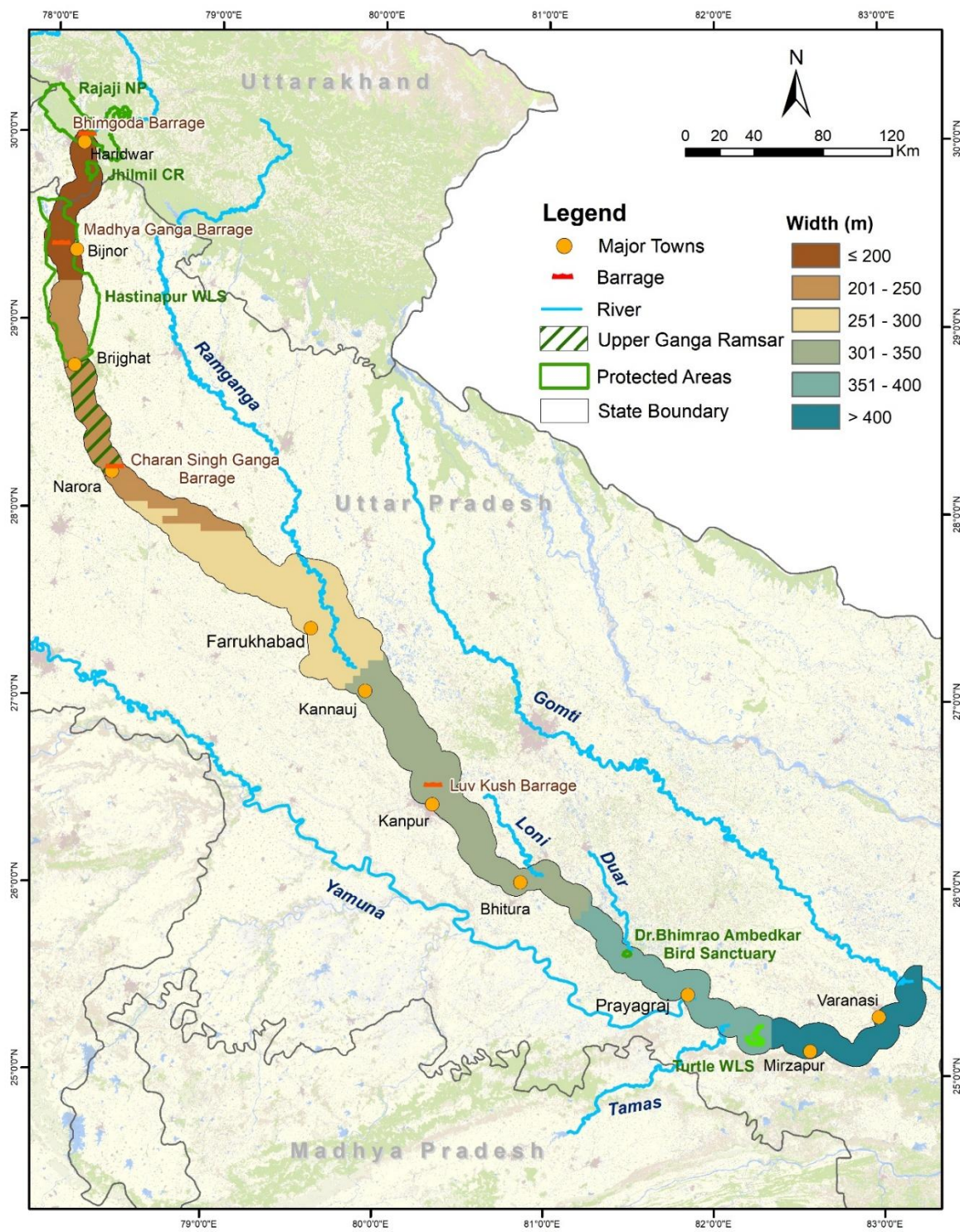


Figure 5.15. Width

- **Precipitation**

Precipitation is fundamental driver of river habitat dynamics, which influences streamflow, water levels, and sediment transport (Das, 2021). Rainfall maximizes river discharge, that alter channel morphology and connect the fragmented habitats into single stretch. Precipitation also leads to rapid erosion, which negatively affects the stable habitat for species occurrence. Lean periods observe low precipitation leading to reduced streamflow which causes river shrinkage. Seasonal and long-term variations in precipitation affects species composition, and migration patterns (Shousha et al., 2023). Precipitation was derived from the Worldclim dataset. Continuous layer was reclassified in five thematic classes (Table 5.18). The Ganga River from downstream of Luv Kush barrage at Kanpur to Tamas River confluence at Sirsa is observed with minimum annual precipitation (≤ 950 mm) covering 3736.97 km² and 20.65% of the total area. The river from Bhimgoda barrage at Haridwar to upstream of Madhya Ganga barrage at Bijnor (> 1500 mm) covers 755.20 km² and 4.17% of the area. The Ganga River downstream Charan Singh Ganga barrage at Narora to Farukhabad having precipitation 1000 to 1200 mm, that covers maximum area of 8129.28 km² which is 44.93% (Figure 5.16).

Table 5.18. Precipitation classes

Serial No.	Precipitation (mm)	Area (km ²)	Area (%)
1	< 950	3736.97	20.65
2	951 to 1000	3378.50	18.67
3	1001 to 1200	8129.28	44.93
4	1201 to 1500	2094.11	11.57
5	> 1500	755.20	4.17

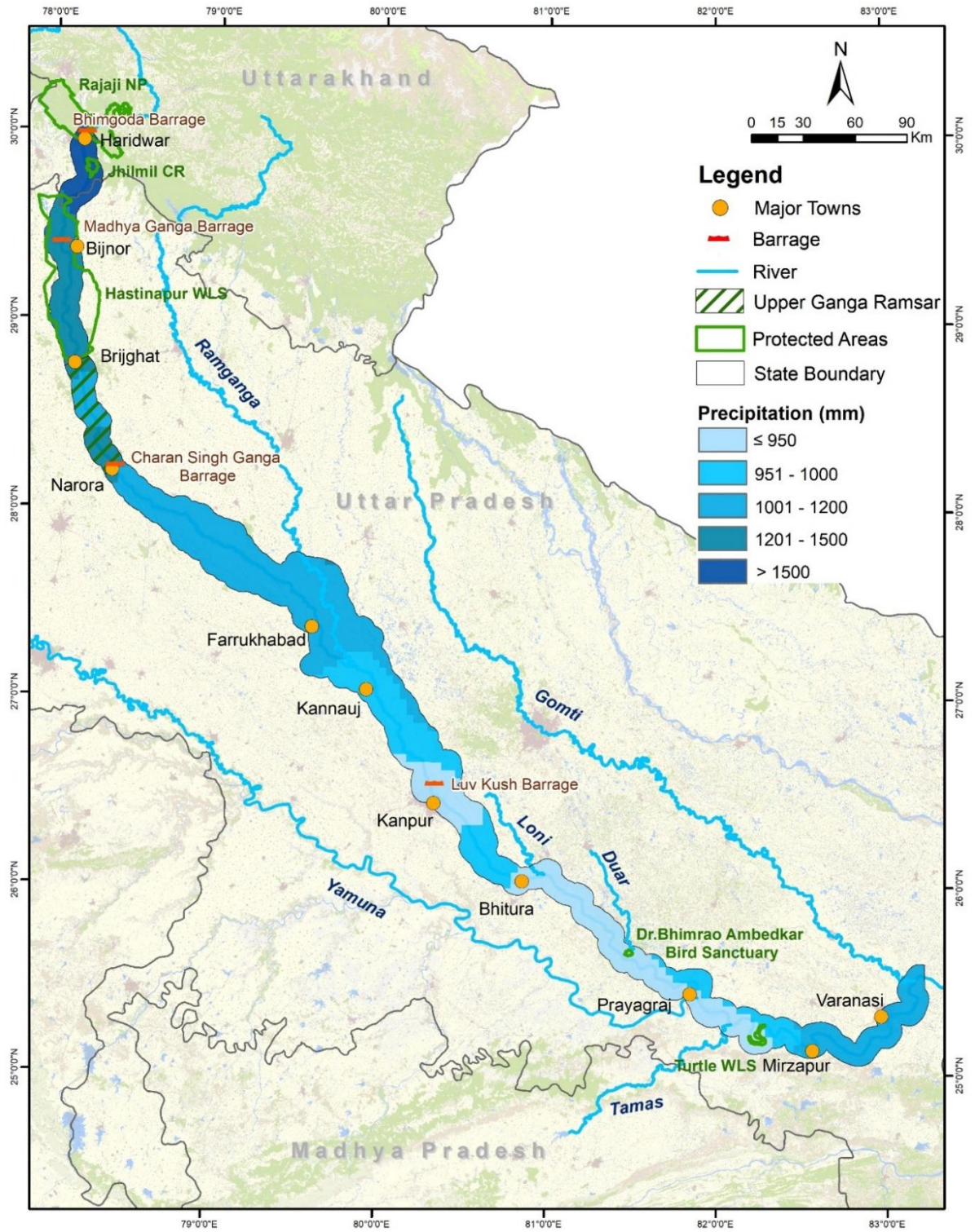


Figure 5.16. Precipitation

- **Land Use Land Cover**

The flooding, erosion, runoff, and sedimentation are prevalent as resultant of Land Use Land Cover (LULC) changes that alter aquatic habitats (Jacobson et al., 2001; Mani et al., 2004; Mandal et al., 2024). It is important for the environment's changing dynamics that impact hydrology and morphology of the river (Mani et al., 2022). The derived LULC summarized in Table 5.19 and Figure 5.17. The area was classified in nine attributes, i.e., River, Sandbar, and Island, Barrenland, Waterbody, Forest, Agriculture, Builtup, and Grassland. The river floodplain is dominated by agriculture in 71.05% area, whereas grassland is the least dominated class with 0.35% area in the river floodplain. The geomorphological features in the river belt are observed with maximum area of river channel covering 3.81% area, whereas, Islands are the least dominated geomorphological feature covering 1.06% area. The sand bars are a very prominent feature present within the river channels as point bar, mid bar and lateral bar covering 2.69% area.

Table 5.19. Land Use Land Cover classes

Serial No.	LULC Class	Area (km ²)	Area (%)
1	River	688.61	3.81
2	Sandbar	486.22	2.69
3	Island	192.13	1.06
4	Barrenland	793.20	4.38
5	Waterbody	749.36	4.14
6	Forest	1161.92	6.42
7	Agriculture	12856.47	71.05
8	Builtup	1103.00	6.10
9	Grassland	63.15	0.35

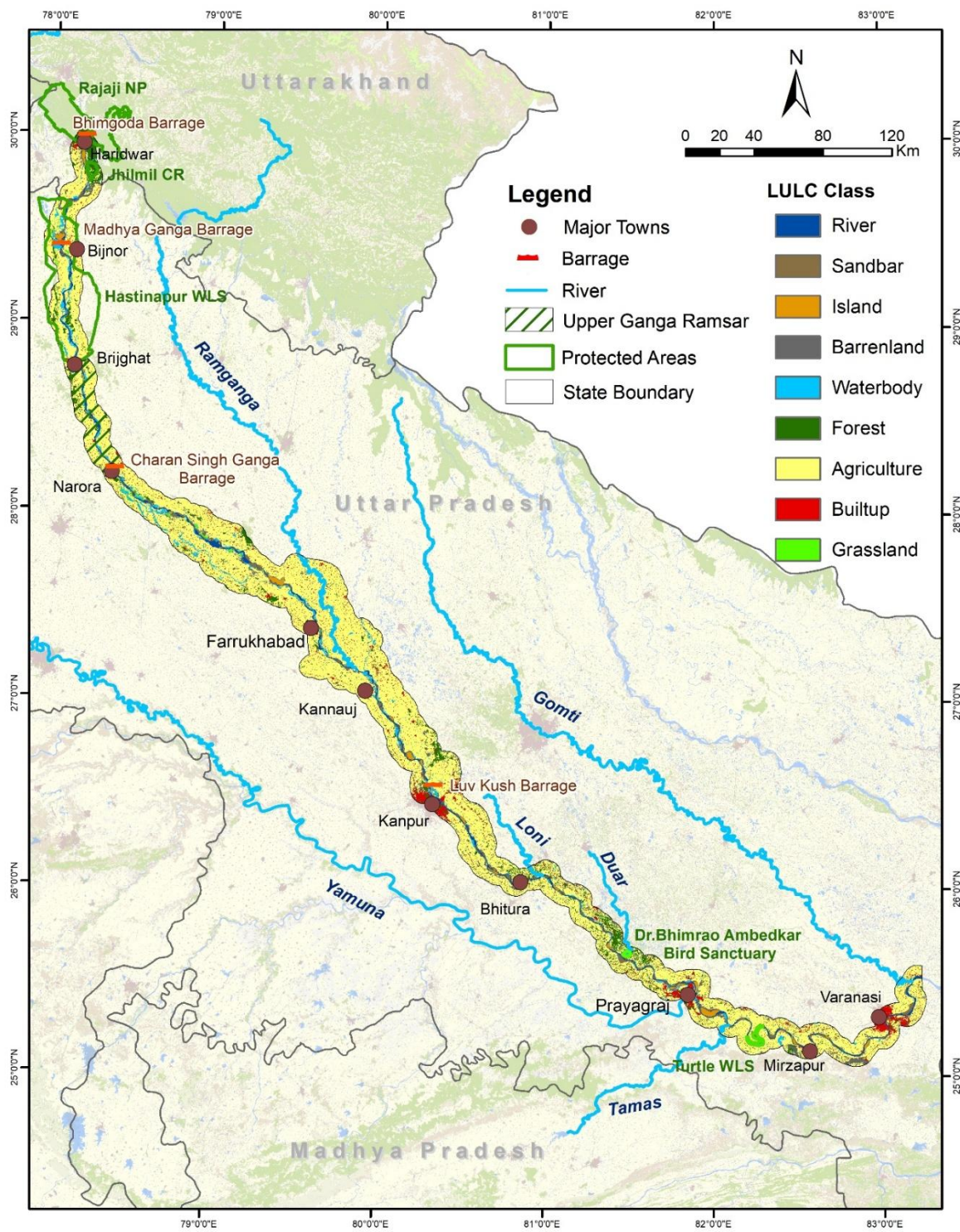


Figure 5.17. Land Use Land Cover

- **Geomorphology**

Geomorphological factors are essential in the hydrological system process on the earth surface. Geomorphological processes result dynamic and diverse habitats in river and floodplain ecotones (Sear et al., 2003). The fluvial morphology, including channel shape, flow patterns, sediment transport, and sediment deposition, determines the diversity of aquatic environments. Meandering rivers with varied depth and flow forms a mosaic of habitats like flowing rifles, moving pools. Geomorphology was derived from the Bhoomi portal, NBSS&LUP. The continuous layer was reclassified in nine thematic classes (Table 5.20). The alluvial plains are predominant in lateral position of the bank of Ganga River, particularly from downstream of Ramganga River confluence at Kannauj to Gomti River confluence at Sirsa. However, a large extent of floodplain is present from Bhingoda barrage at Haridwar to Ramganga River confluence at Kannauj (Figure 5.18).

Table 5.20. Geomorphology classes

Serial No.	Geomorphology	Area (km²)	Area (%)
1	Flood Plain	8407.69	46.47
2	Waterbody	212.16	1.17
3	Alluvial Plain	8756.19	48.39
4	River	350.38	1.94
5	Pediment Pediplain Complex	197.47	1.09
6	Dam and Reservoir	46.10	0.25
7	Moderately Dissected Plateau	47.01	0.26
8	Highly Dissected Hills and Valleys	76.90	0.42
9	Moderately Dissected Hills and Valleys	0.15	0.0008

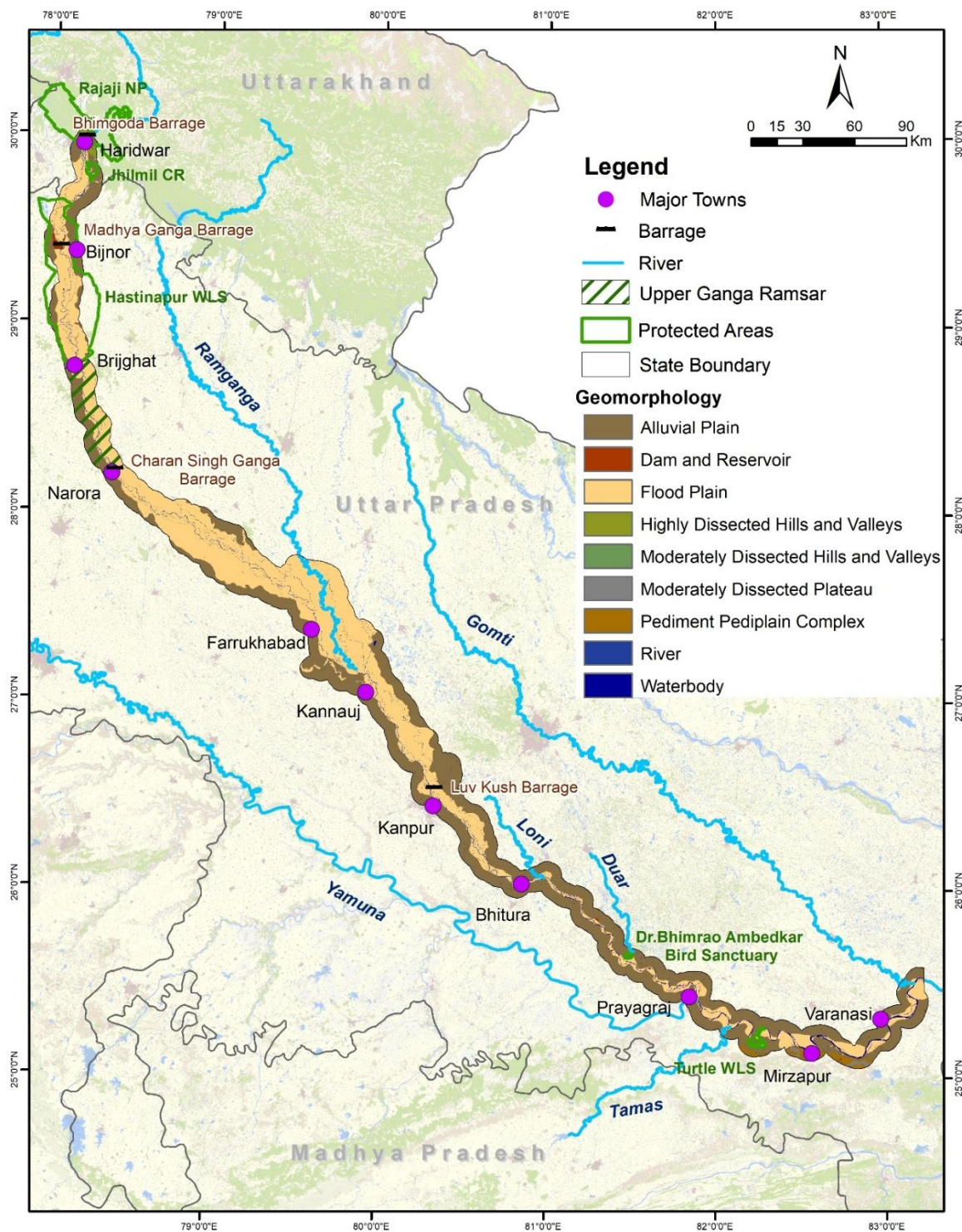


Figure 5.18. Geomorphology

- **Soil texture**

Soil texture influences river systems and aquatic habitats by affecting water infiltration, and sediment transport. The size and composition of soil particles determine water movement through the riverscape (Liu & Wang, 2022). Soil texture shapes river channel morphology. Coarse-textured soils like gravel and sand contribute to dynamic fluvial features of riffles and pools, that act as habitat for several aquatic species. Fine-textured soils tend to produce sluggish flows, reducing habitat complexity and biodiversity (Allan, 2004). Soil texture was derived from the Bhoomi portal, NBSS&LUP. The continuous layer was reclassified in four thematic classes (Table 5.21). The loamy soil is predominant throughout the study region near water channels from Haridwar to Varanasi, particularly in segment between Farukhabad and Kanpur. The loamy soil texture covers 9231.88 km² and 51.02% of the total area. The mid river areas from Haridwar to Farrukhabad and Kanpur to Varanasi is having sandy soil which covers 8082.38 km² and 44.67% of the area. Other soil textures present in the region are clayey and loamy skeletal (Figure 5.19).

Table 5.21. Soil texture classes

Serial No.	Soil texture	Area (km²)	Area (%)
1	Loamy Skeletal	48.71	0.27
2	Loamy	9231.88	51.02
3	Sandy	8082.38	44.67
4	Clayey	731.09	4.04

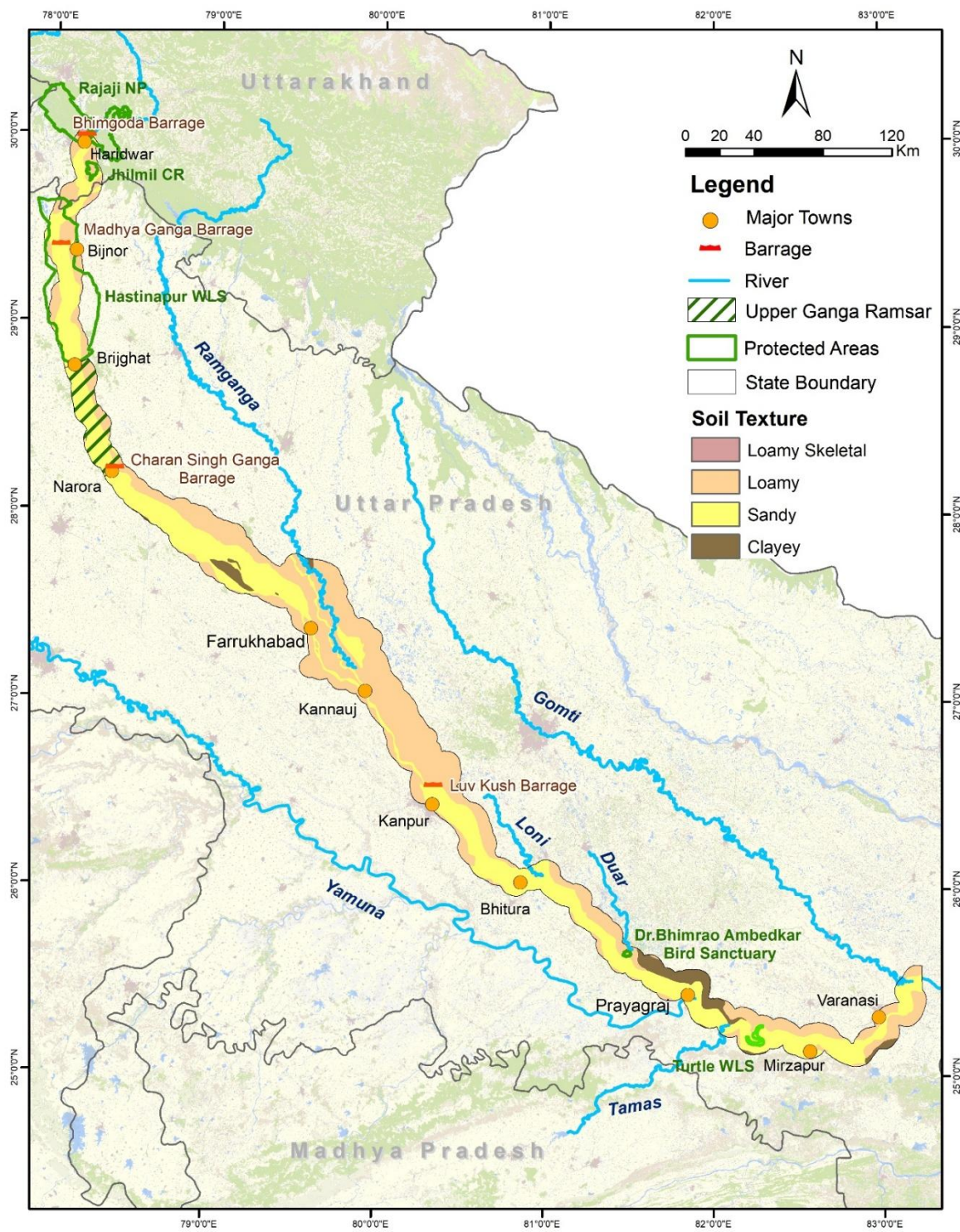


Figure 5.19. Soil texture

- **Parent material**

Parent material plays an important role in shaping river systems. These materials are the underlying geological features from which soils and sediments are derived. The composition and structure of the parent material directly influence sediment types, water chemistry, and river morphology. Rivers in its middle course flow through softer eroded parent material like alluvium, limestone and sandstone, tend to have slower flow with meanders and finer sediments like sand and silt (Tucker & Slingerland, 1997). Parent material was derived from the Bhoomi portal, NBSS&LUP. The continuous layer was reclassified in three thematic classes (Table 5.22). The alluvium is dominant throughout the study region. It is extended from Jilmil CR to Varanasi covering 17260.65 km² and 95.39% of the MGR. Colluvium is present in 193.61 km² near Haridwar which is approximately 1.07% whereas, sandstone is present in 639.80 km² area at Chunar, approximately 3.54% of the area (Figure 5.20).

Table 5.22. Parent material classes

Serial No.	Parent material	Area (km ²)	Area (%)
1	Colluvium	193.61	1.07
2	Alluvium	17260.65	95.39
3	Sandstone	639.8	3.54

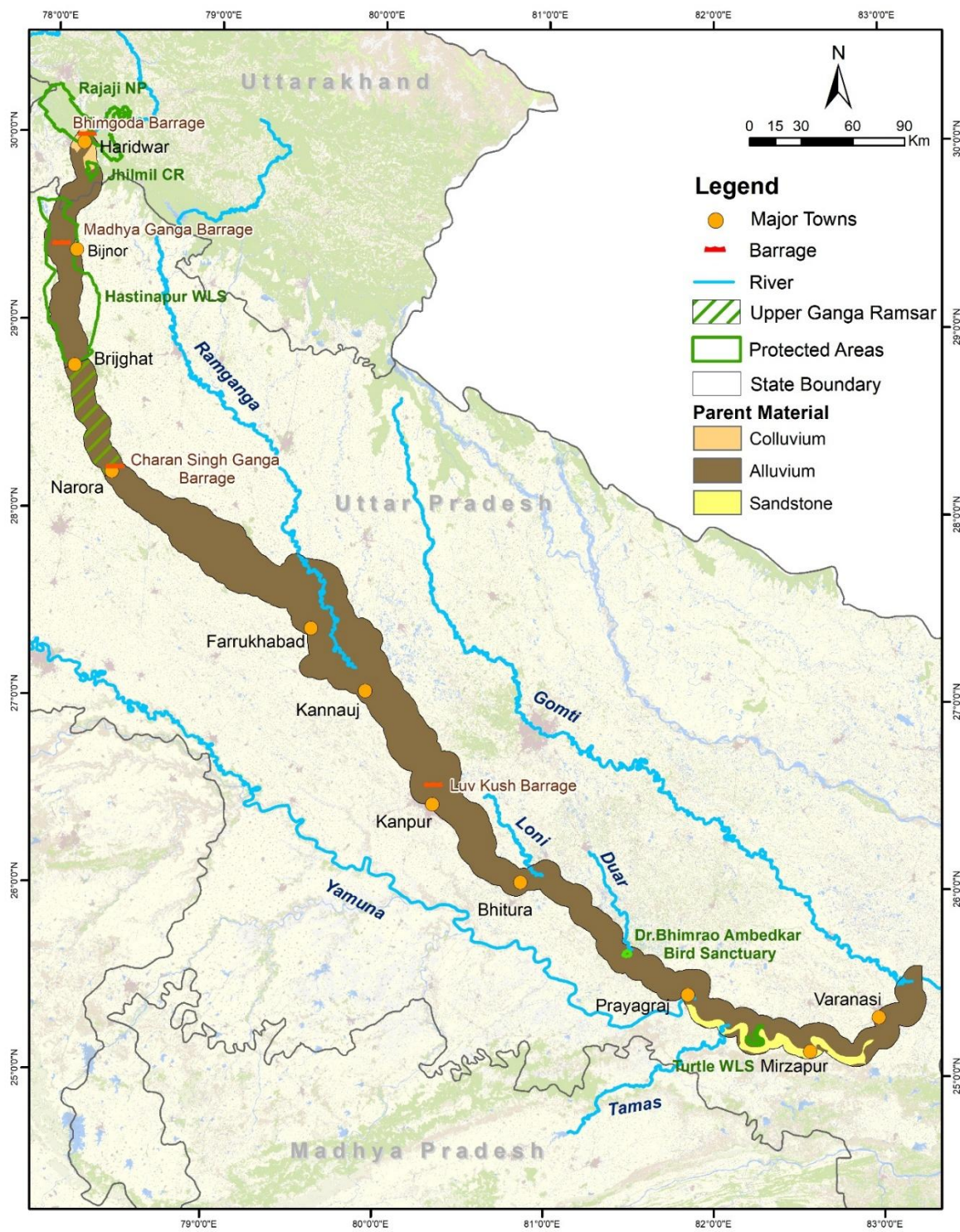


Figure 5.20. Parent material

- **Mineral**

The sediment and chemical composition of parent materials affects the mineral content of river. Transport and fate of minerals and metals in river systems is crucial for environmental management (Zegers et al., 2021). Mineral was derived from the Bhoomi portal, NBSS&LUP. The continuous layer was reclassified in three thematic classes (Table 5.23). The Smectite mixed mineral is dominant throughout the MGR, it covers a major part i.e., 17524.99 km² and 96.85% of the total area. Montmorillonite covers 20.77 km² and 0.11% of the total area. Illite minerals are present near lateral sandbars (Figure 5.21).

Table 5.23. Mineral classes

Serial No.	Mineral	Area (km²)	Area (%)
1	Smectite mixed mineral	17524.99	96.85
2	Illite mineral	548.30	3.03
3	Montmorillonite	20.77	0.11

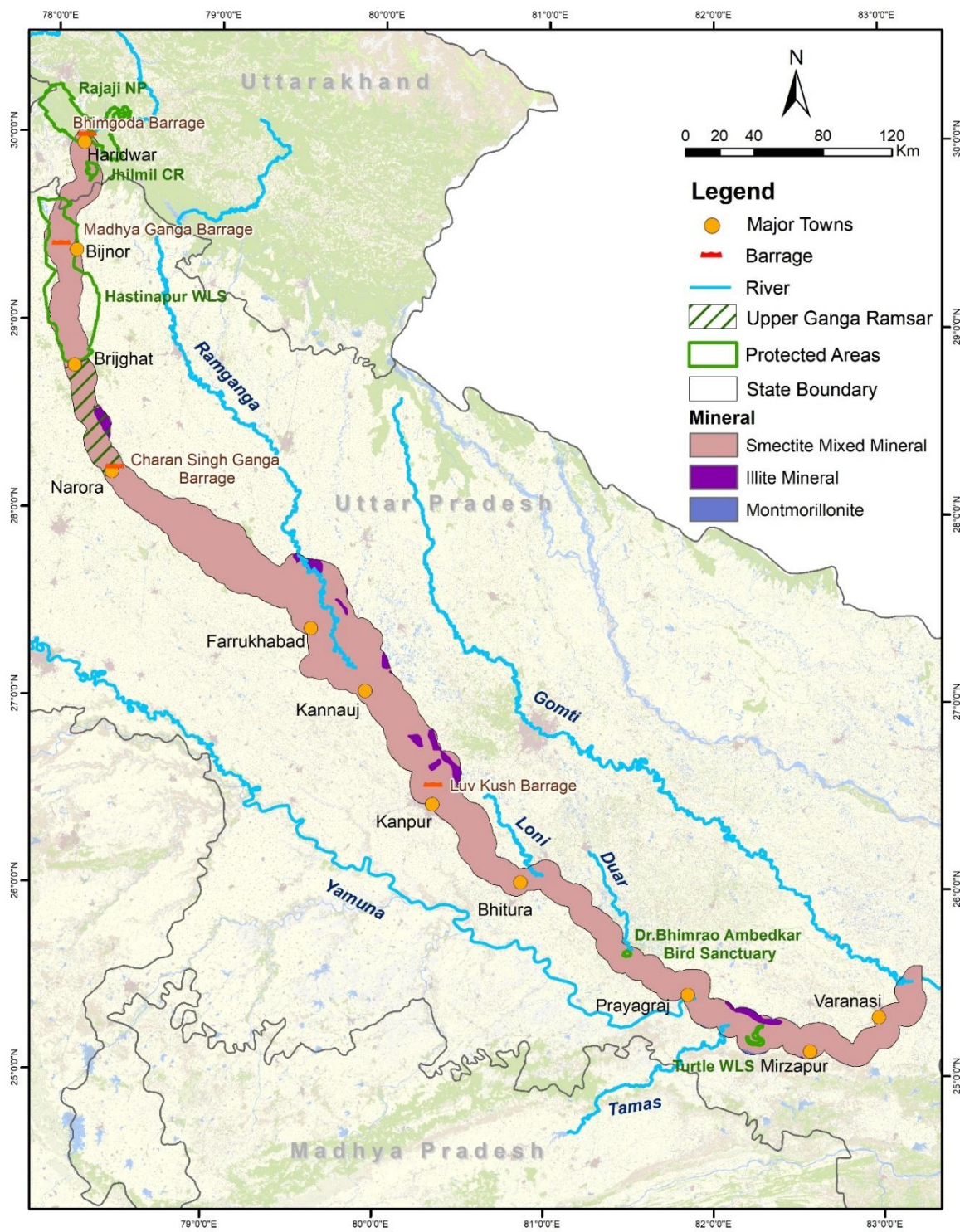


Figure 5.21. Mineral

- **Drainage density**

Water availability is the primary determinant of ecological processes in most drainage networks, with hydrologic connectivity and geomorphic change (Sponseller et al., 2013). Drainage density is the ratio between length of drainage area and the total area. High drainage density indicates a highly dissected landscape with a dense network of streams, which tends to faster runoff. Drainage was derived from the ALOS DEM with 30 m resolution. The continuous layer was reclassified in five thematic classes (Table 5.24). The Ganga River at Haridwar, Bijnor, Kannauj and Kanpur barrage and Farukhabad (> 1.5) covering 6959.56 km² and 38.46% of the area. The river upstream of Madhya Ganga barrage at Bijnor to Brijghat and downstream of Charan Singh Ganga barrage at Narora to Yamuna River confluence at Prayagraj having maximum area of drainage density (1.2 to 1.5) covering 6959.56 km² which is 38.46% of the MGR (Figure 5.22).

Table 5.24. Drainage density classes

Serial No.	Drainage Density	Area (km²)	Area (%)
1	< 0.8	303.07	1.67
2	0.9 to 1.0	2737.54	15.13
3	1.1 to 1.2	6027.96	33.31
4	1.3 to 1.5	6959.56	38.46
5	> 1.5	2065.94	11.42

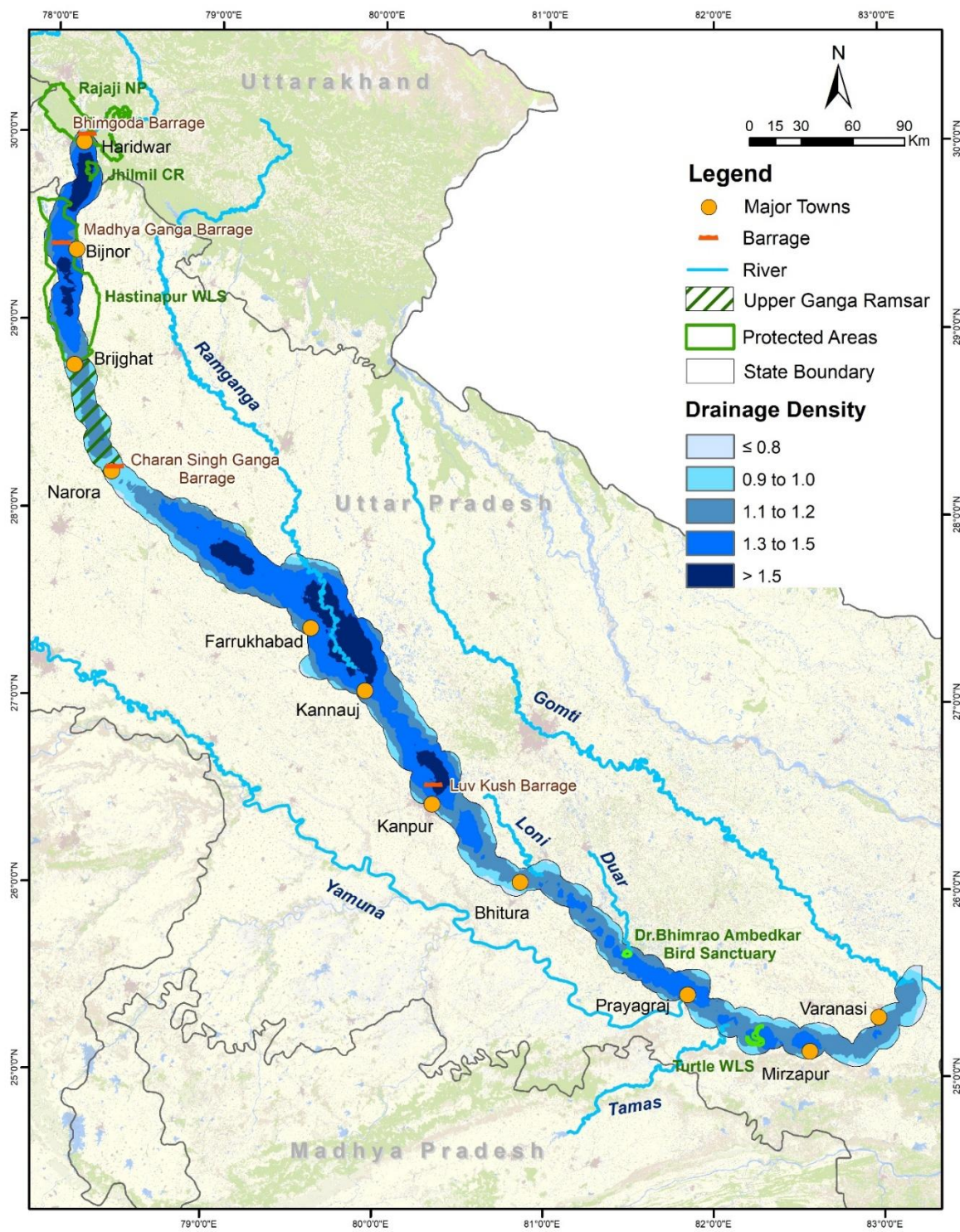


Figure 5.22. Drainage density

- **Elevation**

Elevation plays important role in hydrological processes and structures by influencing the gradient, velocity, and erosion processes within river course (Loritz et. al., 2019). Rivers that originate at higher elevations have steep gradients, resulting in faster flow rates and higher energy levels. This increased velocity accelerates erosion and forms features like rapids, and V-shaped valleys in the upper reaches. In lower elevations, the flow gets slow down and allows the deposition of sediments, which leads to the formation of floodplains and meanders. These geomorphic features act as habitat for many aquatic species. The elevation was derived from the ALOS DEM with 30 m resolution. The continuous layer was reclassified in eight thematic classes (Table 5.25). The Ganga River at Haridwar has the higher elevation (> 400 m) covering 48.04 km^2 and 0.027% of the area. Whereas, lower elevation (≤ 50) has the coverage of 0.17 km^2 and 0.0009% of the MGR (Figure 5.23).

Table 5.25. Elevation classes

Serial No.	Elevation (m)	Area (km²)	Area (%)
1	≤ 50	0.17	0.0009
2	51 to 100	3636.48	20.1
3	101 to 150	8606.18	47.56
4	151 to 200	3372.99	18.64
5	201 to 250	2020.61	11.17
6	251 to 300	345.84	1.91
7	301 to 400	63.75	0.35
8	> 400	48.04	0.27

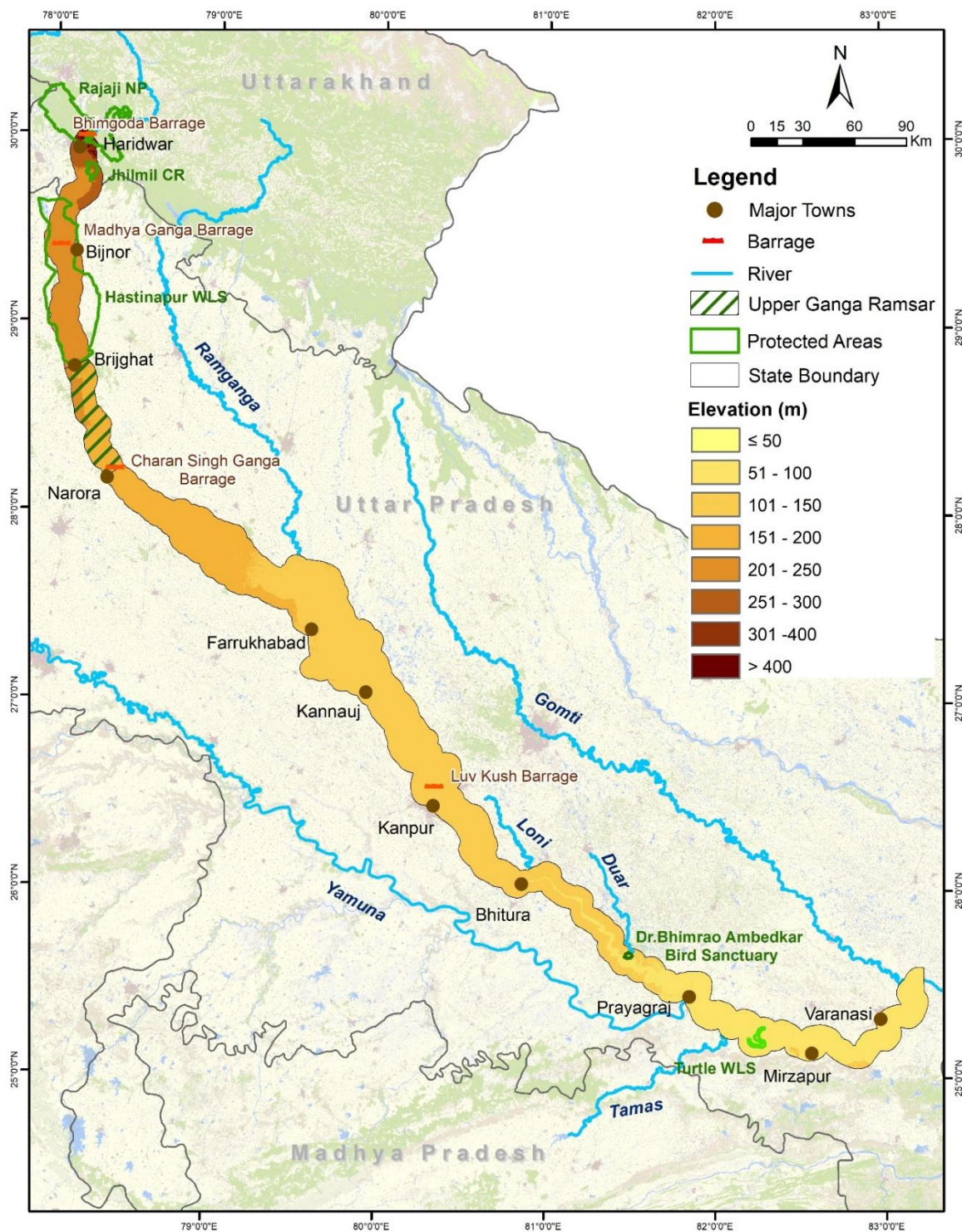


Figure 5.23. Elevation

- **Slope**

Slopes strongly influence interrill erosion processes, with time to runoff, flow velocity, runoff rate, and interrill erosion rate decreasing with increasing gradients (Wu et. al., 2021). Slope was derived from the ALOS DEM with 30 m resolution. The continuous layer was reclassified in seven thematic classes (Table 5.26). The Ganga River at Prayagraj and Varanasi has lower slope (≤ 0.5 degree) covering 3707.91 km² and 20.49% of the MGR. Whereas, higher slope (> 5 degree) has the coverage of 348.43 km² and 1.93% of the area that lies near Bhimgoda barrage at Haridwar (Figure 5.24).

Table 5.26. Slope classes

Serial No.	Slope (degree)	Area (km²)	Area (%)
1	≤ 0.5	3707.91	20.49
2	0.6 to 1	4028.68	22.27
3	1.1 to 2	7256.58	40.1
4	2.1 to 3	1885.22	10.42
5	3.1 to 4	637.43	3.52
6	4.1 to 5	229.82	1.27
7	> 5	348.43	1.93

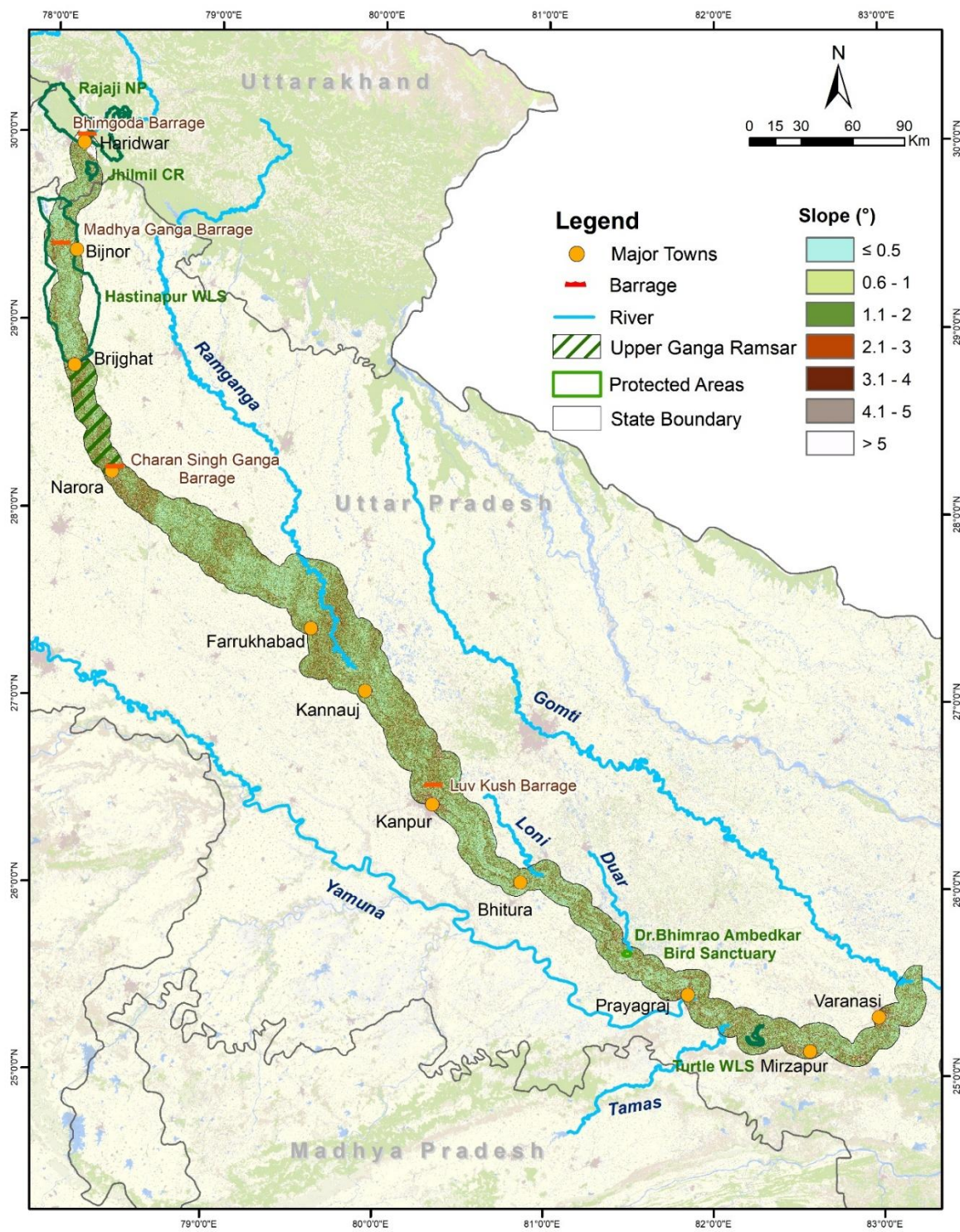


Figure 5.24. Slope

- **Proximity to barrage**

The dams and barrages are major driving forces behind the alteration of fluvial environment at downstream flows (Aguiar et al., 2016). Alteration takes place particularly in aquatic and riparian habitat by affecting river hydrology at downstream (Alldredge & Moore, 2014). The proximity to barrage governs species movement which was measured in field. The continuous layer was reclassified in five thematic classes (Table 5.27). The Ganga River ≤ 20 km from the dams and barrages are covered by 2457.56 km² and 13.58% of the total area. Whereas, the stretch > 200 km from the dams and barrages are covered by 3335.83 km² and 18.44% of the MGR (Figure 5.25).

Table 5.27. Proximity to barrage classes

Serial No.	Proximity to barrage (km)	Area (km²)	Area (%)
1	≤ 20	2457.56	13.58
2	21 to 50	3557.05	19.66
3	51 to 100	4572.05	25.27
4	101 to 200	4171.57	23.05
5	> 200	3335.83	18.44

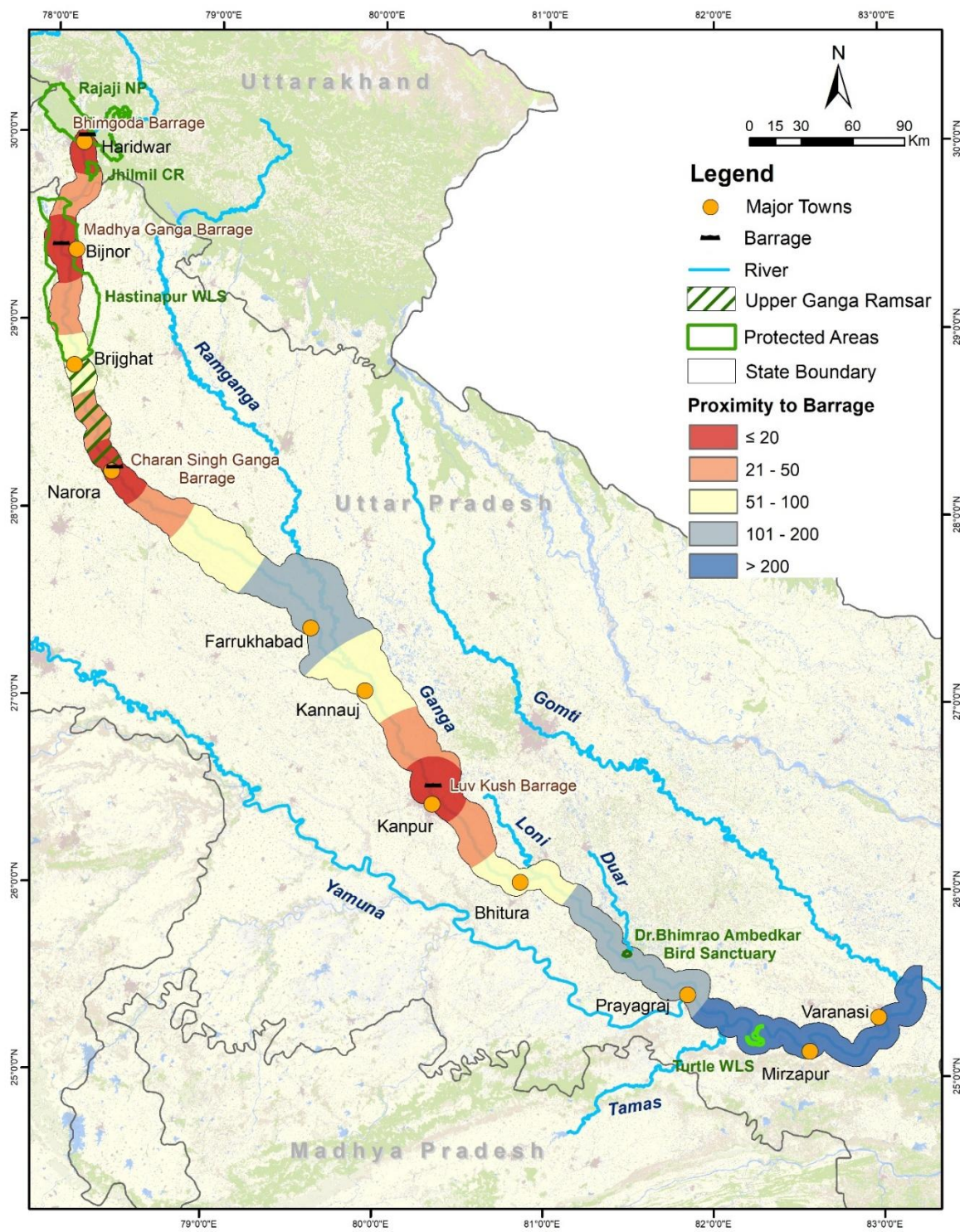


Figure 5.25. Proximity to barrage

- **Human footprint**

Human activities have profoundly altered river systems, often leading to significant ecological and hydrological changes. The human driven modifications exacerbate the vulnerability of river systems towards alteration of flow regimes compromising the resilience system of river to extreme weather events (Bunn & Arthington, 2002). The human footprint was derived from Earthdata, NASA and Socioeconomic Data and Applications Center (SEDAC) (Sanderson et al., 2002). The continuous layer was reclassified in five thematic classes (Table 5.28). The Ganga River channels are minimum human footprint areas (≤ 30) covering 2048.29 km² and 11.32% of the total area, whereas the large cities along the Ganga River are observed with maximum human footprint (> 80) covering 736.43 km² area and 4.07% of the MGR. The largest area of 7859.55 km² which is 43.44% of the total study area is covered under human footprint range 31 to 40 (Figure 5.26).

Table 5.28. Human footprint classes

Serial No.	Human footprint	Area (km ²)	Area (%)
1	≤ 30	2048.29	11.32
2	31 to 40	7859.55	43.44
3	41 to 60	5824.21	32.19
4	61 to 80	1625.58	8.98
5	> 80	736.43	4.07

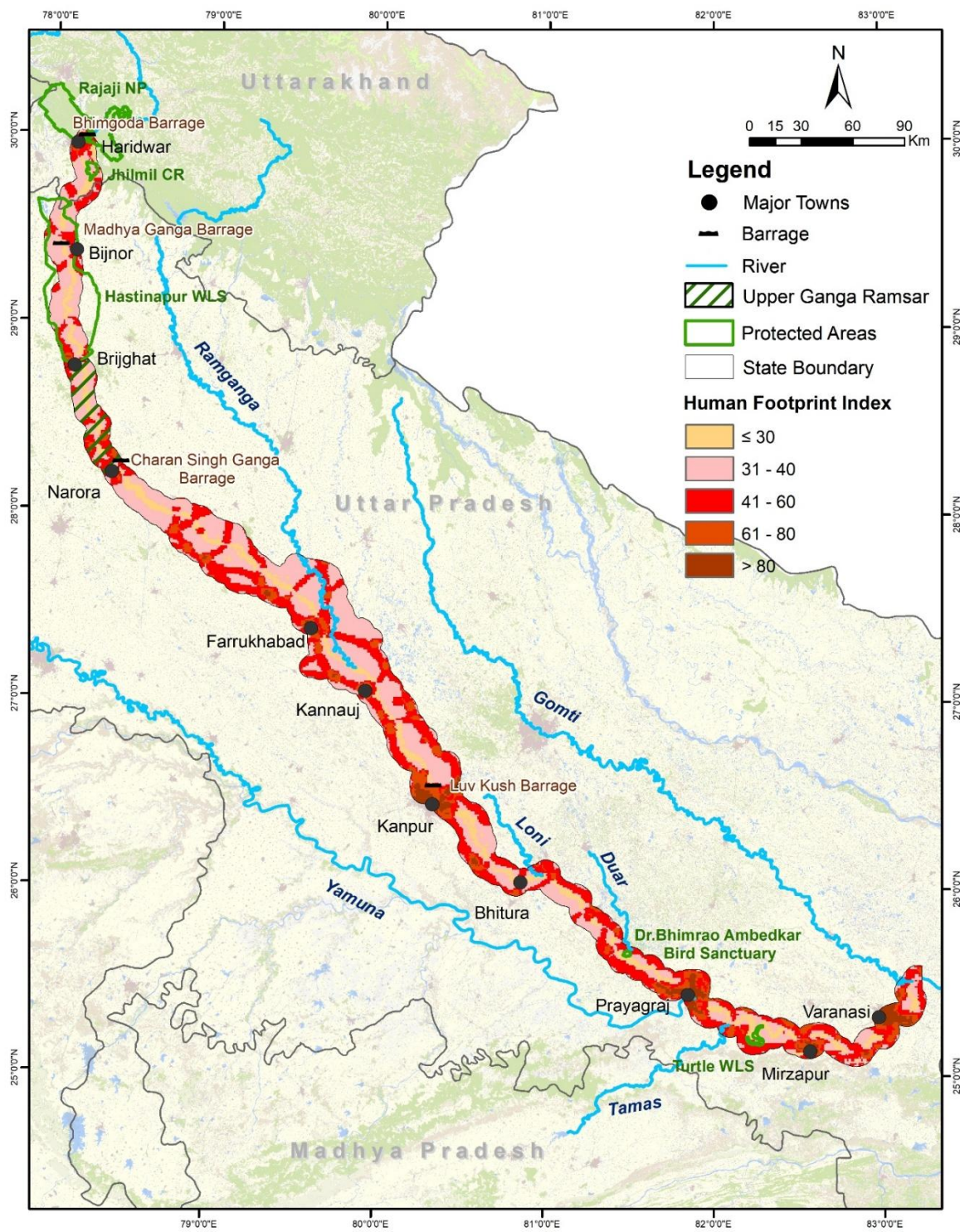


Figure 5.26. Human footprint

- **Temperature**

Warming temperatures, along with changes in precipitation contribute to the effects on aquatic systems (Gleick, 2009). Temperature influences the water flow, aquatic ecosystems, and biogeochemical processes, that lead to climate change, altered flow regime, increased evaporation and lower water levels. The temperature induced changes in river system have cascading effects on water resources and ecosystem services as well highlighting the need for adaptive management strategies. Temperature was derived from the Worldclim dataset. The continuous layer was reclassified in four thematic classes (Table 5.29). The Ganga River from upstream of Farukhabad to Gomti River confluence at Kaithi having higher temperature (>26 °C) covering 12434.57 km² and 68.72% of the total area. The Ganga River near Bhimgoda barrage at Haridwar having temperature ≤ 24 °C covers 29.52 km² area and 0.16% of the MGR (Figure 5.27).

Table 5.29. Temperature classes

Serial No.	Temperature (°C)	Area (km²)	Area (%)
1	≤ 24	29.52	0.16
2	24.1 to 25	772.74	4.27
3	25.1 to 26	4857.23	26.84
4	> 26	12434.57	68.72

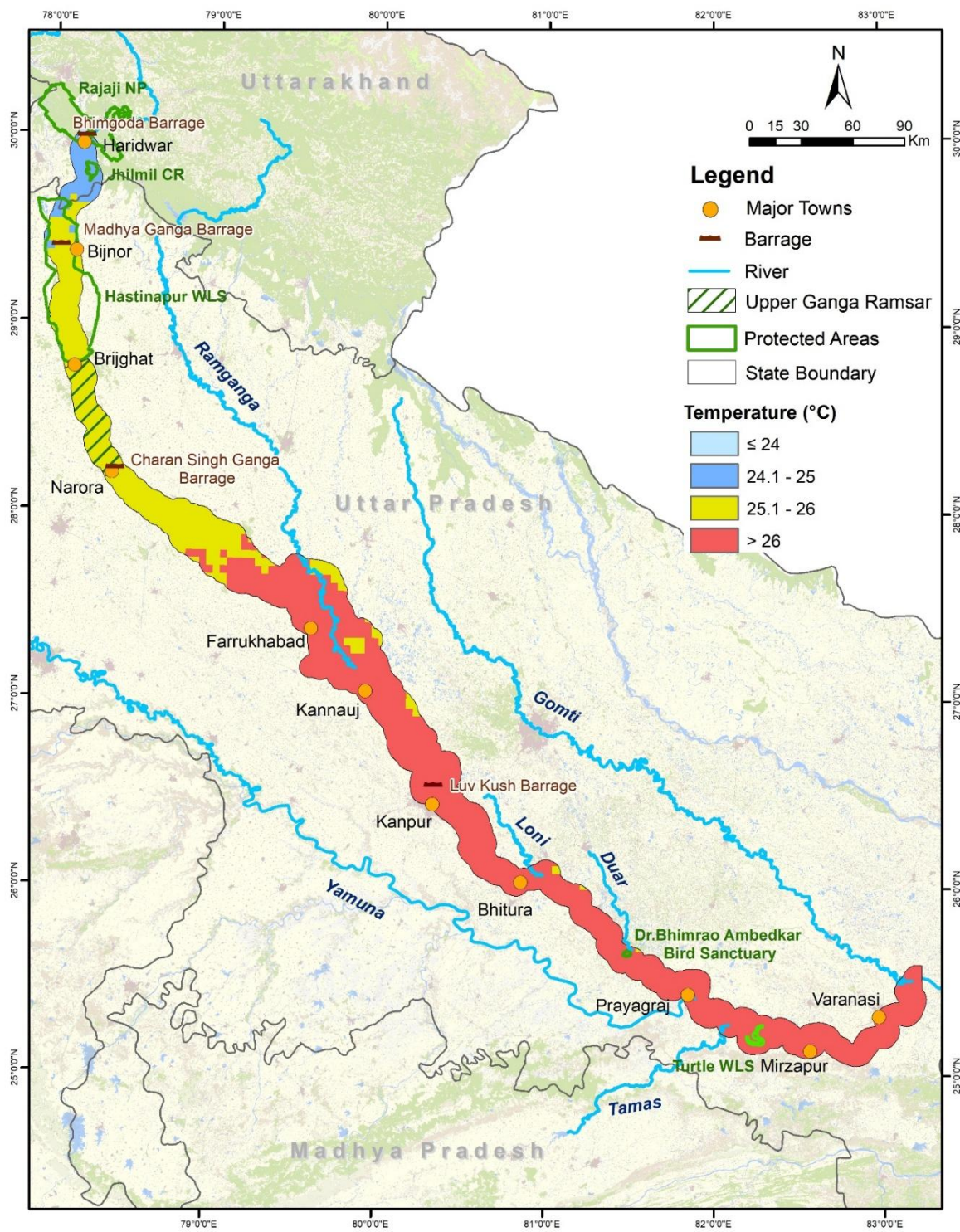


Figure 5.27. Temperature

5.3.4. Potential habitat area using Multi Criteria Decision Making

Assessment of potential habitat areas in river systems using Geographic Information Systems (GIS) combined with the Analytic Hierarchy Process (AHP) is a globally accepted approach for environmental management and conservation planning. GIS and remote sensing support the spatial analysis of riverscape by integrating environmental factors, physical factor, biological factors and anthropogenic factors influences ecological pattern and process in rivers (Eros & Lowe, 2019). The decision-making tool of AHP is used to assign weights to these factors based on their relative importance, facilitating the evaluation of multiple criteria simultaneously by creating weighted suitability map in river to augment suitable conditions for aquatic biodiversity (Zhang et al., 2023). The combined use of GIS and AHP has been successfully applied in various river systems, offering insights for habitat restoration, conservation priorities, and sustainable water resource management. Studies have shown the integrated approach provides more accurate and reliable habitat assessment (Store & Jokimaki, 2003). The derived potential habitat area was classified in four thematic classes (Table 5.30 and Figure 5.28).

The result shows that the Ganga River from downstream of Tamas River confluence at Sirsa to Gomti River confluence at Kaithi has high potential habitat areas for aquatic biodiversity covering 210 km river length and 3015.05 km² floodplain area, which is 21% of length and 16.66% of floodplain in the MGR. Turtle (Kacchua) Wildlife Sanctuary is located in this stretch of the Ganga River. Stretch from upstream of Duar River confluence near Dr. Bhimrao Ambedkar Bird Sanctuary at Kunda to Tamas River confluence at Sirsa has moderate potential habitat areas for aquatic biodiversity covering 110 km river length

and 1546.38 km² floodplain area, which is 11% of length and 8.55% of floodplain in the MGR. Stretch between downstream of Madhya Ganga barrage at Bijnor to Charan Singh Ganga barrage at Narora and downstream of Ramganga River confluence at Kannauj to Duar River confluence near Dr. Bhimrao Ambedkar Bird Sanctuary at Kunda has low potential habitat areas for aquatic biodiversity covering 370 km river length and 6309.31 km² floodplain area, which is 37% of length and 34.87% of floodplain in the MGR. Hydro-geomorphological status of the Ganga River between downstream of Jhilmil CR to downstream of Madhya Ganga barrage at Bijnor and downstream of Charan Singh Ganga barrage at Narora to Ramganga River confluence at Kannauj need to be restored to achieve sustainable habitat for aquatic biodiversity. These restoration areas are covering 310 km river length and 7223.32 km² floodplain area, which is 31% of length and 39.92% of floodplain in the MGR (Figure 6.28). The restoration area has maximum coverage in MGR, where natural flow needs to be maintained to sustain aquatic biodiversity (Figure 5.29).

Table 5.30. Potential habitat area classes

Serial No.	Potential habitat area	Area (km ²)	Area (%)	Length (km)	Length (%)
1	High potential area	3015.05	16.66	210	21
2	Moderate potential area	1546.38	8.55	110	11
3	Low potential area	6309.31	34.87	370	37
4	Restoration area	7223.32	39.92	310	31

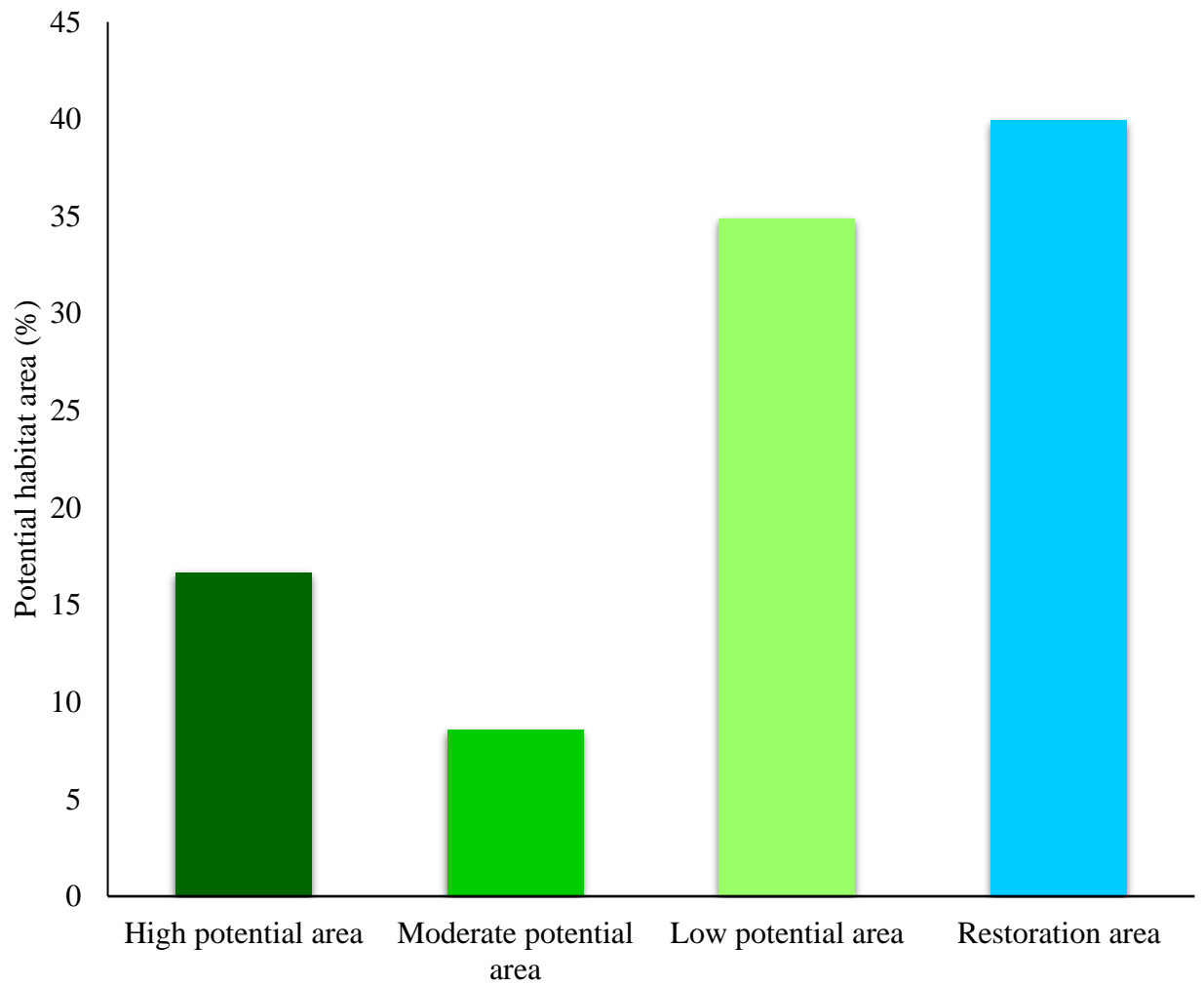


Figure 5.28. Potential habitat areas (%)

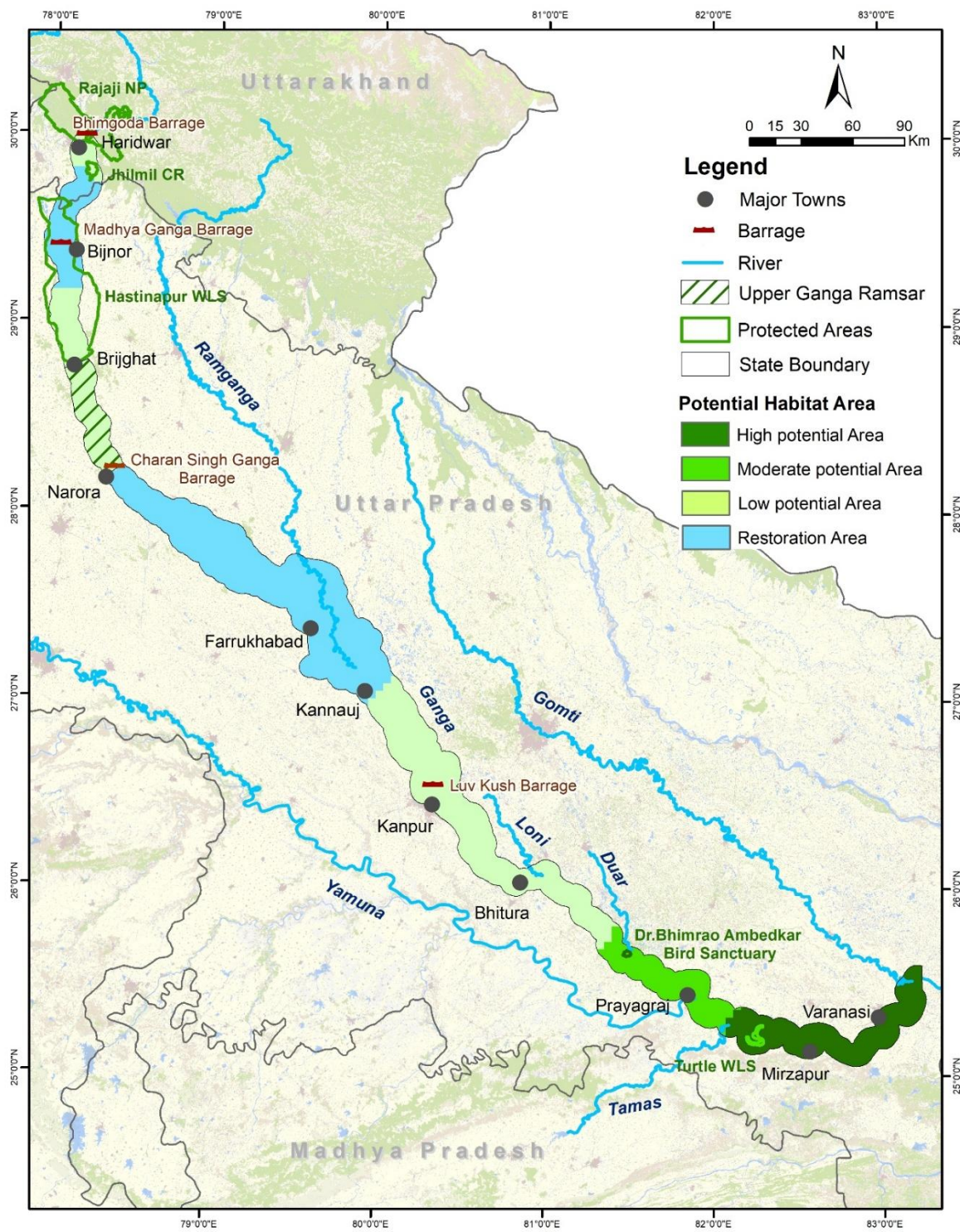


Figure 5.29. Distribution of potential habitat areas

5.4. Discussion

The free-flowing rivers maintains the natural fluvial ecosystem. The natural flow regime of the river, including variations in temporal discharge impacts the physical, environmental, and biological factors that augment to maintain the modifications in river morphology and encroachment to the floodplain changes the river flow. Anthropogenic pressure like over exploitation of freshwater resources is also responsible for the alteration in river's natural flow regime. The minimum flow needs to be maintained in the river system to sustain aquatic biodiversity irrespective of seasonal variation and E-flow in river system. Seasonal flow variations support ecological processes like species migration, and nutrient cycling. Alternated flow regimes impact aquatic biodiversity by affecting physical habitat, life history strategies of aquatic species, connectivity, and facilitating the invasion of exotic and introduced species (Bunn & Arthington, 2002).

Growing human needs altered the river's longitudinal connectivity by construction of barrages, which adversely affected the eco-hydrology of rivers, particularly at downstream of barrages (Mazumder, 2017). All the barrages in the MGR pose an artificial reservoir having higher depth, width, water availability. The river stretches located at downstream of barrages are highly fragmented by braided channels due to low flow regime and change in sediment grain size (Ghosh & Chakraborty, 2022). The downstream stretch having low depth, width and water discharge in general, have artificially formed sandbars, river islands and fragmented deep pools. Seasonal variations in water volume are very common in anthropogenically managed river system, it becomes wider due to

increased water discharge in monsoon and narrow in lean season due to low flow and more water extraction for irrigation, municipal, drinking and domestic usages. The width also varies depending on the surrounding topography and riverbed composition. The width and depth is highly regulated at downstream of barrages in the Ganga River due to diversion of water at upstream of barrages through canal system and release of rest of the water at downstream of barrages. Since the barrage controls the flow, the width and depth changes seasonally at downstream. Furthermore, sediment starvation due to the trapping at barrages may lead to riverbed erosion at downstream, potentially narrowing the channel over long period. In some areas, the downstream river may be submerged during monsoon and form a large floodplain, which is favourable for replenishment but detrimental for social aspect as the situation may create loss of human life. Construction of dams also increase the chance to grow alien species in river, which results to the loss of native species (Liew et al., 2016). The upstream of barrages have higher depth, width and water availability in general in the Ganga River, which forms favourable habitat conditions for key aquatic species like Gangetic dolphin (*Platanista gangetica*) but the condition is less suitable for reptiles like Gharial (*Gavialis gangeticus*), turtles due to low formation of sandbars and islands, which is used for basking sites for Gharial and turtle. However, the river at downstream of barrages are suitable for these reptilians as low water discharge at downstream forms braided channels along with sand bars and islands but species like Gangetic dolphin (*Platanista gangetica*) remains present only in selected deep pools at downstream of barrages in lean season (Sonkar & Gaurav, 2020). The habitats at downstream of barrages are highly fragile and prone to habitat loss due to eco-

hydrologically unregulated water release during monsoon. Conservation measure at upstream of barrages may be taken by restoring the riparian vegetation at river bank. The river islands and sandbars also need to be maintained seasonally to conserve small amphibians, reptiles and odonates. The depth also needs to be maintained throughout the year to fulfil habitat requirements of large species of aquatic mammals. Water needs to be maintained at downstream of barrages to connect the fragmented deep pools which will connect the river longitudinally leading to sustainable restoration of the Ganga River. The impact of barriers like barrages on river habitats is complex. By altering natural flow patterns, reducing water quality, disrupting sediment transport, and destroying surrounding ecosystems, barrages pose significant threats to aquatic biodiversity and the health of riverine environments. The mitigation measures aim to maintain some degree of maintenance for natural integrity and connectivity in the Ganga River systems, allowing for the continued movement of species and the preservation of ecosystem functions.

The assessment of stress factors in river system is critical for understanding their impact on aquatic biodiversity and implementing sustainable river management strategies. Riverine ecosystem is highly susceptible to wide range of stressors, including physical factors like geomorphological change, environmental factors like alteration in precipitation and temperature, anthropogenic factors like water extraction, construction of barrages and biological factors like invasive species to the aquatic ecosystem. Holistic approach with GIS, AHP offers better assessment of stress factors on river systems by allowing systematic mapping, prioritization, and quantification of stressors. GIS allows visualisation of spatial distribution for stress factors with overlapping areas and helps to

implement decision-making methodology like AHP particularly for prioritizing factors by weight calculation and ranking based on relative importance and pairwise matrix. The assessment of aquatic habitats in river systems is essential for managing biodiversity, preserving ecosystems, effective decisions regarding habitat restoration, conservation priorities, and stressor mitigation strategies. Understanding the spatial distribution of potential aquatic habitat is essential for conservation planning and sustainable river management. Natural flow regime of rivers is fundamental to maintain ecological integrity. Alterations to flow regimes, primarily due to human activities, have significant impacts on river ecosystems. High flow events in rivers redistribute sediment, maintain floodplain connectivity, and forms diverse aquatic habitats in river channels and riparian areas. Whereas, low flow condition governs reduction in water quality due to low water discharge and fragmented pools in the river that puts aquatic organisms in stress (Poff et al., 1997). E-flow regime is required in river to achieve desired ecological objectives (Acreman & Dunbar, 2004) that result in ecological recovery in regulated rivers, with 30% of taxa increasing in frequency at regulated sites following the implementation of the flows (Growth, 2016). Ecologically relevant environmental flows are essential for restoring the floodplain of rivers impacted by flow regulation and guiding flow restoration measures (Hayes et al., 2018). River management design must restore natural flow variability and achieve hydrological connectivity between a river and its surroundings for successful restoration (Palmer & Ruhi, 2019). Kaushal et al., (2019) assessed E-flow in the Ganga River basin to understand challenges and opportunities for implementation, which requires enhancement of water in the Ganga River. E-flow can be maintained in

the MGR by allocation of minimum water to all potential habitat areas to sustain aquatic biodiversity. Elevation gradient impacts drainage patterns and hydrology, as higher altitudes receive more precipitation forms snow or rain, feeding into the river system and influencing flow regimes. Rivers in elevated regions are more susceptible to sudden, high-magnitude floods due to rapid runoff during storms. Whereas, at lower elevations, river systems tend to have more stable, slower flow regimes, often heavily influenced by seasonal fluctuations in precipitation (Hanus et al., 2021). Urbanization and increased irrigation demand significantly contribute to increased surface runoff and water yield in the Ganga River basin, impacting hydrological regimes and requiring sustainable water resource strategies (Anand et al., 2018). Climate change and socio-economic changes, such as population growth, land use changes, and water transfers, will significantly impact the Ganga River system's flow and affect the water availability, water quality, and aquatic habitats (Jin et al., 2015). In another study Whitehead et al., 2018 suggested that climate change will increase river flows in India, but socio-economic changes, such as population growth and industrial development, will reduce water availability in drought conditions, threatening water supplies and ecosystems. Soil plays a crucial role in determining the health and diversity of aquatic ecosystems, influencing everything from sediment dynamics to water quality and the stability of habitats (Jana et al., 2018). Sandy soils allow for rapid water infiltration, leading to less surface runoff, whereas clayey or silty soils produce more runoff, increasing sediment delivery to the river, which results in higher turbidity and degrades water quality. Fine sediments in the river system can transport pollutants and excess nutrients, leading to eutrophication, algal blooms, and hypoxic

conditions that harm aquatic life (Wang et al., 2020). Anthropogenic factors like dams and barrages, water extraction, LULC changes have altered natural flow patterns in many rivers globally, which negatively affects species migration and aquatic habitats. Dams and reservoirs, designed to control water flow, interrupt sediment transport and disrupt the natural processes of erosion and deposition, resulting in downstream sediment starvation and altered channel morphology (Dynesius & Nilsson, 1994). Dams and barrages in the Ganga River system affect water flow, resulting in the accumulation of solid waste on the river bed and restricting the migration of aquatic fauna (Kumar et al., 2023). Eco-hydrological approach can enhance the sustainability and human well-being of the Ganga River by managing water, biodiversity, ecosystem services, and resilience (Singh et al., 2020). Conservation measures should focus on maintaining minimum flow for ecosystem processes as Gharial (*Gavialis gangeticus*) prefer sandy river banks and sand bars for basking (Hussain, 2009), alteration in flow regime of the Ganga River has resulted in the isolation and fragmentation of turtle populations (Bajaj et al., 2021), Gangetic dolphin (*Platanista gangetica*) abundance is positively influenced by river depth and adequate dry-season flows is important for ensuring river habitat connectivity for dolphins (Choudhary et al., 2012). Construction of large dams and barrages on the Ganga River has severely fragmented the dolphin habitat, causing changes in hydraulic geometry, flow characteristics, and loss of longitudinal and lateral connectivity (Sonkar & Gaurav, 2020). Freshwater biodiversity is threatened by overexploitation, water pollution, flow modification, habitat destruction, and invasion by exotic species globally, which requires action with a sustainable management approach (Dedgion et al., 2006). The river

modifications for human need are also a global concern. Fragmentation of rivers for over extraction of water and mining activity also forming shallow and narrow paleo channels in the Ganga River. The sufficient water is essential for natural depth and widening of river also. Deeper and wider channels allow dynamic flow patterns, promoting sediment deposition and the formation of different microhabitats essential for species diversity. However, shallow and narrower channels limit habitat availability, concentrate flow velocity, and reduce the diversity of habitats. Changes in channel depth and width, often influenced by human activities or river channelization, significantly impact the ecological health of river (Gregory, 2006). Maintaining natural flow variability is crucial for sustaining river ecosystems and ensuring the resilience of freshwater habitats (Dudgeon et al., 2006). The flow in the Ganga River is highly regulated which needs to be maintained for the natural connectivity of potential habitat and restoration areas.

The presence of multiple stressors significantly impacts biodiversity, water quality, and the overall ecological balance of river systems. Evaluation of direct and indirect effects of stressors helps in sustainable river management strategies for ecosystem resilience and policy making. Increasing pressures on river ecosystems from geomorphological change to human activity, regular monitoring is essential to maintaining ecological integrity and adaptive management. As the types of habitats are analogous to river hydro-geomorphology, the temporal alteration of fluvial dynamics like shifting river channels are important for sustainable river management. Flow dynamics such as discharge rates, seasonal variability, and hydrological patterns directly influence the ecological processes within aquatic habitats. The E-flow supports survival of aquatic species, facilitates

nutrient cycling, and ensures sediment transport, which is crucial for maintaining habitat diversity. Whereas, fluctuating water flows results into habitat degradation and loss of aquatic biodiversity. The maintenance of adequate natural water flow in the Ganga River, particularly in lean season ensures river connectivity and sustenance of aquatic biodiversity. High potential habitat areas are present in the Ganga River from downstream of Tamas River confluence at Sirsa to Gomti River confluence at Kaithi, followed by moderate potential habitat areas from upstream of Duar River confluence at Kunda to Tamas River confluence at Sirsa. Stretch between downstream of Madhya Ganga barrage at Bijnor to Charan Singh Ganga barrage at Narora and downstream of Ramganga River confluence at Kannauj to Duar River confluence at Kunda has low potential habitat areas. The stretches between downstream of Jhilmil CR to Madhya Ganga barrage at Bijnor, downstream of Charan Singh Ganga barrage at Narora to Ramganga River confluence at Kannauj need more conservation effort with strategic river management for aquatic biodiversity conservation.

The challenge of balancing human needs with environmental conservation requires integrated planning and consideration of the ecological sustainability of the Ganga River. The long-term ecological consequences of river modification through barrages need more study and policies to conserve freshwater biodiversity. The policies towards human dimension and alternate livelihood generation will minimize the dependencies of people on the Ganga River in terms of livelihood. Awareness activities about freshwater biodiversity have important role in freshwater biodiversity conservation and freshwater habitat management for aquatic biodiversity along the river. The policy frameworks for

water allocation at downstream of barrages, protection of freshwater species from anthropogenic activities, conservation freshwater biodiversity will help in rejuvenation and conservation of the river.

CHAPTER 6

PREDICTION OF FUTURE SCENARIOS BASED ON EXISTING DEVELOPMENTAL PLAN

6.1. Introduction

The Ganga River flows through the northern plains of India, serving as a source of irrigation, transportation, and a central part of religious and cultural identity of the nation. Over the past few decades, numerous developmental plans have been initiated to address the issues surrounding the river's health and sustainable management (Quadir, 2022). The prediction of future scenarios based on existing developmental plans in the Ganga River is an important aspect for ensuring its long term sustainability. The Ganga River is not only a source of livelihood for millions of people, but it is also an essential component of India's national economy. The future of the Ganga River hinges on the planning of effective management of water resources and environmental protection (Hussain et al., 2020). Prediction involves examining various ongoing initiatives and conservation efforts to forecast the future trajectory of the river in terms of water availability, ecosystem health, and habitat conservation for aquatic biodiversity. The role of scientific models and data analysis has high impact in predicting future scenarios. The developmental plans for the Ganga River are multi-faceted, encompassing a range of efforts designed to tackle

different aspects of river management. These plans include improving Land Use Land Cover (LULC), river discharge to maintain minimum flow, water quality, restoring ecosystems, promoting sustainable economic activities, and enhancing social well-being (Shukla et al., 2018). However, the success of these plans depends on their implementation and adaptation process. Consequently, the prediction of future scenarios requires an interdisciplinary approach, incorporating hydrology, environmental science, and biodiversity conservation. Moreover, it is critical to recognize the challenges involved in implementing large-scale projects, especially in regions those are prone to frequent floods, droughts, and other climate related disruptions. The complexity of predicting future scenarios becomes even more apparent when considering the river's cultural and religious significance. Given the diverse array of factors that influence the future of the Ganga River, the use of advanced technologies such as Remote Sensing (RS) and Geographic Information Systems (GIS) are important in predicting future scenarios. Data from various sources, such as satellite images, topographical sheets, discharge, biodiversity distribution, and demographic data are useful for the prediction of future scenarios (Whitehead et al., 2015).

One of the most pressing concerns when predicting the future of the Ganga is the issue of climate change. The Ganga River basin is junction to several major tributaries that originate from the Himalayas in north and central Indian highland in the south that changes precipitation patterns, shifting monsoon cycles, and significantly affects the Ganga River's flow and water availability. An increase in the glacial meltwater that feeds the Ganga River could lead to increase river flow, but in longer term the river flow will

decline with glacier shrink exacerbating water scarcity issues in the downstream regions (Rowan et al., 2017). Conversely, increased rainfall due to changing climate patterns could cause flooding and disrupt local communities, agriculture, and infrastructure. These scenarios will finally impact on the habitat of the freshwater biodiversity. Predictive models accounts for these uncertainties in order to provide a comprehensive assessment of the river's future.

6.2. Methodology

6.2.1. Future scenario of Land Use Land Cover and water flow

The prediction of future Land Use Land Cover (LULC) in the Ganga River requires an understanding of the interrelationships between socio-economic, environmental, and demographic factors, as well as the application of advanced tools and methodologies for spatial analysis. The process of predicting future LULC scenarios involves the use of both qualitative and quantitative methods (Anand et al., 2017). Traditional methods, such as expert opinion surveys and analysis of land use trends, provides valuable insights into past patterns and potential future developments. However, with the rapid advancements in technology and data collection Remote Sensing and Geographical Information System along with Machine Learning (ML) techniques are widely employed to assess the current state of LULC to forecast future changes under various scenarios. These technologies enable the analysis of large spatial datasets over time and provide more accurate and comprehensive understanding of land dynamics along the middle Ganga River (MGR).

Artificial Neural Networks (ANN) and Random Forests (RF), are increasingly being used to predict future land use changes based on historical data and environmental variables (Gharaibeh et al., 2020). These algorithms analyse complex relationships between various factors, including socio-economic drivers, policy interventions, and environmental constraints. By integrating these factors into predictive model different land use scenarios are generated potential impacts on the region's ecology and socio-economy. In case of the Ganga River, one of the most significant drivers of land use change is population growth (Shukla et al., 2018). As cities like Kanpur, Prayagraj, Varanasi continue to grow, the demand for land for human habitation, transportation, and industrial activities are increasing, potentially leading to the conversion of riparian areas as agricultural lands and natural habitats into builtup areas. This could exacerbate issues such as water scarcity, air pollution, and loss of biodiversity, which would directly impact the health of the Ganga River and its surrounding ecosystems. Agricultural practices along the MGR are also significantly changed. The region has long been a major agricultural hub, with vast areas of cropland supporting the cultivation of rice, wheat, sugarcane, and other crops (Kumar, 2017). However, the intensification of agriculture, driven by the need to feed a growing population, has led to the over extraction of groundwater, the use of chemical fertilizers and pesticides, and the conversion of wetlands into cropland. These practices result in soil degradation, reduced agricultural productivity, and pollution of water resources. Therefore, predicting the future trajectory of agricultural land use in the basin is important for ensuring that land use practices remain sustainable and do not further degrade the river and its resources. Additionally, climate change is a major concern to alter land use patterns

in the Ganga River. Changes in temperature, precipitation, and the frequency and intensity of extreme weather events could alter the suitability of different land types for agriculture, settlements, and natural habitats (Santy et al., 2020). Climate change may lead to shifts in the growing season of crops, affecting food production and land management practices. Furthermore, climate induced changes in the river's flow and sedimentation patterns could influence the location and stability of settlements, agricultural lands, and infrastructure along the riverbanks.

In recent years, the discharge and flow of MGR have been subjected to significant changes due to a combination of natural and anthropogenic factors. Predicting future scenarios of discharge and flow in MGR is essential for water resource management, flood control, agriculture, and the overall health of the river ecosystem. The Ganga River's discharge is influenced by a range of factors, including precipitation, snowmelt from the Himalayas, groundwater contributions, upstream water diversions, and land use changes within the catchment area (Whitehead et al., 2018). In the case of the middle Ganga, the discharge is also significantly impacted by seasonal variations, with monsoonal rains contributing to high flow during the summer months and reduced flow during the dry winter months. Additionally, human activities like, dam constructions, water extraction for irrigation, and pollution, have been altering the natural flow regime of the Ganga River (Gurjar et al., 2022).

To predict future discharge and flow scenarios in the middle Ganga, it is necessary to understand the key drivers that influence these factors. One of the primary drivers of flow

variability is precipitation, which fluctuates considerably due to seasonal monsoon patterns. The monsoon season brings heavy rainfall to the Ganga basin, particularly in the upper reaches of the river. This results in significant runoff that contributes to the river's discharge. However, over the past few decades, the region has witnessed shifts in the timing and intensity of the monsoon, with some areas experiencing erratic rainfall patterns, prolonged dry spells, or extreme flooding events (Swarnkar et al., 2021). These variations in rainfall could have profound implications for the river's flow, making it necessary to predict future monsoon trends and their impact on discharge. Another key factor is the contribution of snowmelt from the Himalayas. The Ganga River is fed by numerous glaciers in the Himalayas, particularly during the summer months when melting snow contributes to the river's flow. However, climate change has led to the accelerated melting of glaciers in the Himalayas, which could have significant consequences for the river's flow (Maurer et al., 2019). As glaciers continue to shrink, the seasonal contributions of snowmelt could become increasingly unreliable, leading to reduced river discharge, especially during the dry months when snowmelt plays a crucial role in maintaining flow. This change in the timing and volume of snowmelt could lead to more erratic flow patterns, with higher flows during the early summer but lower flows during the winter, when reliance on snowmelt is critical.

Human interventions in the Ganga River, particularly water extraction for irrigation and industrial purposes, have been altering the natural flow regime of the river (Swarnkar et al., 2021). The middle Ganga is heavily reliant on groundwater and surface water for agricultural activities, and large-scale diversion projects have modified the river's natural

discharge. This is exacerbated by groundwater depletion in some areas, which further diminishes the available surface water in the river (Kumar et al., 2021). Moreover, pollution, including untreated sewage, industrial effluents, and agricultural runoff, also affects water quality and river discharge by altering the chemical composition and sediment load in the river. These factors, coupled with rapid urbanization and land use changes along the river, are contributing to the disruption of the river's natural flow. Climate change is another significant driver that could impact the future discharge and flow in the MGR. As global temperatures rise, changes in precipitation patterns, snowmelt timing, and evaporation rates are expected to have profound impacts on the river's hydrological cycle. For example, higher temperatures could lead to increased evaporation rates, reducing the amount of water flowing into the river. Additionally, erratic rainfall patterns could result in more frequent droughts or floods, further complicating the prediction of discharge (Chaubey & Mall, 2023). Rising temperatures and changing precipitation patterns may also affect the groundwater recharge in the Ganga River, further influencing the discharge.

The data types have been used and processed in order to prepare spatial variables are slope, elevation, and LULC. The DEM dataset provided information on the elevation, allowing for the derivation of various topographic characteristics. Slope, a derivative from DEM, measures steepness of the terrain. The Euclidean distance approach was used to compute the distance from barrages. The decadal LULC has been processed for the evaluation of future land use pattern based on the present pattern of LULC change. The cellular automata model is used for simulation through Artificial Neural Network (ANN)

(Figure 6.1). The Cellular Automata (CA) and Markov Chain (MC) approaches for LULC future scenarios are well studied method. The spatiotemporal variations in LULC leads to an indication of loss and restoration of land use classes towards efficient land management strategies (Cowie et al., 2018). MC is a stochastic modelling approach and effective for monitoring temporal changes in landscape patterns depending on transitional matrices (Mishra & Rai, 2016). The CA model is capable of predicting the geographical distribution of landscape patterns (Saadani et al., 2020). These models combined with Artificial Neural Networks (ANN) are capable to address the accurate prediction of future scenarios.

6.2.2. Suitable riverine habitat prediction

The Ganga River, often revered as a sacred waterway, is a vital ecological and cultural resource for millions of people in India, particularly in the middle stretch. This stretch is home to a rich array of aquatic biodiversity, including endemic species such as the Gangetic dolphin (*Platanista gangetica*), various species of fish, turtles, birds, and other invertebrates that are essential to the ecological health of the river (Das et al., 2022). The Ganga River's middle reaches provide suitable habitats for these species, supporting not only biodiversity but also the livelihoods of the people who rely on the river for fishing, irrigation, and cultural activities. However, the future of these aquatic habitats is increasingly under threat due to human activities, climate change, and natural environmental shifts. Predicting the future scenario of river habitat status and its

implications for aquatic biodiversity in the MGR is essential for effective conservation strategies and sustainable river management.

MGR encompasses a variety of aquatic habitats, from fast flowing segments to slow moving river stretches, meandering stretches, deep pools and shallow floodplains (Kanhaiya et al., 2017). These habitats support diverse ecosystems and provide essential resources like food, oxygen, and breeding grounds for numerous species. However, the status of these habitats is rapidly changing due to factors like water pollution, over extraction of water for agriculture and industry, encroachment, infrastructure development (dams, barrages, irrigation canals), and climate change. Impact of these changes will affect the aquatic biodiversity in the future.

One of the most significant threats to river habitats and aquatic biodiversity in the middle Ganga is the increasing pollution. The Ganga has long been a recipient of untreated sewage, industrial effluents, and agricultural runoff, all of which contribute to the river's deteriorating water quality (Bowes et al., 2020). Pollutants such as heavy metals, pesticides, and untreated sewage not only reduce the oxygen levels in the river but also contaminate the food chain, posing a direct threat to the survival of aquatic species. The MGR faces severe pollution burden. Large urban centers such as Kanpur, Allahabad, and Varanasi release substantial amounts of untreated wastewater into the river, further degrading the ecosystem. Additionally, agricultural runoff, laden with chemicals like fertilizers and pesticides, often finds its way into the river, exacerbating nutrient loading, which leads to eutrophication, algal blooms, and reduced biodiversity.

The future scenario of river habitat status in the MGR will depend largely on the success of efforts to reduce pollution. If current trends continue, it is likely that the river will experience further deterioration in water quality, with potentially devastating consequences for aquatic biodiversity. Eutrophication could lead to the depletion of aquatic habitats, reducing the availability of food and breeding sites for fish and other MGR is the increasing demand for water due to population growth, agricultural intensification, and industrial expansion (Jaiswal & Pandey, 2019). The Ganga River in Uttar Pradesh is heavily utilized for irrigation, with vast areas of agricultural land dependent on the river for water. However, this extensive water extraction, particularly during the dry season, leads to reduced flow, which significantly affects aquatic habitats. As the river's flow diminishes, especially in the summer months, the aquatic habitats that rely on specific flow conditions, such as shallow riverine pools, floodplains, and wetlands dries up and become fragmented. This reduction in flow can also reduce the availability of oxygenated water, further harming species that rely on these habitats for breeding, feeding, and shelter.

Climate change is another pressing factor that will influence the future habitat status and aquatic biodiversity in the middle Ganga. Rising temperatures, altered precipitation patterns, and changes in the seasonal timing of snowmelt from the Himalayas will have a direct impact on the river's hydrological cycle (Khan et al., 2018). Increased temperatures result in lower water levels, especially in the summer months when river flow is already at its lowest. This would reduce the amount of available habitat for aquatic species, particularly in shallow, slow moving sections of the river. Additionally, warmer waters

can lead to lower dissolved oxygen levels, which would further stress fish and invertebrate populations that depend on higher oxygen concentrations. More extreme weather events, such as floods and droughts, are also expected to increase in frequency and intensity due to climate change, leading to more significant disruptions in aquatic habitats (Kelkar et al., 2022).

The construction of dams and barrages, along with the expansion of irrigation infrastructure, also have significant consequences for the status of river habitats in the middle Ganga. These structures often result in the fragmentation of aquatic habitats by impeding the natural movement of water and sediment. Dams can disrupt the natural flooding cycles that replenish floodplains, wetlands, and other critical habitats, while barrages can alter water flow and sediment transport, negatively impacting the river's aquatic food web (Sonkar & Gaurav, 2021). Additionally, these infrastructure projects can block fish migration routes, which are essential for spawning and dispersal of species. To mitigate these impacts and improve the future habitat status for aquatic biodiversity in the middle Ganga, several strategies may be considered. There is a critical need to improve pollution management, particularly by implementing better wastewater treatment systems in urban areas and reducing agricultural runoff through sustainable farming practices. The enforcement of stricter environmental regulations and policies to limit industrial discharge into the river will also play a vital role in enhancing water quality. Additionally, efforts to restore wetlands, floodplains, and riverbanks through habitat restoration projects can help maintain critical ecosystems and provide refuges for species vulnerable to habitat loss. Integrated water resource management (IWRM) strategies

should be adopted to balance water extraction for human needs with the conservation of aquatic habitats (Singh & Singh, 2020). This could involve the development of water-sharing agreements, better regulation of groundwater use, and improvements in irrigation efficiency to reduce the demand for water from the river. Moreover, modifying infrastructure projects, such as building fish-friendly dams and creating fish passageways, could help restore connectivity and protect migratory species. Addressing the impacts of climate change on river habitats will require adaptive management strategies that consider the changing hydrological conditions of the river. This may involve altering water management practices to accommodate shifting flow patterns, investing in climate-resilient ecosystems, and monitoring the river's health using advanced technologies such as remote sensing and satellite imagery to track changes in water quality and habitat conditions over time. The present habitat areas are considered to evaluate the probable habitat areas in future (Figure 6.1).

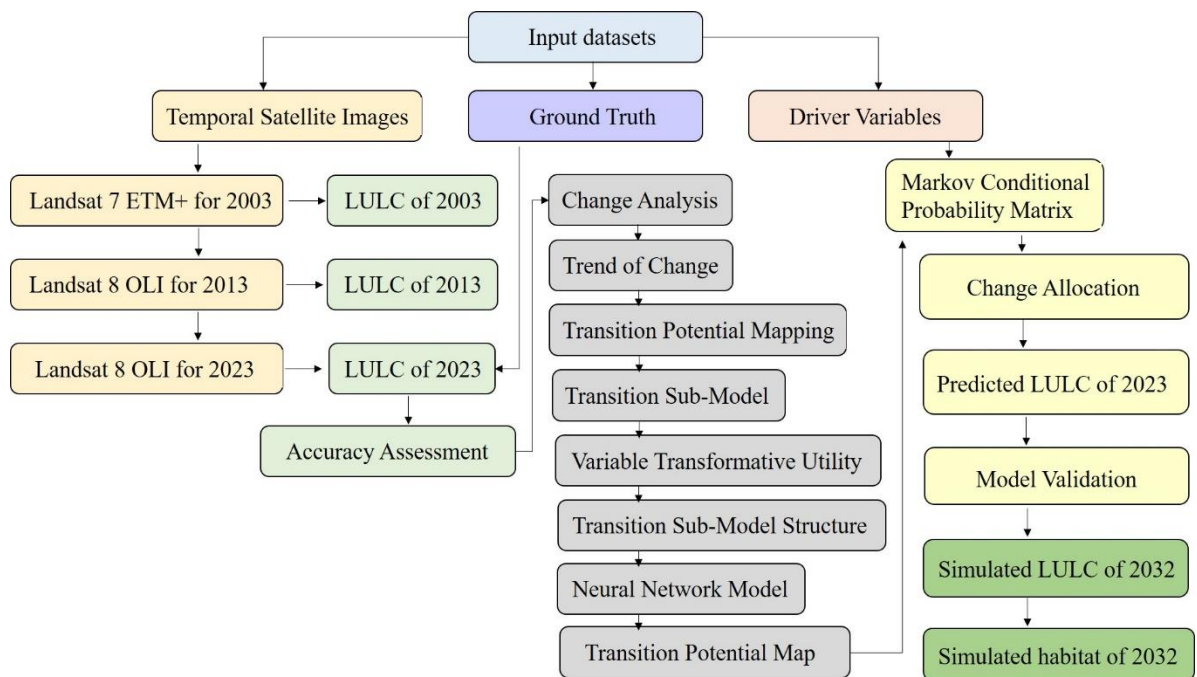


Figure 6.1. Methodology flow chart for prediction of future scenarios

6.3. Result

6.3.1. Predicted Land Use Land Cover

The ANN, CA, and MC algorithms were combined to predict future LULC scenarios for the year 2032 using machine-learning techniques (Gharaibeh et al., 2020). Transition potential maps were prepared to predict future LULC changes for assessment of likelihood in various LULC transitions occurring in the study area (Arora et al., 2021; Hussien et al., 2023). The model considers multiple factors that influence LULC change to generate transition potential maps (Gharaibeh et al., 2020). LULC transformation trend are assumed to have the same underlying driver variables between two periods were

grouped into a series of experimentally evaluated transition sub-models to develop transition potential map. After specifying the sub-models, the driver variables were added to the model as a static and dynamic component. Spatial driver variables are the various biophysical, socio-economic, and demographic factors that influence LULC change (Leta et al., 2021). The significance of the driver variables during the future LULC change projection was tested using Cramer's V coefficient (Girma et al., 2022; Hussien et al., 2023). The coefficient ranges from 0 to 1, with higher values suggesting a stronger relationship between the two variables (Leta et al., 2021). After developing transition potential maps, LULC change prediction was carried out using stochastic modelling algorithms of CA-MC. The CA model simulates the spatial dynamics of LULC changes, while the MC model estimates the probabilities of transition between different land use categories based on trends. The predicted LULC (Figure 6.2) of 2032 shows that the river channels are more fragmented and decreased than 2023 whereas the sandbars and islands have increased particularly at downstream of Bhimgoda barrage, Charan Singh barrage, Madhya Ganga barrage and LuvKush barrage. The downstream area of Prayagraj is also having increasing trend in formation of sandbar and island. In the floodplain of MGR, barrenland has increased mainly at downstream of Charan Singh barrage and LuvKush barrage. Agriculture area has decreased from 2023, because of high dependency of increasing human population on river and higher demand of residential lands lead to conversion of riparian areas into builtup. The builtup areas are showing increasing trend in future prediction (Figure 6.3).

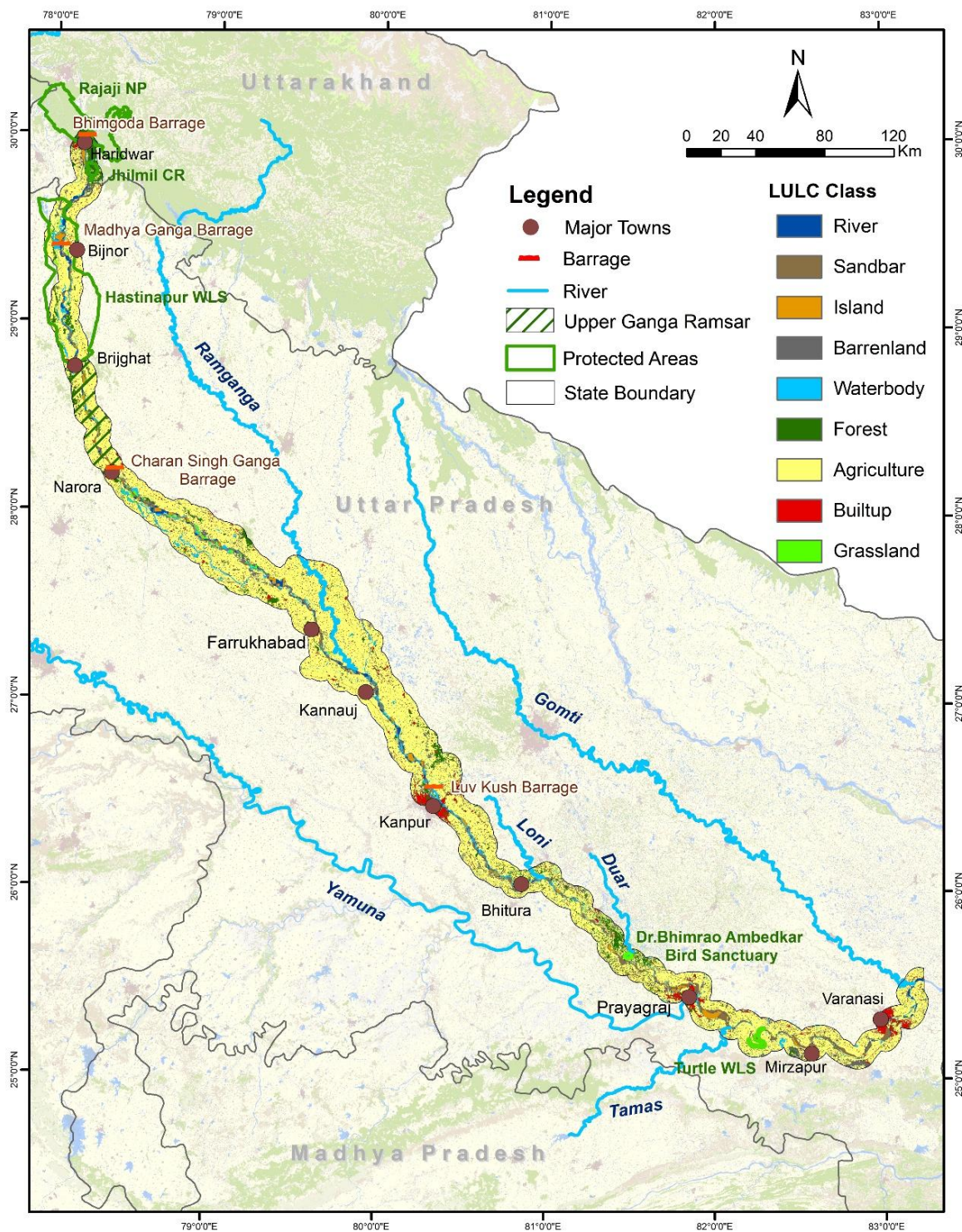


Figure 6.2. Predicted Land Use Land Cover 2032

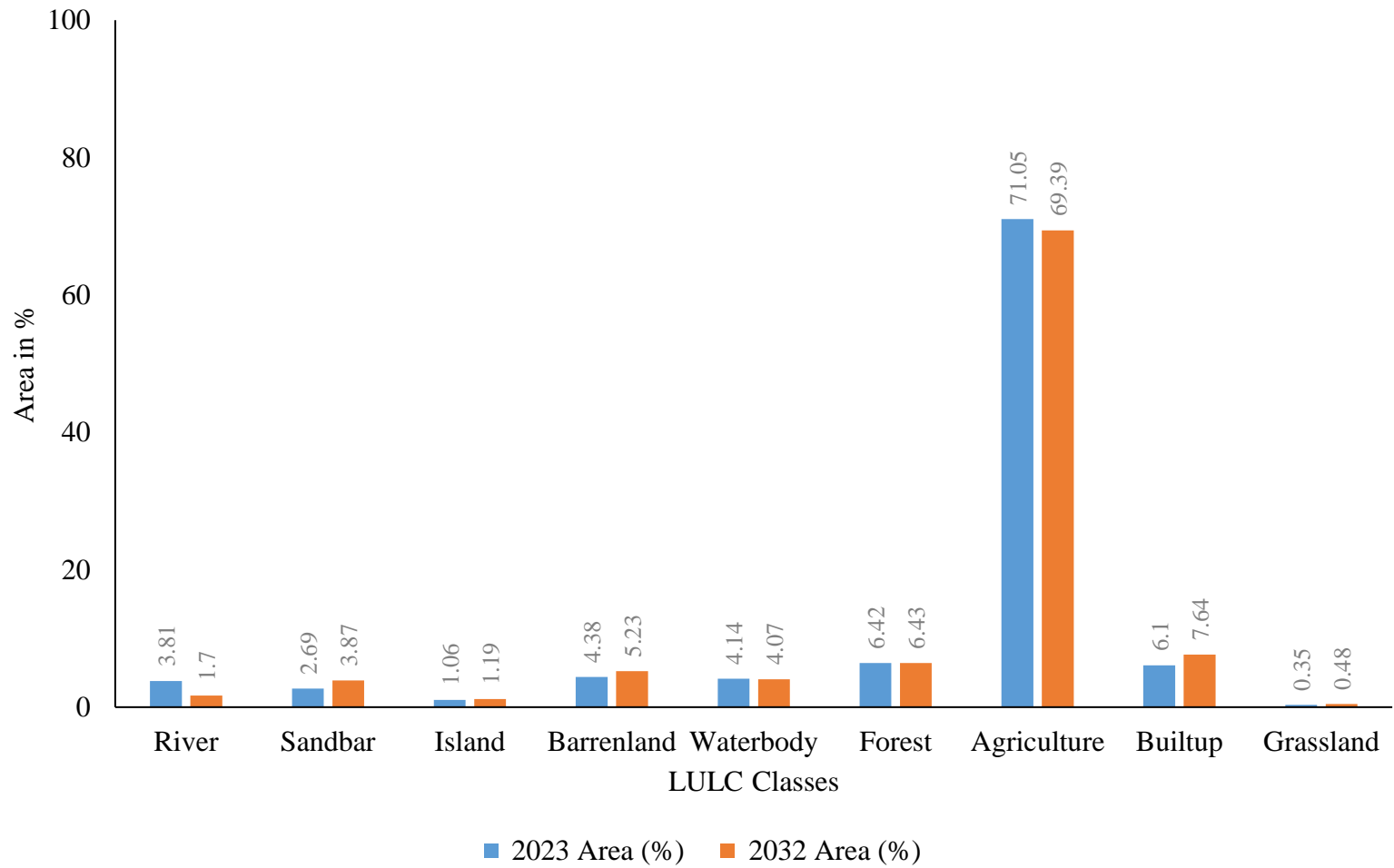


Figure 6.3. Comparative Land Use Land Cover area (%)

6.3.2. Suitable predicted riverine habitat

The predicted riverine habitat for large species like Gangetic dolphin (*Platanista gangetica*) has resulted to be confined in the deep water pools only in fragmented stretches, particularly at upstream of barrages and downstream of the tributary confluences in the Ganga River. The downstream of barrages and the river stretches where inflow of water through tributaries are not present, will lack habitat for these species. Whereas, increasing trend of sandbars and islands indicates that habitat for reptiles like Gharial (*Gavialis gangeticus*), turtles and amphibians will be present in river both at upstream and downstream of barrages and upstream and downstream of tributary confluences. The habitats located at upstream river stretches of barrages and downstream river stretches of tributary confluences will act as regulated habitat for freshwater biodiversity but the habitats located at downstream river stretches of barrages and upstream stretches of tributary confluences may be fragile due to unregulated release of water at downstream of barrages during monsoon season. River stretches flowing through protected areas are conserved due to policy and legislation but the conservation initiatives of river stretches outside protected area boundary are quite challenging. Conservation of riparian habitat is very essential for aquatic biodiversity conservation.

6.4. Discussion

The Ganga River is one of the most significant rivers both geographically and culturally. Middle stretch of the Ganga River, especially areas within the state of Uttar Pradesh has experienced substantial shifts in land use patterns over the past decades (Anand et al., 2017). These shifts, in turn, has profound impacts on aquatic habitats and biodiversity in the region. The middle Ganga have a fertile alluvial plain, where significant changes seen in land use, primarily due to increasing population density, agricultural expansion, industrial development, and urbanization. The floodplain, which is having natural riverine wetlands, have increasingly been converted into agricultural land, urban areas, and infrastructure projects. Land use alteration in the region has been driven by direct and indirect factors, affecting terrestrial and aquatic ecosystems.

Agriculture has been the primary land use in the middle Ganga riverscape, and its intensity has increased over time (Kumar et al., 2023). Historically, the Ganga River's floodplains were naturally flooded, enriching the soil and supporting a diversity of aquatic species. However, as agricultural activities expanded, wetlands were drained, and floodplains were converted into cropland for cultivation. Urban sprawl along the river, particularly in cities like Kanpur, Varanasi, and Prayagraj has led to the encroachment of the Ganga River's natural habitat. The construction of dams, barrages, embankments, and highways has altered the natural flow of the river and disrupted the movement of aquatic species (Kumar et al., 2023). The expansion of urban settlements has also contributed to pollution, with untreated sewage and industrial effluents being discharged into the river. This has

significantly reduced water quality, posing a serious threat to the aquatic biodiversity of the Ganga River. Industrialization has also increased in the middle Ganga region, particularly in areas near urban centers. Industrial activities, including the textile, paper, and chemical industries, have led to the discharge of hazardous pollutants into the river. The alteration of land use in these areas has contributed to habitat fragmentation, further compromising biodiversity. Deforestation and land degradation in the MGR have exacerbated the environmental challenges faced by the river (Singh & Singh, 2020). Forest cover in the upper reaches of the basin, particularly in the states of Uttarakhand and Uttar Pradesh, has been reduced due to logging, agriculture, and infrastructure development. This has increased the runoff into the river, resulting in siltation and the loss of water clarity, which affects aquatic species' ability to thrive. Soil erosion, a result of land degradation, has further increased sedimentation in the river, which affects the habitat of aquatic organisms.

The shifting land use patterns in the MGR have far reaching consequences for the aquatic habitat (Shukla et al., 2018). The river and its tributaries support a diverse range of aquatic species, including several endemic and endangered fish species, amphibians, and invertebrates. The degradation of aquatic habitats is attributed to multiple factors. The changes in land use, especially the increasing agricultural and industrial activities, have led to the deterioration of water quality in the Ganga River. The excessive use of fertilizers and pesticides in agricultural practices has led to nutrient loading, resulting in eutrophication (Shah & Parveen, 2021). This process promotes the growth of algae, which depletes oxygen levels in the water, creating hypoxic conditions that are detrimental to

aquatic life. The discharge of untreated sewage and industrial effluents has further exacerbated the situation, introducing harmful chemicals and pathogens into the water. The contamination of the Ganga River has become a significant concern for both aquatic biodiversity and human health. Middle segment of the Ganga River is home to several species of conservation significance, such as the Gangetic dolphin (*Platanista gangetica*), Gharial (*Gavialis gangeticus*) turtles, and variety of fish species. The alteration of land use has led to habitat loss, particularly in wetlands and floodplains, which serve as critical breeding and feeding grounds for these species (Saha et al., 2022). Dams, barrages, and other infrastructure projects have also obstructed fish migration, further threatening the populations of migratory species. Construction of dams and embankments to control flooding and generate hydroelectric power has drastically altered the natural hydrological flow of the river. The seasonal flooding of the river's floodplains, which was a natural process that enriched the soil and supported biodiversity, has been disrupted. The reduction in the flow of water during the dry season and increased flow during the monsoon period has affected aquatic species that depend on specific flow conditions for breeding and feeding. The altered hydrology has also impacted sediment transport, leading to changes in the riverbed and further disrupting aquatic habitats. Increased soil erosion due to deforestation and agricultural expansion has led to higher levels of sedimentation in the MGR. The deposition of silt and sediment affects the river's water quality, reduces its depth, and alters the composition of the riverbed. These changes affect the habitat of benthic organisms and reduce the availability of suitable habitats for fish

and other aquatic species. Excessive sedimentation also obstructs the flow of water, contributing to the silting of river channels and the destruction of wetland ecosystems.

To address the challenges posed by shifting land use and its impact on aquatic habitats in the MGR, concerted efforts are needed to promote sustainable land use and effective river management. A holistic approach to river basin management is essential to balance the demands of agriculture, industry, and urbanization while safeguarding aquatic habitats (Hussain et al., 2020). This approach should involve the coordination of water management, land use planning, and conservation efforts across different stakeholders. Effective pollution control measures, including the establishment of wastewater treatment plants and stricter enforcement of environmental regulations, are crucial to reducing the discharge of industrial and domestic effluents into the river. Additionally, promoting the use of organic farming practices will be effective to reduce nutrient runoff from agricultural lands. The restoration and protection of riverine wetlands and floodplains along the MGR are essential to maintaining biodiversity and ecosystem services. These areas act as natural filters, providing habitat for a wide range of species and improving water quality by absorbing excess nutrients and contaminants. Local communities living along the Ganga River must be actively involved in conservation efforts. Education and awareness programs will aware people about the importance of sustainable land use and the role they play in protecting the river and its aquatic ecosystems.

The middle Ganga River and its freshwater biodiversity needs to be conserved by implementing sustainable river restoration measures along with biodiversity conservation

activities by both of policy makers and local communities involving multiple stakeholders associated with the Ganga River.

CHAPTER 7

SUMMARY AND CONSERVATION IMPLICATION

7.1. Summary

The Ganga River, which is sacred in terms of its cultural and spiritual heritage, is a symbol of sustenance and life for millions of Indians. It functions as a natural artery linking ecological and human societies is beyond dispute. Nevertheless, in the past decades, the ecological health of the Ganga, especially in the middle reach, has been continually undermined by a range of anthropogenic pressures. This study examined the geomorphological, hydrological, and ecological aspects of the middle Ganga River (MGR) with special emphasis on the impacts of land use and land cover (LULC) transitions, river flow changes, drainage pattern alterations, and habitat fragmentation. Through this study, the need for adopting a region-specific, integrated river basin management approach was reaffirmed, emphasizing the need for restoring the natural dynamics of the river and ensuring sustainable utilization of its resources.

The length of study site is about 1000 km from Bhimgoda barrage, Haridwar to Gomti River confluence, Kaithi in Varanasi flows through ecologically and socio-economically varied landscapes. Through flow of the river between the two states of Uttarakhand and Uttar Pradesh, it is supplied by glacial melting, monsoon rains, and a system of tributaries like the Yamuna, Ramganga, Gomti, and Garra. These tributaries, with a dendritic pattern of drainage, play an important role in the hydrological regime and sediment dynamics of the Ganga basin. The area is rich in biodiversity, sustains intensive agriculture, and supports dense human populations.

Nevertheless, the combined effect of urban sprawl, deforestation, industrialization, and agricultural encroachment has largely altered the morphology of the river and compromised its ecological functions.

One of the main findings of the study is that river hydrodynamics and land use are closely interconnected. Land cover changes e.g., wetland and forested riparian areas converted into agricultural lands or urban settlements, have not only changed runoff characteristics but have also disturbed the geomorphic processes required for the natural development of the river. The application of chemical fertilizers and the dumping of untreated sewage and industrial effluents into the river have reduced water quality and hastened eutrophication. In addition, deforestation and land degradation in the upstream areas have aggravated erosion, raised the sediment load and altered the structure and flow characteristics of the riverbed. These onshore perturbations have produced a shift from the deep, sinuous, and permanent channels to more braided, shallow, and broken streams, especially downstream of barrages and embankments.

Construction of hydraulic works, dams, barrages, and embankments has also enlarged the extent of ecological perturbation. Although these facilities were established for purposes of irrigation, hydroelectric power, and flood protection, they have surprisingly modified the natural flow regimes of the river. Disturbances in longitudinal connectivity have restrained sediment transport, altered the timing and volume of water flows, and diminished the natural variability of the river. These changes are harmful to the ecological integrity of the system, especially for species depending on seasonal and spatial variability in water conditions to feed, migrate, and reproduce.

For example, the Gangetic dolphin (*Platanista gangetica*), a bioindicator of river health, is found in deep, slow-flowing waters and relies on continuous flow for migration and habitat choice. Segmentation of the river and decrease in deep pools due to sedimentation and decreased flow have isolated dolphin populations in disconnected stretches, making them more vulnerable. Likewise, the Gharial (*Gavialis gangeticus*) and freshwater turtles need sandbanks for basking and nesting, which have been reduced as a result of persistent alterations in sediment dynamics and human settlements. Fish populations, some of which are migratory and spawn during particular flow phases, are also highly affected by the flow barriers and water quality alterations. These perturbations have initiated cascading impacts throughout the aquatic food web, resulting in a reduction of both biodiversity and ecosystem function. In addition to biodiversity loss, the alterations of river hydromorphology and water quality have implications for key ecosystem services. Natural processes of sediment transport maintain soil fertility throughout floodplains, facilitating productive agriculture and flood-recession farming. But while too much sediment deposition in channels and limited lateral connectivity between rivers and floodplains caused by embankments have limited this natural advantage, the destruction of wetlands, essential for water purification, nutrient storage, and carbon storage has undermined the ecosystem's capacity to regulate itself. Consequently, the river's ability to supply clean water, absorb floods, and sustain livelihoods has been severely compromised.

7.2. Conservation implication

This research reiterates the necessity for a paradigm shift in river management of rivers such as the Ganga River. Traditional, infrastructure-based river management

approaches focusing on engineering solutions tend to disregard the ecological richness and resilience strategies of river systems. Hence, an integrated river basin management (IRBM) approach is necessary that considers the ecological, hydrological, geomorphological, and socio-economic aspects of river systems.

The protection and sustenance of environmental flows (E-flows) is essential for river's ecohydrology. E-flows are the amount, timing, and quality of the flow of water to maintain aquatic ecosystems and the human livelihoods that depend on them. Maintaining minimum flows throughout the year, particularly during the dry season, is vital in sustaining the hydraulic conditions as per the sustainability of freshwater species demand and ensuring sediment balance. This calls for re-examination of dam operation, water abstraction policy, and inter-basin water transfer. Water governance authorities need to factor in E-flow analysis in their decision-making so that development and ecological sustainability can be maintained together.

Along with hydrological restoration, spatial planning and land use regulation need to be coordinated with river conservation goals. Riparian zones and floodplains must be declared ecological buffer zones, where intensive agriculture, construction, and industrial use are prohibited. Native riparian vegetation should be restored, and riverine wetlands should be reconnected to the main channel, which improve biodiversity, water quality, and carbon sequestration. Contemporary spatial technologies like Remote Sensing, Geographic Information Systems (GIS), and Analytical Hierarchy Process (AHP) models assist in delineating high-priority conservation areas, tracking landscape dynamics, and informing restoration planning. The technologies also enable evidence-based policymaking through data on erosion risk areas and habitat suitability.

Pollution control is also an essential element. The removal of nutrient and contaminant loads into the river must be ensured to stop further deterioration. This involves the reinforcement of wastewater treatment facilities, organic and low-input agriculture, enforcing effluent discharge standards, and persuading industries to use cleaner production technologies. Just as vital is the requirement for community-based monitoring and public education to foster responsible water use and pollution avoidance.

In addition, participatory governance and stakeholder engagement are central. Local people, who are dependent directly on the river for livelihood, should be engaged in river conservation planning and surveillance by straitening them with alternative livelihood options. Their customary wisdom, linked with scientific information provide location-specific, culture-sensitive options. Education, capacity development programs, and stakeholder decision-making processes enable a sense of guardianship and equip communities to push for river well-being.

In the future, the implications of climate change bring new challenges and opportunities to river basin management. Increased temperatures, altered monsoon patterns, and more frequent occurrence of extreme events like floods and droughts will further stress the hydrological regime of the Ganga River. Adaptive management plans have to be framed to accept this uncertainty. These may be nature-based measures like floodplain reconnection, wetland restoration, and green infrastructure that are flexible and resilient to climatic shocks. Climate-smart water allocation, along with early warning systems and risk assessment, help protect the Ganga River ecosystems.

The results of this thesis also have general applicability for other large rivers under similar stresses worldwide. The integrated, science-based approach to river

management presented here may be replicated and adapted to river systems at global scale confronting rapid development, urbanization, and environmental deterioration. This study may be used for promoting interdisciplinary research, and integrating ecological imperatives into development planning by putting in place cross-sectoral collaboration to map out a sustainable way for ecohydrological river management.

In summary, the middle Ganga River is an important segment of the urgent necessity to balance river development and environmental conservation. The sustainability and health of the Ganga River are connected to its geomorphic processes, hydrological cycles, and ecological integrity of habitats. Anthropogenic processes have reorganized and fragmented the river in ways that conflict with both biodiversity and ecosystem services on which human societies depend. In order to meet these challenges, holistic river management based on environmental flows, land use planning, pollution abatement, and participatory governance is critical. Future actions need to be adaptive, based on strong scientific evidence, and driven by an image of ecological resilience and socio-economic justice.

The future relevance of this study is manifold. It offers a strategy for sustainable river management in the context of environmental stress and climatic variability. It appeals to institutionalizing the norms of E-flow, constructing predictive land use and hydrological change models, and including measures of biodiversity in river planning. Most importantly, it appeals to policymakers, researchers, and the people at large to think about the Ganga River as not merely a water source, but a living dynamic entity whose conservation is crucial to ecologic equilibrium, cultural legacy, and inter-generational equity.

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Sk Zeeshan Ali <zeeshanearth@gmail.com>

Discover Applied Sciences: Decision on "Assessment of fluvial stressor dynamics and riverine habitat resilience to environmental flow in the middle Ganga River"

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To: zeeshanearth@gmail.com

Tue, Apr 29, 2025 at 5:15 PM

Dear Dr Ali,

Re: "Assessment of fluvial stressor dynamics and riverine habitat resilience to environmental flow in the middle Ganga River"

We are delighted to let you know that the above submission, which you co-authored, has been accepted for publication in Discover Applied Sciences.

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Assessment of fluvial stressor dynamics and riverine habitat resilience to environmental flow in the middle Ganga River

Sk Zeeshan Ali¹, Ashish Mani¹, Srijani Guha¹, Ruchi Badola¹, Syed Ainul Hussain^{1*}

¹ Ganga Aqualife Conservation Monitoring Centre, Wildlife Institute of India, Chandrabani, Dehradun-248001, Uttarakhand, India

*Corresponding author's email: ainul.hussain@gmail.com

Abstract

Changes in fluvial characteristics, water flow regimes, and anthropogenic pressure have severely impacted the middle Ganga River, leading to resource scarcity for aquatic biodiversity. Despite the importance of habitat assessment in managing these ecosystems, gaps remain in understanding the process to fluvial stress factor, maintenance of minimum water to sustain Environmental flow (E-flow) and delineating potential riverine habitats for biodiversity. This study aims to identify clusters of riverine habitats. We used Geographic Information System (GIS) and Analytical Hierarchical Process (AHP) to undergo Multi Criteria Decision Making (MCDM) analysis. Weights assigned to variables based on their ecological significance, achieving a favourable consistency ratio of 0.0276 in model validation. The resulting potential habitat areas are categorized into four classes i.e., high, moderate, and low potential area along with restoration area. Key findings indicate that Ganga River from Sirsa to Kaithi has high potential habitat for aquatic biodiversity. Stretch between Jhilmil Jheel Conservation Reserve to Bijnor and Narora to Kannauj need more conservation effort for aquatic biodiversity. Particularly, stretches downstream of tributary confluences possess high potentiality for supporting species, such as the Gangetic dolphin (*Platanista gangetica*), whereas, sand bars and islands are important habitat for Smooth coated otter (*Lutrogale perspicillata*), Gharial (*Gavialis gangeticus*), Turtles and birds. River sections between barrages, particularly those lacking tributary input, are critical for species survival. This study underscores the need for effective management strategies to address fluvial stressors and enhance habitat conservation for aquatic biodiversity in the Ganga River system.

Keywords: River, Fluvial, Stress factor, E-flow, Biodiversity, Habitat.



Sk Zeeshan Ali <zeeshanearth@gmail.com>

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ind for <indfor1875@gmail.com>

Tue, Mar 25, 2025 at 4:22 PM

To: zeeshanearth@gmail.com, Syed Ainul Hussain <ainul.hussain@gmail.com>

Sir,

It is to inform that your article titled "Delineation and mapping of riverine wetlands in the middle Ganga River using geospatial technology" authored by SkZeeshan Ali, Srijani Guha, Ashish Mani, AmbikaNandini R Menon, Shivani Barthwal, Ruchi Badola and Syed Ainul Hussain

has been accepted for publication in the early coming issue of the Indian Forester (ISSN : 0019-4816, eISSN 2321-094X), VOLUME 151.

Thanks and regards

THE INDIAN FORESTER

Delineation and mapping of riverine wetlands in the middle Ganga River using geospatial technology

Sk Zeeshan Ali¹, Srijani Guha¹, Ashish Mani¹, Ambika Nandini R Menon¹, Shivani Barthwal¹, Ruchi Badola¹, Syed Ainul Hussain^{1*}

¹ Ganga Aqualife Conservation Monitoring Centre, Wildlife Institute of India, Chandrabani, Dehradun-248001, Uttarakhand, India

*Corresponding author's email: ainul.hussain@gmail.com

Abstract

The wetlands are natural sink of pollutants and provides ecosystem services worldwide. Rapidly declining water resources is a global concern, underscored by international conventions such as the Ramsar Convention on Wetlands. The riverine wetlands are located at river floodplain and seasonally connected with the mainstem river. Delineation and mapping of these wetlands are important to visualize their distribution pattern. We conducted the study in the middle Ganga River using geospatial techniques to delineate and map riverine wetlands. Result shows the wetlands are distributed along the active river channel in the Ganga River floodplain, which are seasonally connected with the Ganga River in monsoon. The wetlands are replenished with nutrients during fluvial connectivity. Wetlands are delineated and mapped (N=788) using Landsat 8 OLI satellite image by Modified Normalized Difference Water Index (MNDWI) by separating the water and land area using green and short wave infrared spectral bands of satellite image. These wetlands are home to various aquatic and water associated avian species, amphibian and reptiles. Conservation measures for these riverine wetlands are essential for sustainability of wetland ecosystem and wetland inhabiting flora and fauna and rejuvenation of the Ganga River system. Some of the wetlands are declared as protected area and Ramsar conservation sites, whereas more wetlands are need to be conserved under national conservation authority to conserve their natural integrity and to protect its biodiversity. This study provides insights and framework for freshwater habitat management for aquatic biodiversity.

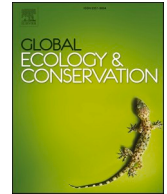
Keywords: Riverine wetland, Floodplain, Habitat, Biodiversity, Mapping.



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Conservation planning for Gangetic dolphin (*Platanista gangetica*) in smaller rivers of the Ganga River Basin, India

Goura Chandra Das^{a,1}, Aftab Alam Usmani^{a,2}, Surya Prasad Sharma^{a,3}, Srijani Guha^{a,4}, Sk Zeeshan Ali^{a,5}, Shivani Barthwal^{a,6}, Arkojyoti Sarkar^{a,7}, Neeraj Mahar^{a,8}, Ajay Rawat^{a,9}, G. Gokulakrishnan^{a,10}, Javed Anwar^{a,11}, Sandeep Kumar Behera^{b,12}, Ruchi Badola^{a,13}, Syed Ainul Hussain^{a,*,14}

^a Ganga Aqualife Conservation and Monitoring Centre, Wildlife Institute of India, P.O. Box # 18, Chandrabani, Dehra Dun, Uttarakhand 248001, India

^b National Mission for Clean Ganga, Ministry of Jal Shakti, First Floor, Major Dhyan Chand National Stadium, India Gate, New Delhi 110002, India

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ABSTRACT

The complex and dynamic networks of river system, vital for the maintenance of biodiversity and ecosystem services, are under pressure due to human-induced water stress disrupting ecological processes. Recognition of the importance of rivers as source of life though has led to efforts towards protecting large rivers, nevertheless the conservation and management of smaller rivers remained mostly neglected, creating significant gaps in ecological restoration initiatives. In the present study, we assess the distribution and population status of Gangetic dolphin (*Platanista gangetica*) in the small rivers in the Ganga River Basin for integrating it into the basin wide river conservation strategy. We observed that the Gangetic dolphin inhabited most tributaries and sub-tributaries of the Ganga River, with a naïve occupancy rate of $\Psi = 0.68 \pm 0.04$ (mean \pm SE) having 606 ± 142.77 (mean \pm SE) individuals and accounts for 15% of the total Gangetic dolphin population in the Basin. The results of *N*-mixture and MaxEnt models demonstrate that channel depth, presence of meanders and water discharge were key predictors of distribution in these rivers, and the proximity to confluences were identified as a critical predictor. About 54%

* Corresponding author.

E-mail address: ainul.hussain@gmail.com (S.A. Hussain).

¹ <https://orcid.org/0000-0002-2009-0045>

² <https://orcid.org/0000-0002-3636-985X>

³ <https://orcid.org/0000-0002-7411-4284>

⁴ <https://orcid.org/0000-0003-2422-6330>

⁵ <https://orcid.org/0000-0002-7580-560X>

⁶ <https://orcid.org/0000-0002-2175-9556>

⁷ <https://orcid.org/0000-0002-6208-0216>

⁸ <https://orcid.org/0000-0001-8746-899X>

⁹ <https://orcid.org/0000-0002-5432-9624>

¹⁰ <https://orcid.org/0000-0002-3574-1891>

¹¹ <https://orcid.org/0000-0001-7525-1291>

¹² <https://orcid.org/0009-0009-7626-4815>

¹³ <https://orcid.org/0000-0001-7124-5134>

¹⁴ <https://orcid.org/0000-0003-3229-806X>

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(620 km) of 1150 km of the surveyed river stretches exhibited suitability for dolphins in the Basin, indicated by a probability distribution score of ≥ 0.50 . Combining this data with the available information, we delineated a total of 2850 km stretch covering entire Ganga River System suitable for Gangetic dolphins within the Basin. Notably, the 620 km of suitable stretches identified in smaller rivers represent 22% of the overall suitable stretches across the entire basin. These stretches were translated to conservation priority stretches for systematic conservation planning involving various stakeholders for improved river conservation in the Basin.

1. Introduction

The network of river systems, sustained by the interplay of biotic and abiotic components, functions as biodiversity hotspots and offer essential services for human needs (Carpenter et al., 2011; Grill et al., 2019; Meybeck, 2003; Ripl, 2003). The spatial and hierarchical structure, as well as the longitudinal connectivity of the river system, hold together the most diverse composition of flora and fauna globally (Collen et al., 2014; Dudgeon, 2000; Reid et al., 2019). In this complex network, each hierarchical order of streams plays a pivotal role, indispensably contributing to the ecological processes that heavily rely on biodiversity (Bouska et al., 2023; Pracheil et al., 2013). As per the classic stream order or Hack's stream order, existence of large rivers is greatly dependent on the vital contributions of their tributaries and sub-tributaries (Rodriguez-Iturbe and Rinaldo, 1997) and these are crucial for strengthening the hydrological network of the river basins (Nel et al., 2007). The small rivers are often characterized by a mosaic of diverse habitats, which support rich biodiversity, serve as migration routes, sources of nutrients, contributors to climate resilience, and significant refuges for macrofauna (Davis et al., 2013; Gido et al., 2016). The small rivers facilitate connectivity, creating a network that allows for the movement of aquatic species essential for maintaining metapopulations. This, in turn, enables the creation of a metapopulation structure, ensuring genetic exchange and preventing isolation of populations, enhancing the resilience of aquatic species to environmental changes and disturbances (Allendorf et al., 2012; Tonkin et al., 2018). Unfortunately, the fundamental attributes that maintain the integrity of riverine networks are increasingly undermined by human-induced stressors such as the construction of dams, reservoirs, canals, and irrigation systems. The evident decline in freshwater biodiversity underscores the urgent need for conservation actions to halt biodiversity loss and deteriorating ecological processes in these vulnerable ecosystems (Dudgeon et al., 2006; Grill et al., 2019; Vörösmarty et al., 2010).

Until recently, the predominant focus of conservation and restoration efforts has been on large rivers, often overlooking the importance of small rivers (Palmer and Ruhi, 2019). The vital contributions of these lesser known small rivers to the health and resilience of larger river systems are increasingly being recognized in the literature, demanding a shift towards more comprehensive and inclusive conservation strategies that adopt basin-wide approach and prioritize the interconnected nature of riverine ecosystems (Dudgeon et al., 2006; Saunders et al., 2002; Thorp et al., 2010).

The Ganga River, one of the most biodiverse subtropical rivers of India, is currently confronting unprecedented threats from various human-induced stresses (Hussain et al., 2020; Kumar, 2017). The tributaries and sub-tributaries of the Ganga River, hereafter called as small rivers, are pivotal in enriching the hydrological processes and ecological health of the entire Ganga River Basin (henceforth GRB) (Singh and Singh, 2020). The biodiversity of these small rivers is declining rapidly and the paucity of robust ecological information has impeded river conservation efforts (Dudgeon, 2000; Hughes, 2017). This dearth of information poses a significant challenge in understanding the intricate dynamics of these ecosystems, thereby hindering the development of effective conservation strategies. In such a scenario, the utilization of the widely-recognized umbrella-species approach can be fundamental in shaping the future conservation strategies for these lesser known small rivers (Branton and Richardson, 2011; Roberge and Angelstam, 2004). The umbrella-species concept operates on the premise that providing adequate space for species with more extensive spatial needs will also serve as protection for an entire assemblage of species with more modest spatial requirements (Wilcox, 1984; Andelman and Fagan, 2000; Roberge et al., 2008). Hence, large-bodied organisms, often vertebrates, particularly large mammalian carnivores, have been favored as potential umbrella species (Carroll et al., 2001; Roberge and Angelstam, 2004). Consequently, the umbrella species approach can play a crucial role in delineating protected areas, assuming that conserving these species will confer adequate protection to coexisting species (Roberge et al., 2008; Roberge and Angelstam, 2004; Sergio et al., 2008). Indeed, this approach aligns with the goal of 'bending the curve of freshwater biodiversity loss' and is instrumental in garnering public support, thereby increasing the likelihood of conservation actions (Kalinkat et al., 2017; Tickner et al., 2020).

Gangetic dolphin (*Platanista gangetica*, Lebeck, 1801), is an obligatory river cetacean endemic to the Indian subcontinent (Kelkar et al., 2018, 2022; Anderson, 1879). It plays a crucial role in stabilizing ecosystems, regulating energy flows and maintaining the prey base (Behera et al., 2014; Gomez-Salazar et al., 2012; Turvey et al., 2012). While the GRB hosts numerous long-ranging large aquatic vertebrates, such as gharial, mugger, otters, and freshwater turtles, the presence of dolphin throughout the basin, along with its specific hydro-geomorphological requirements, renders it an exemplary candidate as an umbrella species. Utilizing the Gangetic dolphin in this role provides valuable insights into the extent of human pressures and aids in prioritizing conservation efforts within the basin (Hussain et al., 2013; Roff, 2013; Sinha and Kannan, 2014). In recent years, the distribution range of the Gangetic dolphin in various rivers has dwindled, particularly in the upstream stretches (Das et al., 2022, Sinha and Kannan, 2014). The species is now believed to be extirpated from the Son, Ken, Betwa, and Sind rivers, the middle and upper stretch of the Sharda River, and the upper stretch of the Yamuna River (Sinha and Sharma, 2003, Behera et al., 2014). Additionally, several tributaries north of the Ganga River, including the Babai, Bagmati, and Sharda rivers, lack updated information on the status of the Gangetic dolphin (Kelkar et al., 2022), while Rapti

River was surveyed a decade back (WWF-UPFD, 2015). Hence, a comprehensive study is essential to assess the current population status, distribution, and perceived threats, with the goal of integrating this information into basin-wide river conservation strategies.

In this study, we assessed the distribution, population status, and habitat suitability of Gangetic dolphin in small rivers within GRB. Through the study we addressed following research questions, (i) What is the extent of current distribution range? (ii) What is the population status and occupancy? (iii). What are the spatial and environmental factors influencing the distribution and abundance of dolphins in small rivers, and how can this information be utilized to prioritize conservation efforts in these rivers?

2. Methodology

2.1. Study area

The study was carried out in the tributaries and sub-tributaries of the Ganga River. We carried out boat-based visual encounter surveys in ten rivers, covering a total linear stretch of 1290 km, viz Girwa (20 km), Kauriyala (15 km), Babai (75 km), Sharda (220 km), Rapti (500 km), Bagmati (60 km), Mahananda (230 km), Ken (40 km), Betwa (90 km), and Sind (40 km) (Fig. 1 and Table S1). The survey of the upstream of the Bagmati River was omitted due to navigability concerns. Of the rivers surveyed, Bagmati, Babai, Girwa, Kauriyala, Mahananda, Rapti, and Sharda are northbound Himalayan rivers, partially snow-fed. Whereas the Ken, Betwa, and Sind are rain-fed and have their origins in the Deccan Peninsula (Singh, 2017). The surveys were carried out during the post-monsoon seasons (November -February) of 2022 and 2023 using an inflatable rubber boat fitted with 25 hp Yamaha engine.

2.2. Data collection

We employed a boat-based visual encounter method to record Gangetic dolphin sightings (Smith and Reeves, 2000; Qureshi et al., 2021). All surveys were conducted using inflatable boats, with two independent observers stationed at the front and rear ends of the boat to simultaneously record Gangetic dolphin sightings. The observers did not maintain visual contact and were instructed to adhere to the same survey protocol described in Das et al. (2022). The boat was kept at an average speed of 6–8 km/hr to minimize the likelihood of missing any surfacing event of the Gangetic dolphin (Smith et al., 2006; Das et al., 2022). The least concurrent sighting records obtained by two independent observers were then fitted into the occupancy framework.

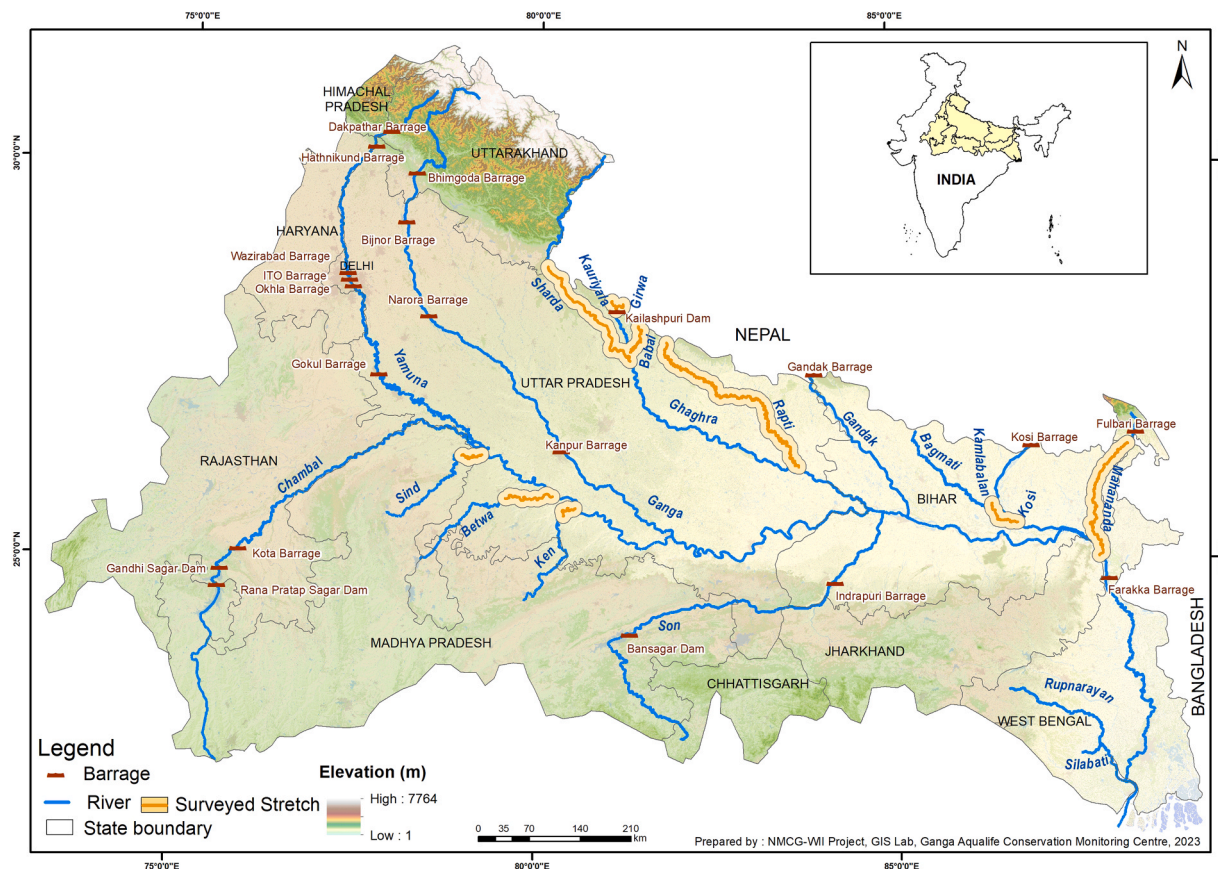


Fig. 1. Location map of the rivers surveyed for recording Gangetic dolphin (*Platanista gangetica*) presence in the Ganga River Basin, India.

In addition to Gangetic dolphin occurrence records across these rivers, we also collected data on (i) hydro-morphological variables ($n=5$) viz. slope, discharge, channel width, channel depth, presence of meanders, (ii) physiochemical parameters ($n=5$) viz. water temperature, dissolved oxygen (DO), pH, salinity, Total Dissolved Solids (TDS) and (iii) human induced stressors ($n=5$) viz. ferry intensity and fishing intensity (number of active nets), sand mining intensity, water extraction pumps and human presence. To mitigate the impact of shallow and unnavigable river sections, the boat-based direct count method utilized the thalweg, or the deepest section of the river channel, to estimate dolphin abundance (Smith and Reeves, 2000; Smith et al., 2006; Braulik et al., 2012; Richman et al., 2014). Leveraging these hydro-geomorphological features and adhering to the assumptions outlined by Charbonnel et al. (2014), we standardized our spatial units to 5 km, in accordance with the methodology proposed by Das et al. (2022). The 1290 km linear stretch was segmented into 258 Biodiversity Evaluation Units (BEUs) (Table S1), and data were collected at 1 km intervals within each BEU. Subsequently, the collected data were averaged and incorporated into the occupancy and N-mixture framework, following the study design outlined in Das et al. (2022). The length of the sampling site i.e. 25 km (five spatial replicates of 5 km segment/BEUs) was selected to meet the assumptions critical for the hierarchical-N mixture model and is based on the following criteria. First, we utilized the mean home range of *Platanista minor* (Toosy et al., 2009) as a surrogate to select the length of the sampling sites for this study, as *Platanista gangetica* and *Platanista minor* both share identical physiological and biological attributes (Smith and Braulik, 2009). Therefore, based on the information, we assumed a maximum daily movement of approximately 25 km for the Gangetic dolphin, considering the intermittent shallow and deep pools in the river stretches. Secondly, the length of the sampling site chosen to meet the closure assumption Royle, (2004), detect the presence of a species, and the requirement for more than three spatial replicates, as recommended by Hines et al. (2010). As the aim of the present study was to assess the abundance and distribution of Gangetic dolphins in the lesser-known rivers of the Ganga Basin, surveys were conducted in narrow channel habitats from November 2022 to February 2023 (low water season). We implemented single observer method, which builds upon the foundation of multiple observers stationed in a single boat, following a thalweg path in the river, are ideal for detecting dolphin sightings (Smith and Reeves, 2000; Paudel et al., 2015; Qureshi et al., 2021). The single observer method always remains a cost-effective survey option for monitoring (Richman et al., 2014). However, unlike the double-observer method, it cannot account for detectability (McConville et al., 2009). To address this, we compared the findings from our study with a correction factor derived utilizing the mean detection probability from double-observer methods (Das et al., 2022).

2.3. Data analysis

2.3.1. River habitat assessment

For habitat assessment, the average values of each variable were computed for a total of 258 Biological Evaluation Units (BEUs). While the presumption was that various rivers possess unique attributes because of their distinct origins and passage through different biogeographical provinces, we employed one-way ANOVA (Analysis of Variance) to assess whether there were significant variations between these BEUs and across rivers.

2.3.2. Encounter rate (ER) and site occupancy

We calculated the Gangetic dolphin encounter rate (sightings per km of linear stretch) for each spatial unit and employed ANOVA to examine variations in encounter rates across the rivers. Gangetic dolphin presence and absence data was pooled from each spatial unit to fit into the occupancy framework (MacKenzie et al., 2002, 2017). We utilized data from repeated visual encounter surveys to fulfill the requirements of single-season occupancy analyses. Key assumptions in single-season occupancy analysis include: (1) closure, assuming the population is demographically closed during surveys, (2) site independence, assuming species detection at one site is independent of detections at others (Fiske and Chandler, 2011), (3) no-false positives, requiring correct species identification and disregarding doubtful detections, and (4) constant probability of occupancy and detection, wherein the default model assumes uniform probability of occupancy and detection across all sites or adjusts for site and observation-level covariates (Mackenzie, 2006). The site occupancy of Gangetic dolphin in the surveyed river was estimated using the *occu* () function in the "unmarked" package (version 1.3.2) in R version 4.3.0, with R Studio version 2023.04.21 (Fiske and Chandler, 2011; RStudio Team, 2022). First, we assessed factors e.g., time spent on each spatial unit (effort), time of the day during survey (time) and channel width influencing the likelihood of detecting Gangetic dolphin (p), while keeping the probability of their presence (Ψ) constant following MacKenzie et al. (2017). Continuous variables were z-standardized, and categorical variables (Table S2) were dummy-coded in order to prevent numerical optimization of the likelihood following Hines, (2006) and Sunarto et al. (2012). To ensure the reliability of our results, we checked for potential multicollinearity among variables using the Pearson correlation test (Graham, 2003). Variables with a Pearson correlation coefficient higher than 0.70 were excluded from the analysis.

2.3.3. Abundance estimation

2.3.3.1. Gangetic dolphin abundance estimation using N-mixture model. We used Binomial N-mixture models to estimate the dolphin abundance and factors influencing their distribution (Royle, 2004; Kéry and Royle, 2020; Kéry, 2018). The N-mixture model accounts for imperfect detection and evaluates the likelihood of an event occurring as well as the likelihood of detecting a species (Mackenzie, 2006; MacKenzie et al., 2002; Rota et al., 2009). These models are known to yield more reliable abundance estimates of rare and cryptic species compared to traditional direct counting (MacKenzie and Bailey, 2004; Rota et al., 2009). This method has been successfully used to assess Gangetic dolphin abundance in major rivers of the Ganga basin and the Karnali River in Nepal (Das et al., 2022;

Paudel et al., 2015). We used dolphin sighting records per spatial unit as baseline data and employed the N-mixture model using the 'pcount' function available in the "unmarked" package in R version 4.3.0, with R Studio version 2023.04.21 (Fiske and Chandler, 2011; R Development Core Team, 2023; RStudio Team, 2022). We administered the spatial counts data into the Negative Binomial distributions as it effectively models abundance, taking into account occupied survey sites with fewer true zeros in the dataset (Barão-Nóbrega et al., 2022). Given the patchy distribution of dolphin during the low water season, Negative Binomial distributions align well with over-dispersion data (Knape et al., 2018; Kéry and Royle, 2020). The upper bound value for K (abundance estimates) were determined through multiple trials iterations (Fiske and Chandler, 2011; Knape et al., 2018; Kéry and Royle, 2020). Site covariates such as channel width, meander, fishing intensity, water discharge, individual river characteristics, and anthropogenic influences are hypothesized to influence the relative abundance (λ) of dolphin and detection covariates (Table S2) influencing detection probability (p), when dolphins are present at a site. These covariates were chosen based on existing knowledge and relevant literature (Das et al., 2022; Paudel et al., 2015). A comprehensive set of 32 N-mixture models, encompassing various combinations of univariate and multivariate factors, were created to evaluate the abundance and detection probability of dolphins, under the Negative Binomial distribution. MacKenzie and Bailey goodness-of-fit test was performed to evaluate model performance (MacKenzie and Bailey, 2004). Models were ranked based on Akaike Information Criterion (AIC) scores and AICc weights were taken into consideration while determining overall covariate significance (Akaike, 1974; Burnham and Anderson, 2004). A final model set was generated from the top-ranked univariate models that included combinations of site use and detection covariates with $\Delta AICc \leq 2$, indicating substantial empirical support. Significant covariate influence was determined if the 95% confidence interval of the beta coefficient ($\beta \pm 1.96 \times SE$) did not overlap zero, with the sign of the coefficient indicating the impact's direction (Searle et al., 2020). The probability of Gangetic dolphin relative abundance (λ) was estimated for each site by averaging the predicted values from the most parameterized top-ranked models within the final model set, using the 'MuMin' package in R (Bartoń, 2013; R Development Core Team, 2023). We performed a goodness-of-fit test for the highest-ranked model with the maximum parameters (Searle et al., 2020).

2.3.3.2. Gangetic dolphin abundance estimation using correction factor (D_{cf}). Correction Factors (D_{cf}) compensate for missed individuals during visual encounter surveys (Bashir et al., 2010; Richman et al., 2014; Vu et al., 2018). Therefore, we determined the relative abundance of Gangetic dolphin using mean correction factors (D_{cf}) obtained from previously published studies conducted in rivers across the Indian subcontinent (Das et al., 2022). These studies encompassed a range of river types, including narrow and wide channels with varying widths, depths, and lengths. The derived indices were then compared with population estimates derived from N-mixture models. The corrected population estimates of Gangetic dolphin were obtained by multiplying the correction factor (D_{cf}) by the total number of sightings recorded in a given river.

2.3.4. Conservation Priority Stretch (CPS)

To predict the potential distribution and delineate priority stretches, we employed maximum entropy (MaxEnt) models. The MaxEnt is one of the effective modelling algorithms, which take environmental variables and species presence-only data to predict and model species distribution. It is also capable of predicting future distributions under the influence of global climate change (Clements et al., 2012; Elith et al., 2006; Phillips et al., 2006).

For MaxEnt modeling, we utilized a total of 176 dolphin presence locations across seven rivers (no Gangetic dolphin presence was recorded in three rivers). To generate the species distribution model, we selected 33 variables comprising bioclimatic ($n=19$), hydro-morphological ($n=4$), physiochemical parameters ($n=5$), and human induced stressors ($n=5$) (Das et al., 2022; Jain and Singh, 2020; Rai et al., 2023). The climatic variables were resampled at 5 km² resolution, obtained from WorldClim version 2 with a spatial resolution of 2.5 arc minutes (approximately 4.5 km²) to ensure uniformity (Fick and Hijmans, 2017). All pairs of variables were assessed for correlation, and variables displaying a Pearson correlation coefficient of ≥ 0.70 were removed if they were found to have minimal ecological significance (Zuur et al., 2010). Finally, a subset of 12 uncorrelated ecologically meaningful variables was used to generate dolphin distribution in the seven rivers using MaxEnt software (version 3.4.4) (Table S2). Model over-complexity and overfitting, were adjusted by optimizing user-modifiable factors, viz., regularization multipliers and the feature classes (Elith et al., 2010). We examined a variety of model combinations, initially individual feature classes (e.g. Linear (L), Quadratic (Q), Product (P), Threshold (T), and Hinge (H) with varying regularization values at 0.5, 1.0, 1.5, and 2.0. For example, within the linear feature class, four different models were assessed L-0.5, L-1.0, L-1.5, and L-2.0 (Table S3). The best fit models were assessed using AIC approaches computed in ENMTools 1.4.4 software (Warren et al., 2010). The prediction probabilities were transformed into a raster layer to generate a probability distribution map using ArcGIS 10.6 (<https://www.esri.com/>). Subsequently, the probability distribution was categorized in three classes viz. >0.70 , 0.61–0.70 and 0.51–0.60. These classes were then translated to priority stretches following Das et al. (2022) as CPS1- >0.70 , (High Conservation Priority Stretches), CPS2 –0.61–0.70 (Moderate Conservation Priority Stretches), and CPS3 –0.51–0.60 (Low Conservation Priority Stretches).

3. Results

3.1. River habitat assessment

The surveyed rivers exhibited diverse hydro-morphological characteristics and physicochemical properties along their lengths. The average channel depth across studies rivers was 3.03 m \pm 2.71 (mean \pm SD), with individual rivers varying significantly between a depth of 1.78 m \pm 0.91 in Sind River and 5.25 m \pm 4.37 in Bagmati River (ANOVA, $F = 15.55$, $p < 0.001$). Notably, the Mahananda,

Rapti, and Bagmati rivers exhibited depth variations, primarily due to the presence of deeper pools compared to the other studied rivers (Figure S1). The mean river width was $253.13 \text{ m} \pm 177.27$, with widths ranging from $83 \text{ m} \pm 24$ in Sind River to $525 \text{ m} \pm 281$ in Sharda River. A significant difference in mean channel width was observed across the studied rivers (ANOVA, $F = 147.26$, $p < 0.001$) (Figure S1). Additionally, the presence of meanders varied significantly among the rivers. Physicochemical properties also displayed substantial variations among the studied rivers (Table S2).

We observed significant variations in various human induced stressors across the studied rivers. The fishing intensity, measured as the average number of active nets per BEU (mean = 8.81, range = 0–131), varied significantly (ANOVA, $F = 23.94$, $p < 0.001$). The Mahananda River had the highest fishing intensity (38.64–131 nets/BEU), while the Sind River had the lowest (0.14, 0–3 nets/BEU). No fishing activity was observed in the Girwa and Kauriyala rivers, as these rivers flow through the Katerniaghat Wildlife Sanctuary a Protected Area declared under the Indian Wild Life (Protection) Act, 1972. The mean number of ferry crossings (1.95, 0–34 ferry/per BEU) also varied significantly (ANOVA, $F = 22.04$, $p < 0.001$) among the rivers. Sand mining intensity, including activities involving boats, tractors, and earthmovers, differed significantly across the rivers (ANOVA, $F = 6.439$, $p < 0.001$), with the highest intensity in the Betwa River (5.52, 0–58 activities/BEU) and the lowest in the Babai River (0.13, 0–2 activities/BEU). Notably, there were no signs of mining activities in the Girwa, Kauriyala, and Rapti rivers. Extraction of water through pumps among the rivers also exhibited significant variations (ANOVA, $F = 34.675$, $p < 0.001$). The Bagmati River had the highest occurrence of water extraction pumps (6.75, 0–10pumps/BEU), while the Rapti River had the lowest (0.11, 0–3) (Table S2).

3.2. Encounter rate (ER) and site occupancy

A total of 359 sightings of Gangetic dolphins were documented within the 1120 km survey stretch across seven rivers, accounting for 41% of the total BEUs covered (Fig. 2 A). Maximum sightings were recorded from the Mahananda River ($n=169$, 47%) followed by sightings in the Rapti ($n=89$, 25%), Bagmati ($n=68$, 19%), Kauriyala ($n=13$, 4%), Girwa ($n=9$, 3%), Sharda ($n=7$, 2%), and the Babai River ($n=4$, 1%) (Table S4).

The average encounter rate of dolphin across rivers was 0.49 ± 0.15 (mean \pm SE) sightings/linear km and ranged between 0.03 ± 0.02 sightings/km in Sharda and 1.13 ± 0.04 sightings/km in Bagmati river. The highest encounter rate was observed in the Bagmati River (1.13 ± 0.04 sightings/km), followed by the Kauriyala (0.87 ± 0.47), Mahananda (0.73 ± 0.1), Girwa (0.45 ± 0.17), Rapti (0.18

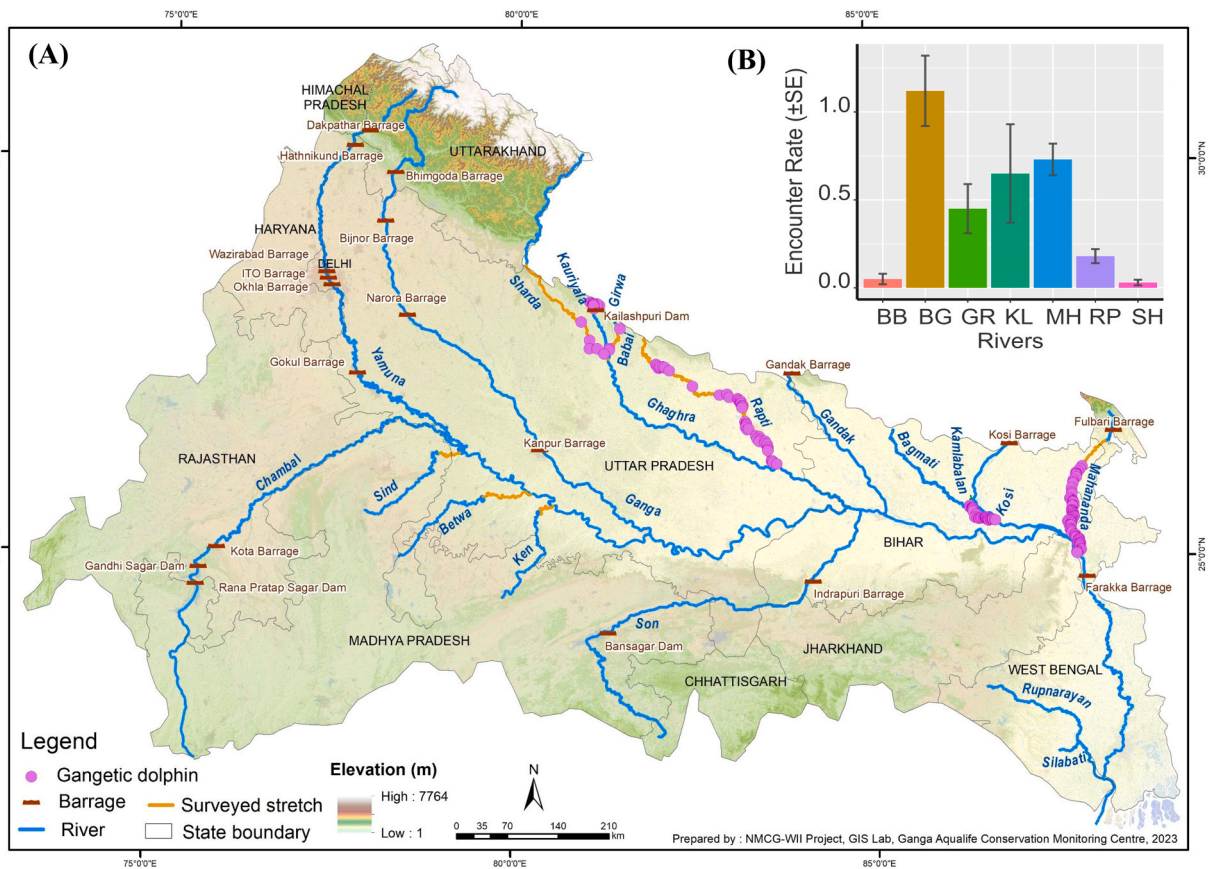


Fig. 2. (A) Sighting locations of Gangetic dolphin and (B) Gangetic dolphin encounter rate (sightings/linear kilometer) recorded in seven small rivers of the Ganga River Basin, India. (BB=Babai; BG=Bagmati; GR= Girwa; KL=Kauriyala; MH=Mahananda; RP= Rapti; SH= Sharda).

± 0.04), Babai (0.05 ± 0.04), and Sharda (0.03 ± 0.02) rivers (Fig. 2 B). A significant variation in encounter rates was observed across the surveyed rivers (ANOVA, $F = 25.20$, $p < 0.001$). Gangetic dolphins were detected in 31 sampling units, resulting in a naïve occupancy of 0.68 ± 0.07 (95% CI = $0.54 - 0.81$). The mean probability of detecting Gangetic dolphin was estimated at (P) 0.61 ± 0.04 , and the average likelihood of these dolphins occupying a site was $\Psi = 0.68 \pm 0.04$.

3.3. Abundance estimation

3.3.1. Gangetic dolphin abundance estimation using N-mixture model

The total estimated population of dolphin across the examined rivers was 606 ± 142.77 (mean \pm SE) dolphins (CI = 381 – 923) (Table 1). Among the rivers, the Mahananda River encompassed 43.56% of the estimated total population, at 264 ± 47.07 individuals (CI = 180–363) and lowest in the Babai River, at 8 ± 7.08 individuals (CI = 4–18) constituting only 1.32% of the total estimated population. The Rapti, with an estimated abundance of 146 ± 45.79 individuals (CI = 79–256) constitutes the second largest population, contributing to 24.09% of the total estimated population. The Bagmati River had an estimated population of 120 ± 22.13 individuals, accounting for 19.80% of the total estimated population. The Kauriyala River was estimated to have 36 ± 8.48 individuals, Girwa River had 19 ± 5.22 individuals, and Sharda River held 13 ± 7.08 individuals using the N-mixture model. The Babai River exhibited the lowest abundance estimate, with 8 ± 7.08 individuals, constituting only 1.32% of the total estimated population across all the rivers analyzed (Table 1).

3.3.2. Gangetic dolphin abundance estimation using correction factor (D_{cf}).

The mean derived correction factor ($D_{cf}=1.52$) and the abundance estimated using correction factor was 546 ± 37.05 individuals (CI = 473–619) (Table 1). The abundance estimate was highest in Mahananda River (47.06%) with 257 ± 11.15 individuals (CI = 235–279). Similar to the estimates obtained through the N-mixture model, the Rapti River displayed the second-largest Gangetic dolphin population of 135 ± 11.67 individuals (CI = 112–158). Following this, the Bagmati River had an estimated 103 ± 8.10 individuals (CI = 87–119), while the Kauriyala accounted for 20 ± 2.26 individuals (CI = 16–24). The Girwa River accounted for 14 ± 1.09 individuals (CI = 12–16), followed by Sharda with an estimate of 11 ± 1.69 individuals (CI = 8–14). The lowest abundance estimate was for the Babai River, with 6 ± 1.09 individuals (CI = 4–8) using the correction factor (D_{cf}).

3.3.3. Factors affecting Gangetic dolphin abundance (λ)

The optimal model for estimating abundance (λ) included factors such as channel depth, meanders, and individual rivers, while for detection (p) it included river width and effort (Table S6). Based on model-averaged parameter estimates (cumulative weight of $\Sigma w = 1.00$), factors such as channel depth, meanders and individual rivers were identified as the most reliable predictors of dolphin abundance (Table S6). While the parameter 'river' was present in the final model set, their individual impact varied. Among these rivers, Bagmati and Mahananda had a notably positive influence on dolphin abundance, whereas the Sharda exhibited a negative influence (Table S6). Moreover, the width of the river was determined to have a notably adverse impact on the detection probability (cumulative weight of $\Sigma w = 1.00$), while the level of effort displayed a positive correlation with the detection probability of Gangetic dolphins in the Ganga Basin (Figs. S3 and S4).

3.4. Identification of Conservation Priority Stretches (CPS)

The Species distribution model (SDM) yielded an impressive Area Under Curve ($AUC = 0.97$, SD 0.008) (Figure S2). The prediction model identified seven bioclimatic variables - Annual Mean Temperature (Bio 1), Isothermality (Bio 3), Temperature Seasonality (Bio 4), Precipitation of the Wettest Month (Bio 13), Precipitation Seasonality (Bio 15), Precipitation of the Driest Quarter (Bio 17), and Precipitation of the Warmest Quarter (Bio 18) as key factors influencing the distribution of Gangetic dolphin. Other hydrological and human induced stressors such as channel depth, channel width, water discharge, fishing, and sand mining contributed significantly in determining the species distribution (Figure S2). The predicted potential distribution of dolphin indicated that water discharge contributed the most (30.6%), followed by Temperature Seasonality (16%) and Annual Mean Temperature (12.5%) in the Basin

Table 1

The length of the river surveyed, number of sightings, abundance estimates derived using the N-mixture model and Correction factor (D_{cf}) of Gangetic dolphin across seven small rivers in the Ganga River Basin, India.

River	Surveyed length (km)	Concurrent least sightings	Population estimates (λ), Mean \pm SE (CI 95%)	Population estimates (D_{cf}) Mean \pm SE (CI 95%)
Babai	75	4	8 ± 3.8 (4–18)	6 ± 1.09 (4–8)
Bagmati	60	68	120 ± 22.13 (81–168)	103 ± 8.10 (87–119)
Girwa	20	9	19 ± 5.22 (10–30)	14 ± 1.09 (12–16)
Kauriyala	15	13	36 ± 8.48 (21–55)	20 ± 2.26 (16–24)
Mahananda	230	169	264 ± 47.07 (180–363)	257 ± 11.15 (235–279)
Rapti	500	89	146 ± 45.79 (79–256)	135 ± 11.67 (112–158)
Sharda	220	7	13 ± 7.08 (7–33)	11 ± 1.69 (8–14)
Grand total	1120	359	606 ± 142.77 (381–923)	546 ± 37.05 (473–619)

(Table S5).

The MaxEnt models predicted a probability distribution of Gangetic dolphin that encompassed a total stretch of 1150 km, including both historical and current ranges. Out of the entire projected distribution, approximately 54% (620 km) of river stretches were identified as suitable for dolphins (based on probability distribution score ≥ 0.50) (Table 2). Priority stretches were delineated and categorized based on the Gangetic dolphin's potential distribution map. About 37.39% (430 km) of the river stretches were designated as High Conservation Priority Stretches, followed by 9.57% (100 km) of river stretches as Moderate Conservation Priority Stretches, and 6.96% (70 km) of river stretches as Low Conservation Priority Stretches. Most of the CPS1 stretches were concentrated in the lower sections of the Rapti, Bagmati, and Mahananda rivers (Figs. 3 and 4), while the remaining CPS1 were located in the confluences of tributaries. Among the rivers with suitable habitat, the Mahananda River had the largest contiguous, suitable river segment spanning 170 km, accounting for 14.78% of the total predicted stretch.

4. Discussion

The dynamic hydrological and morphological characteristics of rivers and their physicochemical attributes contribute to high habitat heterogeneity, which plays a central role in determining the species occurrences (Ward, 1998). Unfortunately, most rivers in the GRB are now highly regulated, thus homogenous and offer limited biodiversity conservation potential (Pradhan et al., 2023). The growing human population in the Basin is predicted to further magnify human-induced stressors, such as agriculture, fishing, and mining during the dry season, making these rivers sub-optimal and less conducive for biodiversity conservation (Haidvogel, 2018; Schmutz and Sendzimir, 2018; Das et al., 2022). Unlike terrestrial ecosystems, the riverine system are more vulnerable and poised with challenges arising from conflicting resource use, direct human dependency and land use conflicts (Ledger et al., 2023). These effects are more conspicuous and cascading in small river systems (Dudgeon, 2000). In such circumstances, delineating areas of conservation significance in these small rivers holds potential for protecting and restoring local ecosystems and maintaining the integrity and health of entire river basins. The umbrella-species concept, advocating that conservation strategies crafted for one species can positively impact co-occurring species, has gained prominence as a framework for conservation planning (Branton and Richardson, 2011). Faced with constraints such as limited funding, knowledge, and time for action, conservation efforts often seek efficient strategies for biodiversity maintenance. The umbrella species concept, recently attracting increased attention, proposes using species requirements as a foundation for conservation planning. This concept serves as a tool for determining the minimum size of conservation areas, selecting sites for inclusion in protected area networks, and establishing minimum standards for the composition, structure, and processes of ecosystems (Roberge and Angelstam, 2004).

The study presents an insight into the distribution and abundance of the Gangetic dolphin and utilizes its presence location to identify conservation priority stretches in the lesser-known tributaries and sub-tributaries of the GRB. In the present study, we found that the Gangetic dolphin distribution, shows a reduction in its range, especially in the peninsular rivers, with the last recorded presence noted in 1998 (Sinha et al., 2000; Sinha and Kannan, 2014). On the basis of the present study and literature, we conclude that the Gangetic dolphin may have locally extirpated from Ken, Betwa and Sind rivers (Behera et al., 2014; Sinha et al., 2000). The encounter rate and distribution of Gangetic dolphins have decreased in the Girwa, and Rapti rivers (Table 3) (Behera et al., 2014; WWF-UPFD, 2015), whereas in Mahananda River encounter rate remains unchanged (Kelkar and Dey, 2021). Gangetic dolphin sightings were more frequent in the lower sections of the rivers, particularly near the confluences (Bashir et al., 2012; Choudhary et al., 2012).

The variations in encounter rates and distribution, especially local extirpation of dolphin from Ken, Betwa and Sind rivers, may be linked to substantial river development projects that resulted in flow alteration (Sinha and Kannan, 2014). Previous surveys were mainly restricted to small stretches where dolphin sightings were common, which could have skewed the results (Das et al., 2022; Paudel et al., 2015). Further, habitat loss related to increasing water demands, creation of physical barriers (Braulik et al., 2014; Aggarwal et al., 2020; Sonkar and Gaurav, 2020; Paudel and Koprowski, 2020), deliberate killing for oil (Kolipakam et al., 2020) and mortality in the fishing gears (Kelkar et al., 2010) may have contributed to these changes. The clustered presence and frequent sightings of dolphins in the downstream sections of rivers could be linked to the presence of optimum habitat such as adequate river depth, discharge, and the presence of meandering habitats which are preferred by dolphins. Variations in the sighting frequency of

Table 2

Delineation of the Conservation Priority Stretches (CPS) in the small rivers of the Ganga River Basin, India.

River	Length (km)	Predicted length (km)	CPS1 (km)	CPS2 (km)	CPS3 (km)
Girwa	20	20	5 (0.43%)	5 (0.43%)	0
Kauriyala	20	15	10 (0.87%)	0	0
Babai	85	75	10 (0.87%)	0	0
Sharda	455	220	30 (2.61%)	25 (2.17%)	0
Rapti	510	510	175 (15.22%)	70 (6.09%)	55 (4.78%)
Bagmati	395	60	50 (4.35%)	0	5 (0.43%)
Mahananda	285	250	150 (13.04%)	10 (0.87%)	20 (1.74%)
Grand total	1685	1150	430 (37.39)	110 (9.57%)	80 (6.96%)

The abbreviations used are as follows: 'CPS1' stands for High Conservation Priority Stretches, 'CPS2' represent Moderate Conservation Priority Stretches and 'CPS3' represents Low Conservation Priority Stretches.

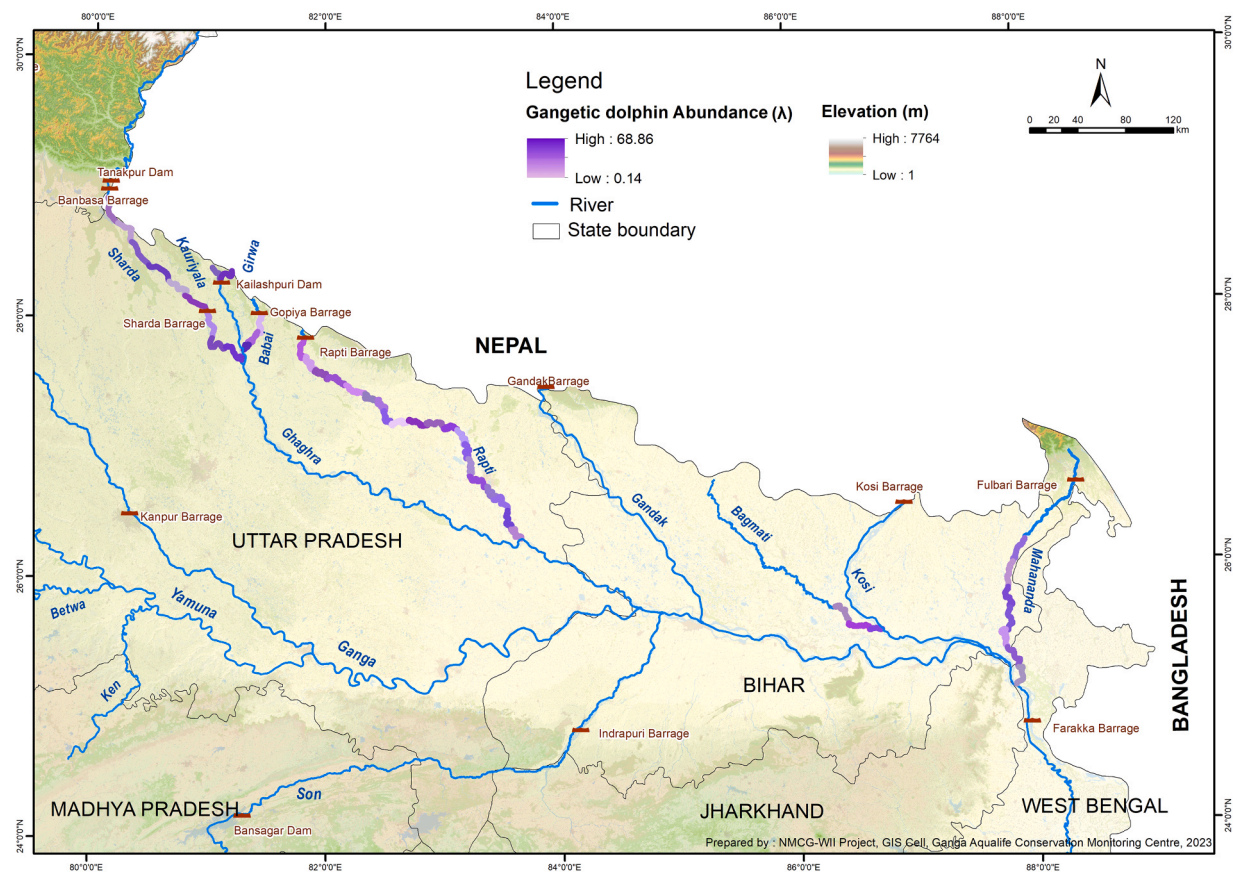


Fig. 3. Model-averaged estimates of Gangetic dolphin relative abundance (λ) (with 95% confidence intervals). Map was generated utilizing the highest-ranked model determined by AICc ranking.

Gangetic dolphin were noted along the studied stretch, with certain sections indicating an upsurge while others exhibited a decline (Behera et al., 2014; Choudhary et al., 2012; Das et al., 2022). In order to comprehend the plausible causes of these apparent increases, changes in barrage operations during the November 2022 survey may be a contributing factor. Sharda and Babai rivers, being alluvial, exhibit inherent dynamism in response to variations in water and sediment inputs during the monsoons (Midha and Mathur, 2014). During November, when there is less demand for irrigation water, the release of water from the lower Sharda Barrage located in Lakhimpur-Kheri to the main channel (Midha and Mathur, 2014) would have deepened the channel profile, potentially influencing dolphin estimates, as observed in our results. Similarly, in the Babai River, the Gopiya barrage's excessive discharge into the downstream river led to increased flows and channel depth during the survey period (Bhattarai, 2009). The river's inherent hydrological dynamics play a pivotal role in shaping the distribution of Gangetic dolphins, and alterations in hydrological processes are likely to impact dolphins spatial and temporal distribution (Braulik et al., 2014; Sonkar and Gaurav, 2020; Rai et al., 2023; Sharma et al., 2022).

The study provides a comprehensive assessment of the Gangetic dolphin populations in surveyed rivers, offering vital insights into the distribution and abundance of this iconic aquatic mammal in the region. The overall abundance estimates of the dolphin across these rivers revealed that small rivers hold 15% of dolphin population of the entire GRB (Table S8). Notably, the Mahananda and Rapti rivers contain 10% of the Gangetic dolphin population of the basin, and thus emerge as a vital dolphin stronghold. The Bagmati River also contributed significantly to dolphin population. Additionally, rivers like Kauriyala, Girwa, and Sharda displayed varying dolphin presence, underlining the need for tailored conservation strategies. Our findings highlight a significant difference in fishing intensity between the Mahananda and Babai rivers. Mahananda exhibited a higher fishing intensity at 38.64 ± 38.01 (mean \pm SD) compared to Babai at 1.27 ± 1.79 . Besides channel depth and the presence of meanders, fishing intensity emerges as another critical factor indicating the presence of an optimal prey base in the Mahananda River, influencing dolphin persistence.

Based on the results of the N-mixture model, channel depth and meanders emerged as significant variables influencing the relative abundance of dolphins. The average channel depth across the studied rivers was $3.03 \text{ m} \pm 2.71$ (mean \pm SD), while the Rapti and Bagmati rivers measured $3.36 \text{ m} \pm 2.85$ and $5.25 \text{ m} \pm 4.37$, respectively, significantly higher than the mean depth of all studied rivers. Moreover, the mean count of meanders per BEU across rivers was 1.11 ± 0.93 , while the Rapti and Bagmati rivers had counts of 1.53 ± 0.95 and 0.83 ± 0.94 , respectively. We would assume that this variation in depth and the presence of meanders in the Rapti and Bagmati rivers may have inflated the abundance estimates. However, during the peak dry period (March-May) when water discharge becomes limiting, fishing intensity may substantially affect dolphin persistence (Kelkar et al., 2010; Paudel and Koprowski, 2020;

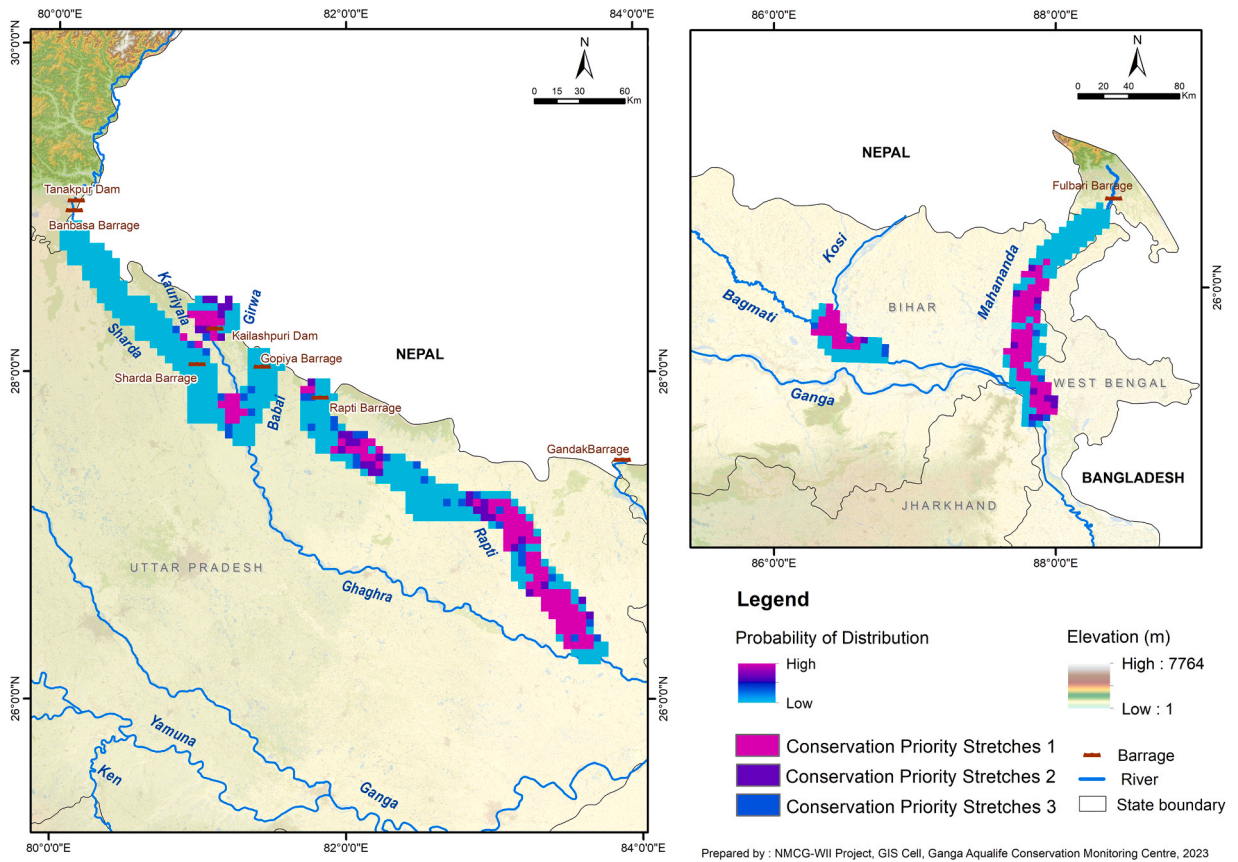


Fig. 4. Map showing Conservation Priority Stretches in the small rivers of the Ganga River Basin, India.

Samad et al., 2022).

Additionally, the lower stretch of the Bagmati River receives adequate discharge from the Kamla River and a distributary of the Kosi River to sustain dolphin population, as evident from the increasing depth as well as the high congregation of dolphins in the lower stretch of the Bagmati River. River systems exhibit inherent dynamism in response to variations in water and sediment inputs, with each element of their hydro-geomorphology playing a vital role in governing species distribution (Nestler et al., 2012). Given that the studied rivers originate from different sources and traverse through varied biogeographic regions and land-use classes are likely to influence species distribution beyond depth and width would contribute to dolphin occurrence. This is well-supported by our findings that the factor 'river' emerged as one of the contributing factors to dolphin abundance in the final model, indicating the complexity of riverine ecosystems and their influence on species distribution patterns. Our results underscore the importance of maintaining adequate dry season discharge and mitigating fishing activity in rivers such as Mahananda, Bagmati, and Rapti to sustain dolphin population and reduce competition from fishing activities. Additionally, the present study was conducted exclusively between November and February months, encompassing only the dry season. The impact of seasonal variations on the abundance of dolphins needs to be studied and considered when formulating conservation strategies. By incorporating data from different seasons, we can gain a more comprehensive understanding of the dynamics of dolphin populations and their habitats. Such consideration would offer valuable insights into formulating effective conservation strategies for Gangetic dolphins and their habitats.

The abundance estimate obtained using the N-mixture model and correction factors (D_{cf}) were comparable and hence provide support for the usability of these for abundance estimate of aquatic species. Nonetheless, the distribution and abundance of Gangetic dolphin were influenced by the availability of fish resources and the presence of deep pools in particular segments, despite the apparent uniformity in hydrological characteristics of these rivers (Bashir et al., 2010; Rai et al., 2023; Samad et al., 2022). Dolphin residing in small river stretches face heightened vulnerability due to their specific requirements within the environment, such as adequate water flow, which enables them to traverse deep pools, and hydraulic shelter to protect them from swift currents (Smith and Reeves, 2000; Smith et al., 2009). Our findings align with the observation that the predominance of Gangetic dolphins in rivers of moderate size within low-lying areas corresponds to their preference for habitats characterized by moderate annual average flow and greater depths. Although, the D_{cf} approach produced better Confidence Intervals (CIs) compared to the N-mixture models. In the absence of river-specific D_{cf} values, we utilized overall D_{cf} values derived from published literature conducted in various rivers with varying channel widths and depths. It is important to note that using an average across rivers may present a limitation, as detection rates may vary among rivers, potentially leading to biases in estimates. Therefore, we opted to apply the N-mixture model in this study,

Table 3
Past and present Encounter Rate of Gangetic dolphin in the Ganga River Basin, India.

River	River Segment	Survey length (Km)	Encounter rate	Year	Reference	Present study
						Encounter rate (SE)
Ganga	Haridwar barrage to Bijnor barrage	100	0	1996	Sinha et al. (2000)	0
	Bijnor Barrage to Narora Barrage	175	0.34	2010	Bashir et al. (2012)	0.33 ± 0.06
	Narora to Kanpur	300	0.01	2010	Behera et al. (2014)	0.05 ± 0.02
	Kanpur to Prayagraj	240	0.39	2012	Behera et al. (2014)	0.43 ± 0.09
	Prayagraj to Buxar	400	0.48	1997	Sinha et al. (2000)	1.7 ± 0.26
	Buxar to Manihari ghat	500	1.62	2006	Sinha et al. (2010a)	1.03 ± 0.14
	Manihari ghat to Farakka	90	1.64	1998	Sinha, (1999)	0.54 ± 0.12
	Farakka Feeder Canal	38.2	0.55	1996	Sinha et al. (2000)	0.06 ± 0.04
	Jangipur to Triveni Ghat	300	0.37	1995	Sinha, (1997)	0.10 ± 0.02
	Triveni ghat to Sagar Island	190	0.51	2008	Sharma, (2010)	0.38 ± 0.09*
	Bareh-Prayagraj	400	0.07	2012	Behera et al. (2014)	0.12 ± 0.06
Chambal	Rajghat-Pachhnada	235	0.36	2012	Behera et al. (2014)	0.37 ± 0.12
Ken	Sindhan kalan village - Yamuna confluence	30	0	2012	Behera et al. (2014)	No sightings
Betwa	Orai - Yamuna confluence	84	0	2012	Behera et al. (2014)	No sightings
Sind	Yamuna confluence to 110 km upstream	110	0.04	1998	Sinha et al. (2000)	No sightings
Girwa	Pathrena-Girijapuri barrage	18	2.17	2012	Behera et al. (2014)	0.45 ± 0.17
Kauriyala	India Nepal border- Girijapuri barrage	15			NA	0.87 ± 0.47
Babai	Gopiya barrage-Ghaghra confluence	75			NA	0.05 ± 0.04
Sharda	Sharda barrage-Palia	100	0	2001	Sinha and Sharma, (2003b)	0.03 ± 0.02
Ghaghra	Girijapuri barrage-Chhapra	630	0.52	2012	Behera et al. (2014)	0.54 ± 0.08
Rapti	Ghaghra confluence to 30 km upstream	30	0.26	2012	Behera et al. (2014)	0.18 ± 0.04
Son	Bichhi-Doriganj	130	0.08	1998	Sinha et al. (2000)	No sightings
Gandak	Valmiki Nagar-Ganga confluence	295	0.77	2010	Choudhary et al. (2012)	0.36 ± 0.05
Bagmati	Jagmohra-Badlaghat				NA	1.13 ± 0.24
Kosi	Kosi Barrage-Kursela	235	0.42	2001	Sinha and Sharma, (2003)	0.76 ± 0.13
Mahananda	Balubari ghat- Jankiramtala	250	0.76	2021	Kelkar and Dey, (2021)	0.73 ± 0.1
Rupnarayan	Bander-Gadiara	80	0.42	2006	WWF Nepal, (2006)	0.68 ± 0.17

as it considers imperfect detection and allows for the straightforward identification of explanatory variables affecting abundance (λ) and detection (p). Additionally, it provides independent estimates for each site, which are comparable to the D_{cf} approach derived from capture-mark-recapture methods (Courtois et al., 2016; Ficetola et al., 2018; Royle, 2004). Despite other sampling methods being available, such as capture-recapture and distance sampling, the minimal data collection effort and cost-effectiveness of the N-mixture model make it a preferred choice for the present study (Dennis et al., 2015).

These lesser-known rivers are home to more than 15% of the Gangetic dolphin population, supporting previous findings that these small rivers function as refuges for macrofauna, support habitat diversity and species assemblage (Bouska et al., 2023; Pracheil et al., 2013). This proffers the importance of protecting these rivers for biodiversity conservation and functioning of the ecological processes. Furthermore, the species distribution model provided valuable insights into the distribution of dolphins across the Ganga Basin. Bioclimatic, hydrological and human-induced stressors emerged as significant determinants of Gangetic dolphin distribution. The predicted probability distribution encompassed a substantial stretch of 1150 km, representing both historical and current ranges of the species. Notably, approximately 54% (620 km) of the river stretches, accounting for 22% of the priority stretches in the Ganga Basin, were deemed suitable for dolphins, underscoring the significance of these stretches for dolphin persistence (Table S9). Bioclimatic variables that significantly influence the distribution of Gangetic dolphins, such as Annual Mean Temperature, Isothermality, and Temperature Seasonality, were found to play pivotal roles. This underscores the importance of considering climatic factors in understanding the habitat preferences and distribution patterns of the species, particularly during water-scarce periods. Interestingly, similar to the findings of previous studies (Choudhury et al., 2019; Sinha and Kannan, 2014), we also observed a high suitability near the confluence areas. Tributary confluences are significant, not just due to their ability to modify environmental conditions and trigger a biological response upon merging with the main channel (Benda et al., 2004; Fernandes et al., 2004; Rice et al., 2008), but they also represent areas of inherent ecological importance, concentrating specific biophysical processes and ecosystem services (Kiffney et al., 2006; Rice et al., 2008). The high suitability of the confluence areas underscores the significance of these regions in the conservation of the Gangetic dolphin. (Choudhary et al., 2012; Das et al., 2022; Kelkar, 2008). The suitability, translated into potential conservation priority stretches, represents a valuable resource for managers and policymakers, by allowing for concentrated efforts aimed at preserving the biodiversity and ecological integrity of the riverine ecosystem.

Identification of the priority river stretches is one of the most important tenets of the systematic conservation planning, which is followed by monitoring of spatial and temporal biodiversity changes, implementing stringent measures to reduce pollution, enforcing sustainable fisheries management practices, implementing measures to safeguard and restore riverine habitats, engaging local

communities and stakeholders participation, awareness programs to enhance understanding about the importance of biodiversity conservation, consideration of socio-economic aspects and potential conflicts between conservation goals and human activities and ensuring alignment with existing conservation laws and policies, along with implementation of new protective measures (Hermoso et al., 2012; Bond et al., 2014; Linke et al., 2019). Addressing these points makes systematic conservation planning a more effective and inclusive process, contributing significantly to the long-term protection of biodiversity and ecosystems. Conservation prioritization of the rivers in the GRB will aid in allocating resources and efforts where they are most needed and where they will have the greatest impact. Such an approach will ensure that conservation efforts are efficient and targeted, addressing the most critical areas first and gradually extending protection to other priority stretches as resources permit. Overall, our approach focuses on preserving the integrity of the priority stretches, as was also recommended in our prior study (Das et al., 2022), which will contribute to the overarching goal of a basin-wide conservation strategy.

5. Conclusions

In the Indian context, the riverine species particularly crocodylians started getting attention in early-1970s (Sharma et al., 2021). However, the conservation of riverscapes and other aquatic species received little attention. The previous efforts to document the aquatic species were limited to the globally known larger rivers such as Ganga, Brahmaputra, and Indus (Dudgeon, 2000). The flagship initiative, 'National Mission for Clean Ganga' by the Ministry of Jal Shakti, Government of India, represents a pioneering effort to develop an integrated basin-wide river restoration strategy through maintaining river habitat and aquatic biodiversity. Yet, the lesser-known smaller rivers, despite their key role in the ecological process received no or very little attention (Richter et al., 1997). The present study provides evidence of smaller rivers as refuges for Gangetic dolphin, thereby supporting the theory that these smaller rivers contributing to the resilience of larger rivers. This contribution is apparent through the presence of a habitat mosaic, diverse species assemblages, and the provision of freshwater inputs. The findings are crucial as a baseline for India's ongoing range-wide population estimation exercise in India and serve as a precedent for future assessments and studies in the region. The establishment of this baseline for the Kauriyala, Babai, and Bagmati rivers sets a precedent. It encourages further research, monitoring efforts, and proactive conservation initiatives in coordination with the State Department of Environment, Forests, and Climate Change and the National Mission for Clean Ganga (NMCG) to safeguard the river's biodiversity, in line with the systematic conservation planning. Community support needs to be harnessed to ensure successful conservation, especially in areas where dolphins are frequently encountered near villages. Linking local concerns about flood erosion, embankments, and livelihood security to biodiversity conservation programs can be a strategic approach to engage and garner support for river conservation efforts.

CRedit authorship contribution statement

Goura Chandra Das: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Aftab Alam Usmani:** Data Curation. **Surya Prasad Sharma:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Srijani Guha:** Visualization. **Sk Zeeshan Ali:** Visualization. **Shivani Barthwal:** Supervision, Writing – review & editing. **Arkojyoti Sarkar:** Data Curation. **Neeraj Mahar:** Data Curation. **Ajay Rawat:** Data Curation. **Gokulakrishnan. G:** Data Curation. **Javed Anwar:** Data curation. **Sandeep Kumar Behera:** Writing – review & editing, Supervision. **Ruchi Badola:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Syed Ainul Hussain:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.gecco.2024.e02900](https://doi.org/10.1016/j.gecco.2024.e02900).

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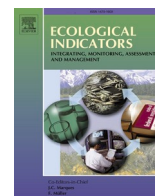
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Prioritising river stretches using multi-modelling habitat suitability of Gangetic dolphin (*Platanista gangetica*) as a flagship species for aquatic biodiversity conservation in the Ganga River Basin, India

Goura Chandra Das, Surya Prasad Sharma, Sk Zeeshan Ali, Saurav Gawan, Aftab Alam Usmani, Arkojyoti Sarkar, Suyash Katdare, Ajay Rawat, Pichaimuthu Gangaimaran, Ashish Kumar Panda, Umang Agnihotri, Aishwarya Ramachandran, Srijani Guha, Shivani Barthwal, Jeyaraj Antony Johnson, Ruchi Badola, Syed Ainul Hussain*

Ganga Aqualife Conservation and Monitoring Centre, Wildlife Institute of India, P.O. Box # 18, Chandrabani, Dehra Dun 248001, Uttarakhand, India

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ABSTRACT

Globally, the river ecosystems are threatened due to human-driven exploitation and indiscriminate resource use. The rate of species loss is a magnitude higher in these ecosystems, hence, identifying conservation priority areas as refugia, using the flagship-cum-indicator species approach can aid in long-term conservation of multiple species and ensure uninterrupted functioning of ecological processes. For effective conservation planning, we derived the site occupancy and abundance of Gangetic dolphin (*Platanista gangetica*) as a flagship species in the Ganga River Basin, and modelled their distribution *vis-à-vis* river conditions for identifying Conservation Priority Stretches (CPS). The study incorporates the first-ever basin-wide (4635 km river) Gangetic dolphin (GD) sightings to estimate range decline, abundance, and identify CPS of select rivers in the Basin. A total of 2151 sightings of surfacing dolphins with mean encounter rate of 0.55 ± 0.09 sightings/km of the river was observed from the surveyed stretch. The GD encounter rate varied significantly across the surveyed rivers (Analysis of Variance, $F = 3.08$, $p < 0.001$). We estimated 24.37 % decline in the dolphin distribution range in the basin since 19th Century. The estimated population size of the dolphin in the Basin was $3330 \text{ individuals} \pm 620$ individuals (Confidence Interval 95 % = 2304–4668; Coefficient of Variance = 18.61) which varied across the river. The site occupancy and abundance were best predicted by channel depth ($\beta = 0.82 \pm 0.46$), meanders ($\beta = 0.256 \pm 0.87$) and individual rivers, whereas channel width ($\beta = 0.11 \pm 0.08$) and survey efforts influenced detection probabilities. Further, we identified 610 km (12.2 %) of river stretches as high CPS in the Basin based on the prediction probability (≥ 0.70) of GD. Protection of these stretches is likely to ensure sustained reproduction of GD and provide refugia for other threatened species of the Ganga River and its tributaries, which is under increasing anthropogenic pressure.

1. Introduction

Freshwater ecosystems such as rivers, streams and associated wetlands are an integral component of the global water cycle, flow regulation, and effective functioning of associated ecosystems (Matthews, 2016; Grantham et al., 2019). The freshwater ecosystem comprises less than 1 % of the Earth's surface yet has the most diverse habitats, species, and biodiversity (Dudgeon et al., 2006). Besides, the freshwater ecosystems represent 9.5 % of all faunal species and harbour approximately 6 % of all described species and a third of all vertebrate species globally

(Balian et al., 2007; Strayer and Dudgeon, 2010). These vital ecosystems are threatened by several human-induced factors, such as rapid infrastructure development, widespread habitat degradation, pollution, and hydrological alteration due to dams and barrages (Alizadeh et al., 2018; Alvarado et al., 2021; Kouadri et al., 2021). The upsurge in river infrastructure developments has disrupted longitudinal connectivity causing fragmentation leading to biodiversity loss and threatening ecosystem functioning (Dudgeon, 2000; Guo et al., 2019). Furthermore, the unprecedented impacts of these factors have potentially affected migration, breeding biology, habitat use pattern and has resulted in

* Corresponding author.

E-mail addresses: ruchi@wii.gov.in (R. Badola), ainul.hussain@gmail.com (S.A. Hussain).

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population isolation of many freshwater species (Strayer and Dudgeon, 2010; Boscarì et al., 2022). Additionally, rivers are vulnerable to global climate change associated uncertainties of precipitation and temperature patterns, which would worsen rivers' hydrological conditions (Schneider et al., 2013). The impact of climate change is likely to have an irreversible cascading impact on thousands of freshwater species that are currently on the verge of extinction (Vörösmarty et al., 2010). Consequently climate change impacts have drastically modified trophic interactions and altered prey species distribution, limiting the top predators' physiological and biological requirements (Learmonth et al., 2006; Wynn et al., 2007).

River systems in Asia are considered among the most dynamic and threatened ecosystems (Dudgeon, 2000, 2002), as more than half of the global human population resides in 13 % of the world's land mass (Hannah et al., 1994). The rate of biodiversity loss is a magnitude higher in tropical rivers of Asia due to escalating human demands on the river ecosystems (Guo et al., 2019). The Ganga Basin (henceforth, GB) is the largest river basin in India, which supports ~650 million people and rich aquatic biodiversity, is experiencing increased human footfall leading to population declines and range reduction of riverine biota inhibiting vital ecological processes (Nautiyal, 2010). In a nutshell, despite the high ecological significance of the GB, socio-political demands, development and religious activities, and economic feasibility have become major obstacles in developing a comprehensive and systematic conservation plan for the basin. In the current epoch of Anthropocene, biodiversity conservation has become the world's most essential shared responsibility (Sun et al., 2022). The flagship species approach can be instrumental in invoking this shared responsibility. In recent years, the flagship species approach has gained much support and acceptance as a management tool for starting point to monitor biodiversity changes and developing conservation plans (Kim et al., 2021). The flagship species are relatively large, top predators, charismatic vertebrates that can significantly promote environmental awareness (Barua et al., 2011). Consequently, flagship species are explicitly perceived as 'umbrella' species in identifying protected areas, assuming their conservation will confer appropriate protection to other species (Piatt et al., 2007; Sergio et al., 2008).

The Gangetic dolphin (*Platanista gangetica*), (henceforth, GD) was first scientifically documented in the year 1801 by Heinrich Julius Lebeck (Lebeck, 1801; Kinze, 2000). Earlier the GD was considered a sub-species of the South Asian River dolphin. However, a recent phylogenetic study revealed GD as a distinct species from the Indus River dolphin (*Platanista minor*) (Braulik et al., 2021). The GD is a top predator that influences the food chain structure, thereby plays a critical role in maintaining the vital ecological processes of the river ecosystems and serve as a potential indicator for monitoring status of river health (Gomez-Salazar et al., 2012; Turvey et al., 2012; Sinha and Kannan, 2014). Its extirpation from river systems serves as a tool to measure the extent of human footprints exploiting riverine resources (Sinha et al., 2010; Sinha and Kannan, 2014; Behera et al., 2014). Once commonly distributed in major river systems between longitudes 77° E and 89° E in India, Nepal and Bangladesh (Anderson 1879, Smith, 1993; Mohan et al., 1997), the species is now restricted to disjunct stretches of the Ganga-Brahmaputra-Barak river system in India (Wakid, 2009; Behera et al., 2014; Sinha and Kannan, 2014; Choudhury et al., 2019), Karnali, Sapta Koshi and Narayani river systems in Nepal (Shrestha, 1989; Paudel et al., 2015) and Meghna, Karnaphuli and Sangu river systems in Bangladesh (Reeves et al. 2000; Smith et al. 2006). The GD is now isolated into small groups and is under severe threat due to a wide array of factors such as flow modification, habitat degradation, prey depletion, noise pollution, poaching and net entanglement (Dey et al., 2019; Paudel and Koprowski, 2020; Kolipakam et al., 2022). Owing to these threats, the GD experienced a ~30 % decline in its population (Paudel and Koprowski, 2020) and a range reduction between the late 19th and early 21st century (Mohan, 1989; Shostell and Ruiz-García, 2010; Sinha and Kannan, 2014).

The species in the past has attracted multiple conservation efforts; the Government of India has accorded utmost protection to the species by including it in Schedule I of the Wild Life (Protection) Act, 1972, since its inception in 1972 (Sinha and Kannan, 2014). The species has been listed in the Endangered category in the International Union for Conservation of Nature Red List of Threatened Species since 1996 (Kelkar et al., 2022). To prohibit international trade, the species was enlisted in Appendix I of the Convention on International Trade in Endangered Species (CITES) and in Appendix II of the Convention on Migratory Species (CMS). To further strengthen its conservation, the Government of India has declared GD as the National Aquatic Animal of India with a clear mandate of spreading awareness among local communities to protect and conserve GD and its habitats.

Despite these efforts, the information on current distribution, abundance and factors affecting GD is limited, and information on their distribution from previous studies are from specific short stretches and in different time scales (Behera et al., 2014; Sinha and Kannan, 2014; Chowdhury et al., 2016). Hence, there is little comprehensive information on the status of the GD from its range, which is crucial for the long-term conservation of this species. Moreover, information on the extent of suitable habitats for the GD in many parts of its range in India is lacking, which hinders conservation planning. Additionally, it is paramount to configure the impacts of climate change on the distribution of the GD (Paudel and Koprowski, 2020).

In the present study, we aimed to assess the occurrence, population status, and habitat suitability of GD in GB, India, to address the following research questions (a) what is the current distribution range of GD in the basin? (b) What is the current population status of the GD in the riverscape of the GB? (c) What is the extent of occupancy of the GD in the basin? (d) What factors influence site occupancy and abundance of GD across the basin? and (e) What is the extent of best suitable areas available in the basin for the conservation of GD as an indicator species, which ultimately may improve overall river conservation in GB.

The GD and other large vertebrates such as crocodiles are the large predators found in the GB and are potential flagship species. However, the basin wide distribution of GD and its greater hydrological requirements compared to other predators in the basin makes it an ideal choice as a flagship species. It provides ample data points required for increased efficacy and to draw reliable inferences. Large-scale visual encounter survey data was employed to assess the status of GD and their site use across riverscape in the GB. We used an occupancy framework to delineate the proportion of the riverscape used by GD and evaluate how suites of environmental and anthropogenic predictors influence their site use. We then derived the abundance of GD using N-mixture models and evaluated factors influencing the abundance. We also administered a flagship-cum-indicator species based systematic conservation planning approach to identify priority stretches for effective GD conservation. The identification of conservation priority stretches of the Ganga River and its tributaries is likely to enable the policymakers and managers to develop basin-wide conservation and restoration plans. This will be in line with India's international commitment to the United Nations Decade on Ecosystem Restoration.

2. Materials and methods

2.1. Study area

The present study was conducted in the Ganga River and its major tributaries viz. Yamuna, Chambal, Ghaghra, Son, Gandak, Kosi and Rupnarayan to record the sightings of the GD (Fig. 1). The GB alone drains an area of 8,61,404 sq. km ($\geq 26\%$) of India's geographical area (Dwivedi et al., 2018). The GB is surrounded by the great Himalayas in the north, the Chota Nagpur plateau and Vindhya in the south, Aravalli range in the west, and the Brahmaputra Ridge in the east, which has given rise to climatic, topographical and hydrological variations (CWC, 2014). The hydrological regime also varies across seasons, with reduced

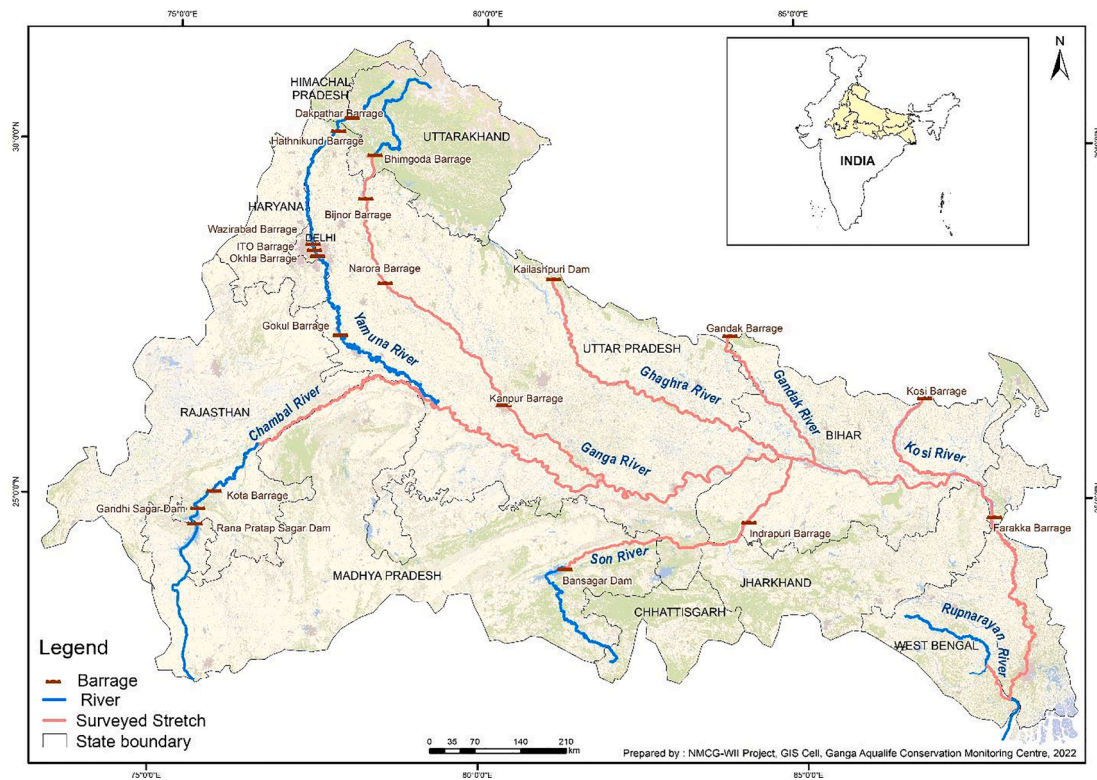


Fig. 1. Map of surveyed rivers for Gangetic dolphin in the Ganga Basin, India.

flow occurring between winter and summer and the highest river discharges recorded during the monsoon. The wide range of geomorphological and hydrological variations provides a mosaic habitat suitable for diverse flora and fauna (Hussain et al., 2020; Sonkar and Gaurav, 2020). The GB is one of the most densely populated regions of the world (>1400 individual/km²). The high human density results in higher demand of water for agriculture, industry, electricity generation and navigation. Sand mining, unplanned developmental activities and point and non-point source discharge have further degraded the river habitat including water quality (Hussain et al., 2020; Dagar et al., 2021).

The GB is spread across 11 Indian states and lies within five distinct biogeographic zones, viz. Himalaya (North-West Himalaya 2A and West Himalaya 2B), Semi-Arid (Punjab Plains 4A and Gujarat Rajputana 4B), Deccan Peninsula (Central Highlands 6A and Chota Nagpur Plateau 6B), Gangetic Plain (Upper Gangetic Plain 7A and Lower Gangetic Plain 7B) and Coasts (East Coast 8B) (Rodgers and Panwar, 1988; CWC, 2014). The climate of the GB varies from alpine, temperate, to sub-tropical and tropical. The annual mean precipitation ranges from 500 mm to 2500 mm, and ~80 % of the precipitation occurs between June and September (Nandargi and Shelar, 2018).

In the GB, we studied eight major rivers through literature survey and field sampling (Supplementary Fig. S1). Of these, Ganga, Yamuna, Ghaghra, Gandak and Kosi are snow fed, whereas the Chambal, Son and Rupnarayan are rain fed. The smaller tributaries such as Girwa, Sharda, Rapti and Mahananda were not surveyed due to logistical constraints even though GD were reported from these rivers. Brief description of studied rivers has been provided in the supplementary information (Supplementary Table S1).

2.2. Data collection

We surveyed 4635 km of the rivers, viz. Ganga (2070 km), Yamuna (435 km), Ghaghra (615 km), Gandak (295 km), Kosi (235 km), Chambal (405 km), Son (500 km), and Rupnarayan (80 km) for their ecological condition *vis-à-vis* occurrence of GD using boat based visual

encounter survey between 2020 and 2021 (Smith and Reeves, 2000; Sinha and Sharma, 2003a) (Fig. 1).

Each of the surveyed rivers were divided into 5 km segments referred to as Biodiversity Evaluation Unit (BEU) in ArcGIS 10.2 (ESRI, Redlands, USA). We collected information on five hydro-morphological and four anthropogenic variables at 1 km intervals, which were averaged for each BEU (Supplementary Table S2). The surveys were conducted during post-monsoon (November to February) season in daylight between 8:00 hrs to 12:00 hrs and 15:00 to 17:00 hrs using an inflatable rubber (25 hp)/country boat following thalweg (deeper part of the river) (Oliveira et al., 2017). The speed of the boat was kept constant at 6–8 km/hr to avoid missing any sightings of surfacing GD. A team of four trained observers equipped with binoculars (NIKON 8 × 42), GPS (GARMIN e-Trex 30), depth sounder (HONDEX PS7), and range finder (HAWKE Endurance LRF-1000), were stationed at the front of the boat to obtain concurrent least counts of GD sightings and associated habitat variables following Smith et al., (2006). In each team, three observers were responsible for looking for surfacing GD, and the fourth observer for recording associated habitat variables at each sighting.

Habitat parameters such as channel width (m), efforts (duration of time spent in each BEU), time (time of the day), channel depth (m), water flow (m³/sec.), river slope (degree), number of meanders (meanders/BEU), fishing intensity (active nets and boats/BEU), sand mining intensity (mining boats/BEU) as well as anthropogenic factors were recorded within each BEU (Supplementary Table S2).

2.3. Data analysis

2.3.1. Distribution and range decline

The decline in species' historical range and understanding the associated causes is central to species conservation and management. The decline is often measured through distribution or abundance changes (Gaston et al., 2000; Uzqueda et al., 2020). The use of reduction in distributional area is useful when there is no abundance data available but sufficient historical occurrence records exist (Shaffer et al.,

1998). To estimate the range decline in the GB, dolphin sighting records from recent surveys (2020 and 2021) and previous records of GD occurrences were obtained from the literature (Behera et al., 2014, Sinha and Kannan, 2014) and compared. Further, the local extinction was confirmed when it was not encountered/reported in a particular river for more than ten years' time frame (Mitra and Chowdhury, 2018). Potential hydro-morphological variables and encounter rate of GD (sightings/ km linear stretch), were evaluated for inter-river variation using Analysis of Variance (ANOVA) test (Supplementary Text S1).

2.3.2. Site occupancy and abundance

In ecological modelling, regression-based approaches such as Generalized Linear Model (Rushton et al., 2004) and Generalized Additive Models (Leathwick and Whitehead, 2001) are frequently used to evaluate species association with environmental and/or habitat variables (Guisan and Zimmermann, 2000; Rushton et al., 2004). However, these approaches do not estimate site-specific species occurrences. Unlike these approaches, models based on occupancy frameworks can produce unbiased estimates of occupancy (Ψ) and provide insights into the habitat use of a species simultaneously considering detection probabilities (p) (Mackenzie et al., 2002). The occupancy model also allows the inclusion of covariates to explain heterogeneity in both occupancy and detection probability (Mackenzie et al., 2006).

Selecting an appropriate method for population estimation is challenging, particularly for species having low detection probability, such as the GD. The occupancy models take into account detection and non-detection over multiple surveys of a sampling site to estimate detection probabilities (p) to derive unbiased estimates of occupancy (Ψ) (Mackenzie et al., 2002). Here, we used site occupancy models in maximum-likelihood frameworks to determine the probability of site use (Mackenzie et al., 2002), and the N-mixture model (Royle, 2004; Kéry and Royle, 2015) to estimate abundance (λ) of the GD in GB using spatial replicate counts while accounting for imperfect detection. *Platanista gangetica* and *Platanista minor* being identical in their external appearance, have similar physiological requirements (Smith and Braulik, 2009), and thus mean home range of the *Platanista minor* was used as a surrogate for designing the length of the sampling sites for the present study (Toosy et al., 2009). The GD is assumed to have a maximum daily movement of ~25 km given the river stretches are characterized by intermittent shallow and deep pools. Secondly, a linear river stretch of 25 km can be easily surveyed for GD detection within a day without any logistical constraints with a vessel speed of 6–8 km/ hrs. The surveyed stretch of 4635 km was split into 927 BEUs that were considered as spatial sub-units to assess the extent of site use of the GD. Five adjacent BEUs (sampling sites of 25 km) were considered as spatial replicates to accommodate it in site-occupancy and N-mixture framework (Mackenzie et al., 2002; Charbonnel et al., 2014; Searle et al., 2020). We chose a length of 25 km as the best compromise between the need to detect the presence of a species and that of having more than three spatial replicates, as recommended by Hines et al. (2010). Double counting of GD due to overnight movement from surveyed to non-surveyed segments was considered, assuming an equal probability of GD being missed due to opposite-direction movement (Braulik, 2006).

We used 156 sampling sites out of 185 as we did not record GD sightings in the surveyed stretch of the Son River, 180 km stretch of the Chambal River between Pali and Dang Basai and 70 km stretch of the Ganga River between Bhimgoda and Bijnor barrages. For deriving site-occupancy, the dolphin presence/absence at each spatial unit and the covariates that may influence occupancy and detection probability were included in the analysis (Mackenzie et al., 2006). The covariates were selected based on *a priori* understanding and literature search that may influence the occurrences of GDs (Kelkar et al., 2010; Choudhary et al., 2012; Paudel et al., 2015). The detection covariates are presumed to influence the likelihood of detecting a species, given its presence at a site (p). We considered channel width, effort, and time of the surveyed day as detection covariates for both site occupancy and N-mixture

modelling, assuming these variables would influence the detection of a GD given its presence at a site. Site covariates are factors that are hypothesised to influence the probability of a species' site occupancy (ψ). The same suite of variables were selected for estimating abundance (λ) using N-mixture models (Supplementary Table S2). Each of the continuous covariates were z-standardized before analysis and categorical variables were dummy coded following Sunarto et al. (2012), Searle et al. (2020). Variables were checked for multicollinearity using Pearson's correlation test, and variables having Pearson's correlation coefficient ≥ 0.70 were excluded from the analysis following Graham (2003). Additionally, the GD count, along with covariates influencing the abundance, was included in the N-mixture modelling.

In this study, site occupancy models (MacKenzie et al., 2002) were used with detection and non-detection data using the "unmarked" package's 1.2.5 *occu ()* function (Fiske and Chandler, 2011). A multi-stage modelling approach was adopted, in which covariates influencing detection probability p were run first, keeping the occupancy probability Ψ constant. Then, using multivariate occupancy models, we investigated whether environmental covariates influenced detectability (Supplementary Text S2).

The N-mixture model was performed using the *pcount ()* function in "unmarked" package in R version 4.1.3 (Fiske and Chandler 2011; R Development Core Team 2022), using R Studio version 2022.02.3 (RStudio Team 2022). We fitted the N-mixture models, combining all the spatial counts data with Negative Binomial distributions (Joseph et al., 2009; Knappe et al., 2018) as it allows for modelling over dispersion data with significantly fewer true zeros in the dataset (Wenger and Freeman, 2008; Barão-Nóbrega et al., 2022). We used a numeric upper bound value for K for abundance estimates following multiple trials without affecting the model outcome (Fiske and Chandler, 2011; Kéry and Royle, 2015; Barão-Nóbrega et al., 2022). Models were ranked based on their Akaike Information Criterion (AIC) scores (Akaike, 1974; Burnham and Anderson, 2004) (Supplementary Text S3). The predictor variables associated with top-ranked univariate model were evaluated to determine GD habitat use (Ψ). We then modelled covariates hypothesised to affect detection (p), channel width, effort and time using a global model considering remaining habitat use covariates constant. A final model set was generated for all possible additive combinations of detection and site use covariates with $\Delta AICc < 2$, representing models with substantial empirical support. The goodness of fit for the most parameterized and highest-ranked models were assessed following Mackenzie and Bailey's goodness of fit test (MacKenzie and Bailey, 2004).

The AICc weights of all models in the final model set, in which the covariate appeared, were summed to assess the overall importance of the covariates (Burnham and Anderson, 2004). The sign of the covariate's beta coefficient estimates represented the direction of impact, and only if the beta coefficient's 95 % confidence interval ($\beta \pm 1.96 \times SE$) did not overlap zero, the effect of covariates was deemed significant. The predicted probability of site occupancy for each site was obtained via model averaging the final model set using the package MuMin (Bartoń, 2013). The sum of squared errors, chi-square, and freeman-tukey tests were used to evaluate the goodness of fit for the top-ranked model and the model with the most parameters in the final model set.

2.3.3. Abundance estimation using correction factor (D_{cf})

GD rely upon their surfacing, however, there is a chance of missing few individuals during the survey. Correction factor for missing/unmarked individuals is an essential precursor to estimate population figure precisely (Vu et al., 2018). Thus, correction factor (D_{cf}) was derived using detection probability extracted from published work conducted in the rivers in the Indian subcontinent and was used as an index to verify the outcome of our model-based results. The mean correction factor for GDs was derived from various studies (Supplementary Table S3). D_{cf} account for missed individuals while conducting

visual encounter surveys (Smith et al., 2006; Richman et al., 2014). The D_{cf} for GD was derived by dividing 1 by detection (p) and the corrected population estimates of GD were calculated by multiplying D_{cf} by the total number of GD sightings obtained during the visual encounter survey.

$(D_{cf}) = 1/(\hat{p})$, where (D_{cf}) is the correction factor for GD estimates and \hat{p} is the detection probability.

2.3.4. Conservation priority stretches (CPS)

Scholars have identified conservation priority areas using either species or habitat, or both (Asaad et al., 2017; Maire et al., 2017). The species-based criteria include species of conservation significance, restricted-range species, biological diversity, and areas important for life history stages (e.g. Stewart et al., 2022; Banerjee et al., 2022), and habitat criteria includes unique and rare habitats, fragile and sensitive habitats, ecological integrity, and representativeness (e.g. He et al., 2018). These criteria were further categorized as five factors (habitat cover, species attribute, species richness, geographic range, and species abundance) for identification of priority areas (Assad et al., 2017). We have used flagship-cum-indicator species based approach for identification of conservation priority stretches, which essentially includes species of conservation significance, and ecological integrity criteria. These two criteria represent the four factors suggested by Assad et al. (2017), which makes our approach robust.

We used Maximum entropy (MaxEnt, version 3.4.4) models to predict the potential distribution and to identify conservation priority areas in the GB (Phillips et al., 2017). MaxEnt models are based on the principle of maximum entropy that accounts for presence-only data of rare or threatened species with environmental variables (Elith et al., 2006; Phillips et al., 2017; Clements et al., 2012; Kramer-Schadt et al., 2013) to project future distributions under global climate change impacts (Hu and Jiang, 2011) and considered as one of the efficient models for predicting species distribution models. There are many other well established species distribution modelling approaches such as Generalised Additive Models, Genetic Algorithm for Rule-set Prediction (GARP) and BIOCLIM that uses presence only data. MaxEnt has an advantage over them, as it has a higher predictive accuracy (Elith et al. 2006, Wisz et al. 2008). MaxEnt is suitable for simple as well as complex models with wide array of predictor variables. However, it can produce biases due to over-fitting of the models and influence the predictive performance when using large set of predictor variables (Phillips and Dudík, 2008).

A total of 758 presence locations of GD were used for distribution modelling. We selected 28 variables (Bioclimatic = 19, hydro-morphological = 5, and anthropologic = 4) based on *a priori* understanding of the species ecology and literature search for species distribution modelling using MaxEnt (e.g. Kelkar et al., 2010; Choudhary et al., 2012; Paudel et al., 2015). The bioclimatic layers were downloaded from WorldClim version 2 at a spatial resolution of 2.5 arc minutes ($\sim 4.5 \text{ km}^2$) (Fick and Hijmans, 2017) and resampled at 5 km^2 to have a uniform spatial resolution. Each of these variables were checked for multicollinearity, and highly correlated (Pearson correlation ≥ 0.70) variables with low ecological influences were removed from the modelling (Zuur et al., 2010).

Finally, presence location of GD, along with 16 uncorrelated ecologically meaningful variables (Bioclimatic = 7, hydro-morphological = 5, and anthropologic = 4) were used to predict the suitable habitat of the species using MaxEnt (Supplementary Table S2). Two key user-modifiable parameters influence the predictive performance of the MaxEnt, viz. feature classes and regularization multipliers (Elith et al., 2010). These parameters were optimized to prevent model over-complexity and/or overfitting. We experimented with multiple combinations of feature classes (L = Linear, Q = Quadratic, P = Product, T = Threshold and H = Hinge) and regularization parameters (0.5, 1.0, 1.5 and 2.0). The models were ranked based on AIC to obtain the best-fit

model. The ASCII file of prediction probability was projected to ArcGIS 10.6 and reclassified to generate a probability distribution map. Potential dolphin distribution stretches (probability distribution score > 0.50) were categorised into three major conservation priority stretches, ≥ 0.70 High Conservation Priority Stretches (CPS1), 0.61–0.70 Moderate Conservation Priority Stretches (CPS2) and 0.51–0.60 Low Conservation Priority Stretches (CPS3).

3. Results

3.1. River characterization

The mean depth of the eight surveyed rivers was 3.49 m (± 0.42 , $n = 927$) and among these the Ganga River was the deepest (5.78 m ± 0.27 m). Significant variation in mean depth was found between the rivers (ANOVA, $F = 59.88$, $p < 0.001$). The mean river width was 531.69 m ± 86.65 m, which was more than the mean width of Chambal, Son, Yamuna, Ghaghra and Gandak rivers. The mean channel width shows significant variation across studied rivers (ANOVA, $F = 74.9$, $p < 0.001$). The mean channel flow across the rivers was 531.43 $\pm 86.65 \text{ m}^3/\text{s}$ and ranged between 80.31 $\text{m}^3/\text{s} \pm 102.37 \text{ m}^3/\text{s}$ (Rupnarayan River) and 762.36 $\text{m}^3/\text{s} \pm 490.45 \text{ m}^3/\text{s}$ (Ghaghra River). We observed significant difference in the mean flow between rivers (ANOVA, $F = 19.76$, $p < 0.001$). The mean number of meanders (1.34 ± 1.06 meanders/BEU) showed significant variation between rivers (ANOVA, $F = 18.72$, $p < 0.001$). The number of meanders was found to be highest in the Chambal River (1.34 ± 1.06 meanders/BEU). The mean slope (0.75 ± 0.38 degree) across the basin showed significant variation between the studied rivers (ANOVA, $F = 9.75$, $p < 0.001$). The Yamuna River was the steepest among the eight surveyed rivers (1.38 ± 2.4 degree) (Supplementary Table S4).

Our assessment suggests that in comparison to other rivers, the Chambal River is relatively disturbance free due to its protected nature. The mean fishing intensity (22.67 ± 25.70 nets/ BEU) indicated significant variation between the rivers (ANOVA, $F = 9.75$, $p < 0.001$). The fishing intensity was highest for the Rupnarayan River (72.19 ± 61.25 nets/ BEU) and lowest for the Chambal River (0.05 ± 0.21 nets/BEU). The sand mining intensity in the basin was 4.23 ± 3.24 activities (boats, tractor and earthmovers) with highest for the Yamuna River (9.64 ± 28.68) and lowest for the Chambal River (0.59 activities ± 1.47 activities). We found significant differences in the mining activities across studied rivers in the basin (ANOVA, $F = 6.038$, $p < 0.001$). The mean water extraction pumps in the GB was 0.76 ± 0.20 (pumps/ BEU) with highest in the Rupnarayan River (7.5 ± 8.37) and lowest in the Chambal River (0.05 ± 0.21) due to above stated reasons. The occurrences of water extraction pumps within rivers showed a significant variation (ANOVA, $F = 18.57$, $p < 0.001$).

3.2. Distribution and range decline

First ever description of GD range was given by Anderson (1879). In the basin, the GD used to occur between Haridwar and Ganga Sagar prior to the initiation of water resource development projects in the mainstem of the Ganga River during the 19th Century (Supplementary Fig. S2). In the present study, the occurrence of GD in the mainstem Ganga was found to be confined in two disjunct stretches (Fig. 2). The first between Bijnor barrage and Kanpur barrage, and the second one between Fatehpur and Ganga Sagar. The current occurrence of GD in the Ganga, indicates 6.51 % decline in its range, which contributes to 2.74 % decline in the GB. In the Yamuna River, the historical range was between Delhi and Prayagraj (Yamuna - Ganga confluence). During present study GD sightings were recorded downstream of Bareh (Chambal - Yamuna Confluence) up to Prayagraj, indicating 58.57 % decline in the Yamuna, which contributes to 12.04 % decline in its entire distribution range. In the past, the GD sightings in Chambal River were recorded between Batesura and Bareh. However, in present survey the GD distribution was

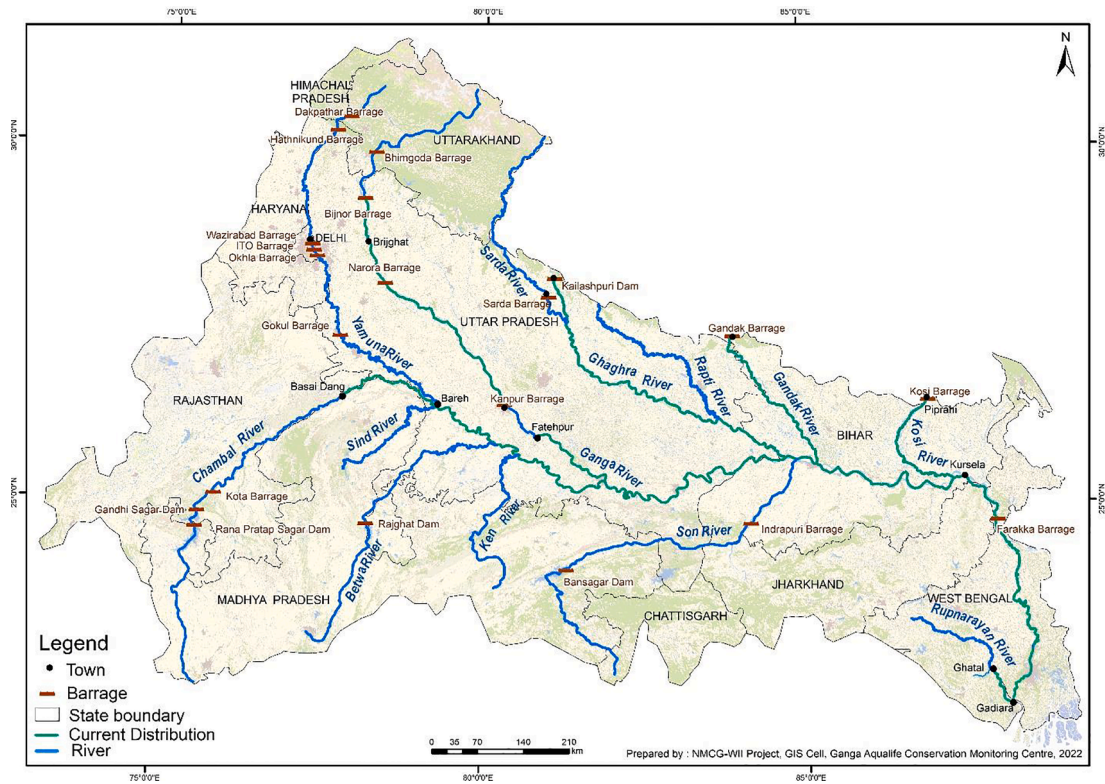


Fig. 2. Current distribution range of Gangetic dolphin in the Ganga Basin, India.

restricted between Basai Dang and Bareh, which suggests range decline of 17.54 % in Chambal, and 0.98 % of its entire distribution range. The GD range decline in the Kosi River was 4.26 % and 0.20 % in its distribution range. The GD distribution was found to be intact in the other northern snow fed tributaries such as Ghaghra, and Gandak. In the present study we recorded no dolphin occurrences from Son River, and is

the first report of GD extirpation from entire Son River. The GD is now believed to be extirpated from Ken, Betwa, and middle stretch of Sharda rivers mainly due to reduced depth caused by water abstraction. However, in the Rupnarayan River, we observed increase in GD range, which accounted for 40 % increase from its earlier records, and 0.01 % increase in its entire range. Overall, our estimate suggest that the current

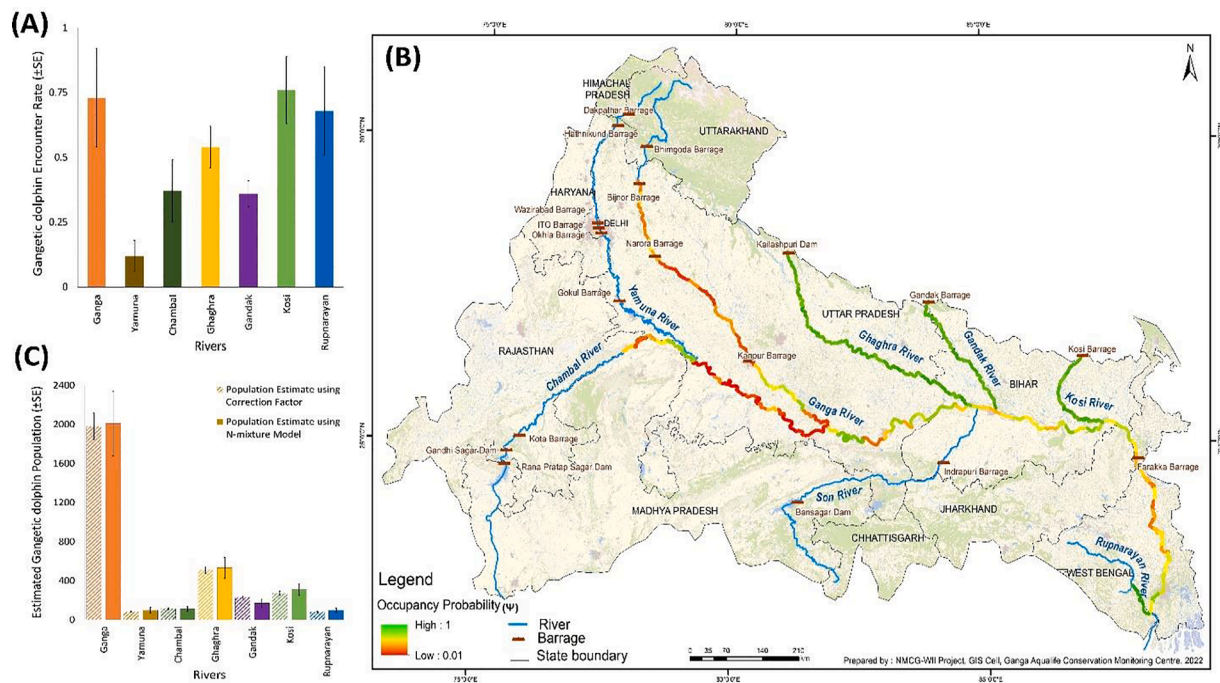


Fig. 3. (A) Encounter rate of dolphin sightings per km in eight major rivers of Ganga Basin, India, (B) Model averaged estimates of Gangetic dolphin site occupancy (Ψ), and (C) abundance estimate of Gangetic dolphin using N -mixture and correction factor (D_{cf}).

distribution range of the GD has been reduced by almost 24.37 % (1245 km) in the GB since 1878 and 7.44 % over the last two decades (Supplementary Table S5).

3.3. Encounter rate

In total, 2151 sightings of surfacing GDs were recorded in 4635 km survey stretch of eight rivers. Maximum of 1303 (60.57 %) sightings were recorded from the Ganga River followed by Ghaghra, Kosi, Gandak, Chambal, and Rupnarayan rivers, and least from the Yamuna River (Supplementary Table S6). The overall mean encounter rate was 0.51 ± 0.11 sightings/km that indicated significant variation across the surveyed rivers (ANOVA, $F = 3.08$, $p < 0.001$). We recorded the highest dolphin encounter rate in the Kosi (0.76 ± 0.13 sightings/km), followed by Ganga, Rupnarayan, Ghaghra, Chambal, Gandak and Yamuna Rivers (0.12 ± 0.06) (Fig. 3A). No dolphins were recorded from the Son River.

3.4. Factors affecting dolphin site occupancy and abundance

GD was detected in 132 out of 156 sampling units of 25 km linear stretch, accounting for a naïve occupancy of 0.85. The estimated mean detection probability was $(p) 0.60 \pm 0.03$, and the mean probability of site occupancy was $\Psi = 0.85 \pm 0.04$.

In total, 35 models, including univariate and multivariate, were generated to infer the influence of predictor variables on the detection probability (p) and site occupancy (Ψ) of the GD. The best fit model (AICc = 0.0) for site occupancy (Ψ) includes channel depth, meander and river, and for detection probability (p) includes channel width as the best predictor variable (Table 1A). Model averaged estimates revealed high GD site occupancy across the study area (Fig. 3B). The variables defining the site occupancy, viz. depth summed model weight ($\Sigma w = 1.00$), meanders ($\Sigma w = 1.00$), and individual rivers ($\Sigma w = 1.00$) were found to be positively associated with GD occurrence (Table 1B). In contrast, channel width ($\Sigma w = 1.00$) defining the detection probability showed a negative but insignificant association as beta coefficient yield overlapping zero ($\beta \pm SE = 0.11 \pm 0.08$) (Supplementary Fig. S3).

A total of 31 N-mixture models considering all possible combinations of covariates (univariate and multivariate) were generated under Negative Binomial distribution. The best fit model for abundance (λ) includes channel depth, meanders and individual rivers, and for

Table 1

Results of site occupancy model selection (A) Best model for Gangetic dolphin site occupancy (B) Parameter estimates (SE) of the final model set ($\Delta AICc < 2$) for models estimating Gangetic dolphin site occupancy.

(A) Best models for Gangetic dolphin site occupancy (Ψ)					
Model	nPars	-2*LogLike	AICc	Δ AICc	AICwt
1 Ψ (cd + me + river), p(cw)	11	467.81	957.62	0	0.66
2 Ψ (cd + me + river), p(cw + effort)	12	467.81	959.63	2	0.24

(B) Parameter estimates (SE) of the final model set				
Model	β (cd)	β (me)	β (Yamuna)	β (cw)
1 Ψ (cd + me + river), p (cw + effort)	0.82 (0.46)	2.56 (0.87)	-3.34 (1.50)	0.11 (0.08)
2 Ψ (cd + me + river), p (cw + effort + time)	0.82 (0.46)	1.04 (0.10)	-3.37 (1.51)	0.11 (0.08)

Δ AIC is the relative difference in AIC values compared with the top ranked model; where AIC is Akaike's information criterion; AICwt is the Akaike weight of the model; nPars is the number of parameters; -LogLike is the negative log likelihood value; Ψ is estimated site occupancy; p is the estimated detection probability; Lambda (λ) is the abundance estimates. Cd = channel depth; me = meanders; river = individual river; cw = channel width.

detection probability (p) include channel width and effort (Table 2A). Based on model-averaged parameter estimates, channel depth ($\Sigma w = 1.00$), meanders ($\Sigma w = 1.00$) and river ($\Sigma w = 1.00$) were the best predictors of the dolphin abundance (Table 2B). As seen in the site occupancy modelling, we observed a positive influence of channel depth, and meanders on GD abundance. Although parameters like individual river appeared in the final model set, the influence of it varied from river to river. Ganga, Ghaghra and Kosi had a significant positive influence on abundance, whilst the remaining had no influence (Table 2B). Channel width significantly negatively impacted detection probability ($\Sigma w = 1.00$), while effort was positively associated with the detection probability of GD in the GB ($\Sigma w = 1.00$) (Supplementary Figs. S4 and S5).

3.5. Population estimation

3.5.1. Population estimation based on N-mixture model

The overall abundance estimate of GD across the GB was 3330 ± 620 individuals (Confidence Interval (CI) = 2304–4668; Coefficient of Variance (CV) = 18.61) (Fig. 3C), the abundance was highest in Ganga River (60.36 %) with estimated 2010 ± 332 individuals (CI = 1455–2718; CV = 16.52). Of all tributaries, the Ghaghra River holds the second largest population of GD (16.01 %) with an abundance estimate of 533 ± 108 individuals (CI = 350–766; CV = 20.34) followed by the Kosi River (9.34 %) with an estimate of 311 ± 59 individuals (CI = 209–434; CV = 18.81) and Gandak River accounted for 169 ± 45 individuals (CI = 95–268; CV = 26.53). The abundance estimate for Chambal River was 111 ± 27 individuals (CI = 70–172; CV = 24.54) followed by Rupnarayan River with an estimate of 99 ± 21 individuals (CI = 64–146; CV = 20.85). The abundance estimates were least in the Yamuna River at 97 ± 28 individuals (CI = 61–164; CV = 29.33), which accounted for 2.91 % of the total estimated population in the basin (Table 3A).

3.5.2. Population estimation based on correction factors (D_{cf}) derived from other studies

The estimates of GD abundance were obtained by multiplying the mean correction factor ($D_{cf} = 1.52$) by the number of GD sightings in each river. The estimated population of GD in the GB was thus 3270 ± 229 individuals (CI = 2821–3718). The highest estimated number of GD for the Ganga River was 1981 ± 138 individuals (CI = 1709–2252). Similar to the estimate obtained using N-mixture, the Ghaghra River was estimated to have the second largest population of GD at 509 ± 36 individuals (CI = 439–579) followed by Kosi River with an estimate of 272 ± 19 individuals (CI = 235–309) and Gandak River accounted for 231 ± 16 individuals (CI = 199–263). The abundance estimate of Chambal River was 114 ± 8 individuals (CI = 98–130) followed by Rupnarayan River with an estimate of 82 ± 6 individuals (CI = 71–93). The estimated population of GD was least in the Yamuna River at 81 ± 6 individuals (CI = 70–92) (Table 3B).

3.6. Identification of conservation priority stretches (CPS)

We obtained a total of 124 models considering multiple combinations of feature classes and regularization multipliers (Supplementary Table S7). The prediction model generated using cross validation with 500 iterations had an Area Under Curve [AUC = 0.91 (SD 0.0089)] (Fig. 4A). The SDM analysis revealed that eight bioclimatic variables viz. fishing, annual mean temperature (Bio 1), channel flow, precipitation of driest quarter (Bio 17), precipitation of warmest quarter (Bio 18), precipitations of the wettest month (Bio 13), meanders, and depth had ≥ 5 % contribution in defining GD distribution under current climate conditions. The predicted potential distribution of GD showed that the contribution of fishing was maximum (18.4 %) followed by annual mean temperature (15.5 %) and channel flow (12.9 %) (Supplementary Table S8).

The species distribution obtained using MaxEnt models predicted

Table 2

Results of *N*-mixture model selection (A) Best models for Gangetic dolphin abundance (λ) (B) Parameter estimates (SE) of the final model set (Δ AICc < 2) for models estimating Gangetic dolphin abundance.

(A) Best models for Gangetic dolphin abundance (λ)								
Model	nPars	-2*LogLike	AICc	Δ AICc	AICwt			
1	$\lambda(\text{cd} + \text{me} + \text{river}), \text{p}(\text{cw} + \text{effort})$	13	1942.35	3910.69	0	0.56		
2	$\lambda(\text{cd} + \text{me} + \text{river}), \text{p}(\text{cw} + \text{effort} + \text{time})$	14	1941.57	3911.15	0.45	0.44		
(B) Parameter estimates (SE) of the final model set								
Model	β (cd)	β (me)	β (Ganga)	β (Ghaghra)	β (Kosi)	β (cw)	β (effort)	
1	$\lambda(\text{cd} + \text{me} + \text{river}), \text{p}(\text{cw} + \text{effort})$	0.20(0.08)	1.03(0.10)	1.88(0.32)	1.11(0.33)	1.01(0.39)	-0.23(0.04)	0.11(0.03)
2	$\lambda(\text{cd} + \text{me} + \text{river}), \text{p}(\text{cw} + \text{effort} + \text{time})$	0.20(0.08)	1.04(0.10)	1.88(0.32)	1.11(0.33)	1.00(0.39)	-0.23(0.04)	0.11(0.03)

Beta coefficients (β) shown in bold indicate significant impact on site occupancy of the model as 95 % CI \neq 0 ($\beta \pm 1.96 * \text{SE}$). River which were insignificant are not included in the table. Cd = channel depth; me = meanders; river = individual river; cw = channel width.

Table 3

River wise abundance estimates of the Gangetic dolphin in the Ganga Basin (A) using *N*-mixture model (B) using Correction factor (D_{cf}).

(A) Abundance estimate using <i>N</i> -mixture					
River	Surveyed length (km)	Mean \pm SE	95 % CI-lower	95 % CI-upper	CV
Ganga	2070	2009.76 \pm 332.04	1454.95	2718.18	16.52
Yamuna	435	97.14 \pm 28.49	60.98	164.05	29.33
Chambal	405	110.86 \pm 27.2	70	172	24.54
Ghaghra	615	532.83 \pm 108.38	349.95	766.03	20.34
Gandak	295	169.02 \pm 44.84	94.98	268	26.53
Kosi	235	311.38 \pm 58.56	209	434.05	18.81
Rupnarayan	80	99.48 \pm 20.74	64	146	20.85
Ganga Basin	4135	3330 \pm 620	2304	4668	18.61
(B) Abundance using correction factor (D_{cf})					
River	Surveyed length (km)	Observed sightings	Population estimates $D_{cf} = 1.52 \pm \text{SE}$	95 % CI-lower	95 % CI-upper
Ganga	2070	1303	1981 \pm 138.49	1709.12	2252.00
Yamuna	435	53	81 \pm 5.63	69.52	91.60
Chambal	405	75	114 \pm 7.98	98.38	129.62
Ghaghra	615	335	509 \pm 35.61	439.41	578.99
Gandak	295	152	231 \pm 16.16	199.38	262.70
Kosi	235	179	272 \pm 19.03	234.79	309.37
Rupnarayan	80	54	82 \pm 5.74	70.83	93.33
Ganga Basin	4135	2151	3270 \pm 228.62	2821.43	3717.61

~5000 km of river stretch including historic and current distribution range of the GD (Supplementary Table S5). Of the total predicted distribution, 2040 km (40.8 %) of stretch was found suitable (probability distribution score \geq 0.50) for GD in the GB (Table 4). Identification and classification of priority stretches based on potential distribution map of the GD revealed that 12.2 % (610 km) of the river stretches fall under High Conservation Priority Stretch (CPS1) (>0.70), 14.3 % (715 km) under Moderate Conservation Priority Stretch (CPS2) (0.61–0.70) and 14.3 % (715 km) under Low Conservation Priority Stretch (CPS3) (0.51–0.60). The majority of the CPS1 was confined between the Ganga-

Yamuna and Ganga-Kosi confluences (Fig. 4B), while the remaining CPS1 was located in the tributaries. Among the rivers that showed suitable habitat, the Ganga River had the largest contiguous, highly suitable river segment of 200 km in the basin representing 6.5 % of total available stretch. CPS2 and CPS3 were interspersed with CPS1 of the Ganga River and its tributaries (Fig. 4C and 4D).

4. Discussion

Rivers are dynamic systems that vary with changes in flow regimes, which regulate intricate hydro-morphological processes (Zeiringer et al., 2018). Species occurring in these habitats are highly reliant on established patterns of habitat dynamics maintained by the natural hydrological regime and their biology is closely linked with seasonal change in the hydrological regime (Poff et al., 1997; Thorp et al., 2006). However, anthropogenic stressors have disrupted the natural hydrological cycle resulting in biodiversity loss and interrupted vital ecological processes in these ecosystems (Dudgeon et al., 2006; Strayer and Dudgeon, 2010; Alizadeh et al., 2018). These underlying effects make maintaining critical ecological processes in these threatened ecosystems challenging. Studies have highlighted the importance of dedicated geographical areas identified through comprehensive scientific methods in maintaining biodiversity and ecological functioning (Belote and Wilson, 2020). In the present study the GD sighting was used to derive their distribution patterns, abundance, *vis-à-vis* influence of hydrological, anthropogenic and climatic factors and prioritise conservation for long-term survival of the aquatic species and functioning of riverine ecological process.

The distribution pattern of GD in the Basin revealed a decline in its range since 1878. The observed sightings of GD showed clustered distribution and relatively high sightings in lower stretches of the rivers where mean depth, confluences, river constrictions and meanders were significantly high (Sinha & Kannan, 2014; Choudhury et al., 2019). The low sightings of GD in the upper stretches of the river was attributed to small cross-sectional area with high degree of channel bifurcation and comparatively low flow with shallow depth. The encounter rate also varied across the study area with several stretches showing an increase while others showed a decline. The difference in hydrological regimes of surveyed rivers due to their nature of origin and course through different biogeographic zones and terrain types would have resulted in variation in GD occurrence across the basin.

The reduction in distribution range, specifically in the upstream of the river, is likely due to the structural barriers, which alters the hydrological regime and disrupts lateral connectivity. Additionally, water development projects such as dams, barrages and embankments are likely to interrupt dolphin movement and result into fragmented populations. The impact of anthropogenic activities such as fishing, in-stream mining and heavy vessel movement also led to disruption of

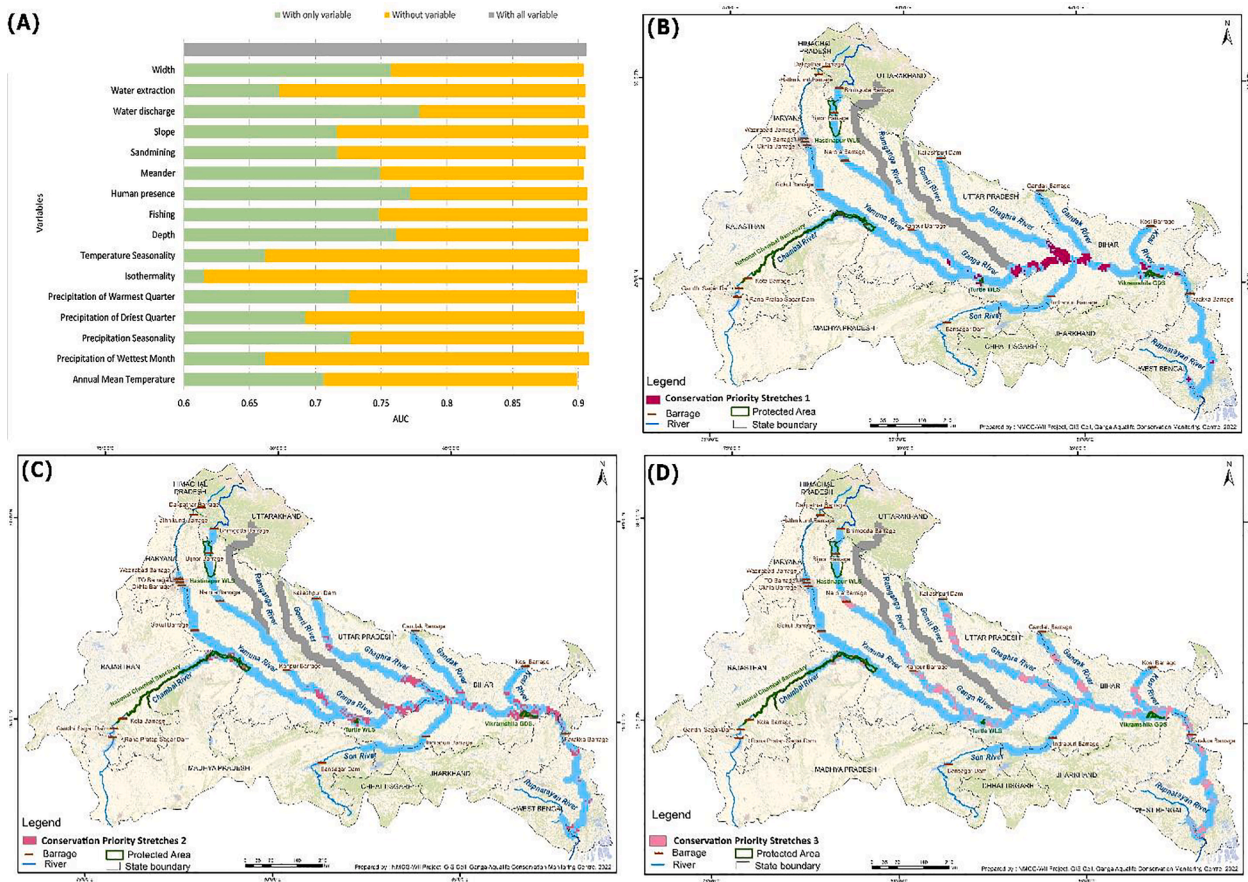


Fig. 4. Identification of Conservation priority river stretches in the Ganga Basin, (A) Jackknife test using AUC on test data, (B) Conservation Priority Stretches 1, (C) Conservation Priority Stretches 2, (D) Conservation Priority Stretches 3.

Table 4

Length of identified priority river stretches in Ganga Basin for conservation. The values in parentheses are the percentage (%) of priority river stretches for each category.

River	Total length (km)	Surveyed length (km)	High Priority Stretches (CPS1) (km)	Moderate Priority Stretches (CPS2) (km)	Low Priority Stretches (CPS3) (km)
Ganga	2525	2070	325 (6.5)	435 (8.7)	310 (6.2)
Yamuna	1435	435	20 (0.4)	50 (1.0)	45 (0.9)
Chambal	960	405	85 (1.7)	60 (1.2)	50 (1.0)
Ghaghra	1123	615	85 (1.7)	55 (1.1)	150 (3.0)
Son	784	500	5 (0.1)	5 (0.1)	20 (0.4)
Gandak	775	295	5 (0.1)	35 (0.7)	75 (1.5)
Kosi	729	235	70 (1.4)	45 (0.9)	45 (0.9)
Rupnarayan	280	80	15 (0.3)	30 (0.6)	20 (0.4)
Total	8346	4635	610 (12.2)	715 (14.3)	715 (14.3)

connectivity between tributaries and the mainstem river (Aggarwal et al., 2020; Paudel and Koprowski, 2020; Samad et al., 2022). The lower stretches of the river, due to the hydrological complexities particularly availability of higher mean depth, confluences, meanders, unbraided channel and possibly low impacts of dams and barrages are suitable for GD presence (Sinha and Sharma, 2003b; Choudhary et al., 2006; Kelkar et al., 2010; Behera et al., 2013; Mazumder et al., 2014).

Consistent with the findings of Kelkar et al., (2010), Bashir et al., (2012), Paudel et al., (2015), the site occupancy and N-mixture models revealed a positive association of GD site occupancy and abundance with channel depth, meanders, and river type, particularly in mainstem Ganga and snow-fed tributaries such as Ghaghra, Gandak and Kosi

ivers. (Tables 1B and 2B). Findings of Kelkar et al. (2010) explained that a high occurrence of GD occurred at > 5.2 m depth, and also emphasized that a contiguous series of deep pools with high prey availability are suitable for providing ample space for dolphin movement. Owing to the physiological needs of the GD, the deep pools, meanders and confluence tend to provide ample foraging opportunities, predator avoidance and escape from entrapment in shallow pools (Kelkar et al., 2010; Bashir et al., 2010; Khanal et al., 2016; Choudhary et al., 2019; Paudel et al., 2021). The deep pools are good fish habitat, thus have high fish abundance (Smith et al., 1998; Zhou et al., 2022), which results in increased foraging ability of GD by reducing foraging time and degree of metabolic investment. The deep pools provide the highest possible usable area for GD due to presence of higher cross-sectional area, and depth (Braulik et al., 2012; Paudel et al., 2021). Low-velocity in the deep pools favour efficient diving for prey capture and predator avoidance, if necessary. Further, the significance of deep pools increases particularly during the low-water season when suitable habitat shrinks manifolds compared to the high-water season (Braulik et al., 2012; Paudel et al., 2021; Samad et al., 2022; Sharma et al., 2022) and GD tend to occupy and congregate in these deeper areas for their survival (Bashir et al., 2010; Kelkar et al., 2010).

N-mixture models have been applied to a wide range of wildlife species ranging from invertebrates to large mammals (Paudel et al., 2015; Kidwai et al., 2019; Manica et al., 2019; Searle et al., 2020; Than et al. 2020; Barão-Nóbrega et al., 2022), that explicitly allow for assessing abundance estimates and detection probability from a repeated count data of unmarked individuals (Kéry and Royle, 2015; Bötsch et al., 2020). N-mixture model is cost effective and widely used to estimate the abundance of population from count data with both spatial and temporal replications while accounting for imperfect detection

(Royle, 2004; Joseph et al., 2009). There are many alternative sampling methods exist for obtaining estimates of abundance such as capture-recapture, distance and multiple-observer sampling; however the N-mixture model is comparatively cost-effective and requires minimum effort for data collection and does not require individuals to be identified (Dennis et al., 2015). Nonetheless, N-mixture model is particularly promising for wildlife studies because it has the potential to produce estimates that are comparable to those obtained by intensive surveys such as capture-mark-recapture approaches.

Previous studies were conducted in different time scales and were subjected to disjunct pockets. The available studies utilizing similar methodology were either conducted in small segments of high GD occurring stretch (Paudel et al., 2015) or for different species, rivers or terrestrial systems with varied geomorphological characteristics (Barão-Nóbrega et al., 2022; Than et al., 2020; Searle et al., 2020). Hence direct comparison of efficacy of N-mixture model in riverine system is not feasible as the present study is the first ever comprehensive survey conducted in the major rivers of the GB which is beyond the scale of comparison to earlier studies (e.g. Paudel et al., 2015; Than et al., 2020).

The findings of N-mixture model also revealed that channel depth, meanders and river type act as a crucial factor in determining GD abundance, which is evident from the fact that lower segments of the river are laden with deep pools and have more meanders. Channel width and efforts were considered as covariates of detection as it was quite obvious from the fact that increase in channel width resulted in decreasing detection of GD as it disrupts visual efficiency of the observer. Under such conditions, efforts of the observer team to detect individuals would be considered for optimizing detection.

This is the first study from India that employed the N-mixture models in large riverscapes to assess the abundance of GD and one of the first to do so for a flagship species in freshwater systems. Presumably, we can argue that the N-mixture framework applied to heterogeneous datasets offers a flexible approach for abundance estimates when ecological conditions are conducive for optimizing detectability, and provided reliable and insightful abundance estimates of GD and its detection across the study site. Earlier, the approach had been successfully employed to obtain abundance estimates of GD in the Karnali River of Nepal (Paudel et al., 2015). We also compared the estimates of GD derived from the N-mixture models with the correction factors (D_{cf}) extracted from published literature while accounting for imperfect detection. Both the approaches resulted in similar estimates as the probability of detection (p) was 0.66 and 0.65 for correction factor and N-mixture model, respectively. The mean population estimates of the individual rivers followed similar pattern as derived using correction factors for the GD. However, the abundance estimates of GD generated using N-mixture models cannot be exclusively interpreted as absolute abundance, as individuals whose home range spans multiple sites would have been accounted for multiple times within their home range (Link et al., 2018; Nakashima, 2020). Nevertheless, it can be safely said that the derived abundance of GD using correction factors (D_{cf}) (Fig. 3B) as an indices and the population estimates derived from N-mixture model make appropriate inferences about abundance across the riverscapes.

We believe that the N-mixture model, as compared to the conventional direct count method, would yield reliable abundance estimates for the heterogeneous detection population like GD that spend most of their time underwater. The N-mixture model is regarded as most suitable framework for estimating abundance (λ) and detectability (p) of unmarked individuals, which describes count data (sightings) replicated in time and space. Our analysis demonstrates that sighting-based occupancy modelling can be employed to monitor top predator's habitat use across large riverscapes such as GB (Bashir et al., 2012; Paudel et al., 2015). Findings of occupancy surveys and its insights can therefore be supplemented to mark-recapture surveys that yield robust population estimates at finer scales. However, the present work proposes robust survey designs combining visual and acoustic framework to yield reliable population estimates of GD where the acoustic survey will aid in

underwater missing animals (Richman et al., 2014). This approach would greatly enhance the detection probability of GD; hence, reliable estimates can be used to formulate strategies for conserving viable populations along its distribution range, including GB.

In our study, the predicted probability distribution used for prioritisation of conservation stretches was supported by high AUC (0.91 ± 0.0089). We highlight the potential bioclimatic variables governing GD distribution under the current climate change scenario and modelled probable high distribution stretches for prioritisation. Several identified priority stretches fall within the delineated boundaries of the Protected Areas (PAs) such as the Turtle Sanctuary, the Vikramshila Gangetic Dolphin Sanctuary and the National Chambal Sanctuary. The highest priority for conservation should focus on the stretches that are currently outside the PA network and are suitable for dolphins. These stretches were mostly confined in around the confluence of tributaries with the mainstem Ganga River. In the wake of growing demand for river resources and increasing threats to the freshwater ecosystem, it is crucial to protect these CPS to prevent habitat degradation and species loss. Societal reliance on the services provided by vast expanses of river stretches complicate management interventions, particularly those aimed at offsetting human footprints on riverine ecosystem (Pracheil et al., 2013). The identified river stretches with high biodiversity value in the Basin give an opportunity for targeted conservation actions and provide options to conserve the optimal stretches of the river for the continued flow of ecosystem services. This may serve as a blueprint for biodiversity conservation while preserving the societal benefits without de-linking the natural resources and human ecological requirements (Wang et al., 2015).

5. Conclusions

The GB is one of the largest and most densely populated regions of the world that supports more than 25,000 floral and faunal species and serves as a lifeline for over 650 million people (Dwivedi et al., 2018; Hussain et al., 2020). Over the past decades, population growth, agricultural and industrial expansion have led to the over-exploitation of riverine resources leading to its fragmentation. The inadequate water management policies to address the extensive use of water for irrigation, industry, and public supply have emerged as obstinate challenges for river conservation. Furthermore, the future climate change scenarios encompassing melting headwater glaciers, and changes in rainfall patterns have triggered extreme events and altered drought and flooding cycles that threaten the natural flow regime of the rivers. These adversely affect the species diversity of the basin, which are either currently endangered or are likely to become endangered in the foreseeable future. The riverine impoundments and reservoir-induced habitat fragmentation restrict connectivity in the aquatic system and impede natural migration of the aquatic fauna resulting in spatially and genetically fragmented populations. Conservation prioritisation of river stretches has been advocated to counter the impact of negative factors, and enable the riverine ecological process and functioning.

The first ever comprehensive surveys conducted in all major rivers in the GB covering a length of 4635 km revealed that the basin holds ~65 % of the total population of the GD. We also identified a 610 km river stretch, accounting for 12.2 % of the GB as a high conservation priority stretch (CPS1) for the conservation of the GD and other riverine associated species. The sub-optimal stretches between the CPSs need to be restored to enhance the connectivity and improve ecological functioning within the basin. Conservation of these stretches will provide a safety net against the cascading ecological and socio-economic impacts of climate change.

The assessment of large river habitats and estimation of the abundance of cryptic species within a vast stretch of linear system is a challenge for field ecologists. To overcome this limitation and challenge, a survey protocol for field observation and data recording was developed after thorough review of published literature and pilot survey. This

protocol was then followed by the multiple survey teams, deployed across the GB. In future, the population estimation of Gangetic dolphin in the GB can be further validated using the capture-mark-recapture framework, which can elucidate the loss of information due to under or over-estimates occurring due to false-negative or false-positive counts of the species, respectively (Barker et al., 2018). Further, spatio-temporal variation in the GD sightings can be estimated using a dynamic version of the N-mixture modelling approach using multi-season data, and multi-species-based ensemble modelling can be applied for delineating CPS in a river system.

CRedit authorship contribution statement

Goura Chandra Das: Data curation, Formal analysis, Software, Writing – original draft. **Surya Prasad Sharma:** Data curation, Formal analysis, Writing – original draft. **Sk Zeeshan Ali:** Data curation, Formal analysis, Visualization. **Saurav Gawan:** Data curation. **Aftab Alam Usmani:** Data curation. **Arkojyoti Sarkar:** Data curation. **Suyash Katdare:** Data curation. **Ajay Rawat:** Data curation. **Pichaimuthu Gangaimaran:** Data curation. **Ashish Kumar Panda:** Data curation. **Umang Agnihotri:** Data curation. **Aishwarya Ramachandran:** Visualization. **Srijani Guha:** Visualization. **Shivani Barthwal:** Supervision, Writing – review & editing. **Jeyaraj Antony Johnson:** Supervision, Writing – review & editing. **Ruchi Badola:** Conceptualization, Funding acquisition, Project administration, Supervision, Methodology, Writing – review & editing. **Syed Ainul Hussain:** Conceptualization, Funding acquisition, Project administration, Supervision, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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Evaluating performance of four species distribution models using Blue-tailed Green Darner *Anax guttatus* (Insecta: Odonata) as model organism from the Gangetic riparian zone

Kritish De¹ , S. Zeeshan Ali² , Niladri Dasgupta³ , Virendra Prasad Uniyal⁴ ,
Jeyaraj Antony Johnson⁵ & Syed Ainul Hussain⁶

¹⁻⁶ Wildlife Institute of India, Chandrabani, Dehradun, Uttarakhand 248001, India.

¹kritish.de@gmail.com (corresponding author), ²zeeshanearth@gmail.com, ³niladri4all@gmail.com, ⁴uniyalvp@wii.gov.in, ⁵jaj@wii.gov.in, ⁶hussain@wii.gov.in

Abstract: In this paper we evaluated the performance of four species distribution models: generalized linear (GLM), maximum entropy (MAXENT), random forest (RF) and support vector machines (SVM) model, using the distribution of the dragonfly Blue-tailed Green Darner *Anax guttatus* in the Gangetic riparian zone between Bijnor and Kanpur barrage, Uttar Pradesh, India. We used forest cover type, land use, land cover and five bioclimatic variable layers: annual mean temperature, isothermality, temperature seasonality, mean temperature of driest quarter, and precipitation seasonality to build the models. We found that the GLM generated the highest values for AUC, Kappa statistic, TSS, specificity and sensitivity, and the lowest values for omission error and commission error, while the MAXENT model generated the lowest variance in variable importance. We suggest that researchers should not rely on any single algorithm, instead, they should test performance of all available models for their species and area of interest, and choose the best one to build a species distribution model.

Keywords: Generalized linear model, Kappa statistic, maximum entropy model, omission and commission error, random forest model, receiver operating characteristic curve, sensitivity, specificity, support vector machines model, true skill statistic

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Author details: KRITISH DE is working as project fellow at Wildlife Institute of India. His research interests are biodiversity and ecology. SK. ZEESHAN ALI is working as spatial analyst at Wildlife Institute of India. His research interests are geospatial modelling and spatial ecology. NILADRI DASGUPTA is working as project coordinator at Wildlife Institute of India. His research interests are river ecology and aquatic wildlife conservation. VIRENDRA PRASAD UNIYAL is working as Scientist G at Wildlife Institute of India. His research interests are ecology and systematics of insects, bioindicators, biodiversity surveys and ecological monitoring. JEYARAJ ANTONY JOHNSON is working as Scientist E at Wildlife Institute of India. His research interests are ecology and monitoring of aquatic ecosystem. SYED AINUL HUSSAIN worked as Scientist G at Wildlife Institute of India. His research interests are aquatic ecology and conservation biology.

Author contribution: KD—conceptualization, field work, formal analysis, writing original draft; SZA—field work, formal analysis, writing original draft; ND—editing the draft; VPU—supervision, review and editing the draft; JAJ—supervision, review and editing the draft; SAH—supervision, review and editing the draft, funding acquisition.

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INTRODUCTION

Species distribution models (SDMs) are tools that integrate information about species occurrence or abundance with environmental estimates of a landscape, used to predict distribution of a species across landscapes (Elith & Leathwick 2009). When applied in a geographic information system (GIS), SDMs can produce spatial predictions of occurrence likelihood at locations where information on species distribution was previously unavailable (Václavík & Meentemeyer 2009). Though various types of algorithms are used to build different SDMs (Elith et al. 2006), they share common and general approaches (Hirzel et al. 2002) such as: (i) at a specified resolution, the study area is divided into grid cells; (ii) species presence localities (and sometimes absence localities) data are used as the dependent variable; (iii) several environmental variables (e.g., temperature, precipitation, soil type, aspect, land cover type) are collected for each grid cell as predictor variables; and (iv) the suitability of each cell for the species distributions defined as a function of the environmental variables (Stanton et al. 2012). The species distribution prediction is central to applications in ecology, evolution and conservation science (Elith et al. 2006) across terrestrial, freshwater, and marine realms (Elith & Leathwick 2009). But it remains a question for researchers which model should be selected for particular organisms and habitats of interest, particularly when few samples are present for large under-sampled areas (Mi et al. 2017).

Riparian zones are broadly defined as terrestrial landscapes with characteristic vegetation associated with temporary or permanent aquatic ecosystems (Meragiaw et al. 2018). These areas are highly complex biophysical systems, and their ecological functions are maintained by strong spatio-temporal connectivity with adjacent riverine and upland systems (Décamps et al. 2009). It has been observed that species distribution models are used more often for terrestrial environments than for aquatic or riparian ecosystems. Globally, odonates are used as model organisms to study climate change, data simulation, environmental assessment and management, effects of urbanization, landscape planning, habitat monitoring and evaluation, and conservation of rare species (Bried & Samways 2015). To date, no work has been done on the comparative use of species distribution models in India using insects as model organisms in riparian or freshwater ecosystems. With this background, in the present work we evaluated the effectiveness of four species distribution models using odonates from the Gangetic riparian zone as

model organisms.

MATERIALS AND METHODS

Study area and field data collection

For the study, we selected *Anax guttatus* (Burmeister, 1839) commonly called Blue-tailed Green Darner (Image 1) as the model insect species. It is a dragonfly (suborder Anisoptera Selys, 1854) under the family Aeshnidae Leach, 1815 and superfamily Aeshnoidea Leach, 1815 (Dijkstra et al. 2013). The species can be identified in the field due to its large size, highly active behaviour, green colour of the thorax & first, second, & third abdominal segments, and presence of turquoise blue colour on the dorsal part of the second abdominal segment (Subramanian 2005).

We conducted the study during May 2019 from Bijnor, Uttar Pradesh to Kanpur, Uttar Pradesh (Fig. 1). The river flows through alluvial plain and covers a length of about 450km in this stretch. For the study we selected four sites, and the distance between each two successive sites was about 150km. In each site we chose a 10km river stretch and observed the presence of Blue-tailed Green Darner. We collected a total of 10 sighting locations.

Data processing and analysis

We derived the thematic layer of LULC (N.R.S.C. 2016) from multi-temporal advanced wide field sensor (AWiFS) images with 56m spatial resolution using digital and rule-based image classification methods, and forest



Image 1. *Anax guttatus* (Burmeister, 1839) – Blue-tailed Green Darner

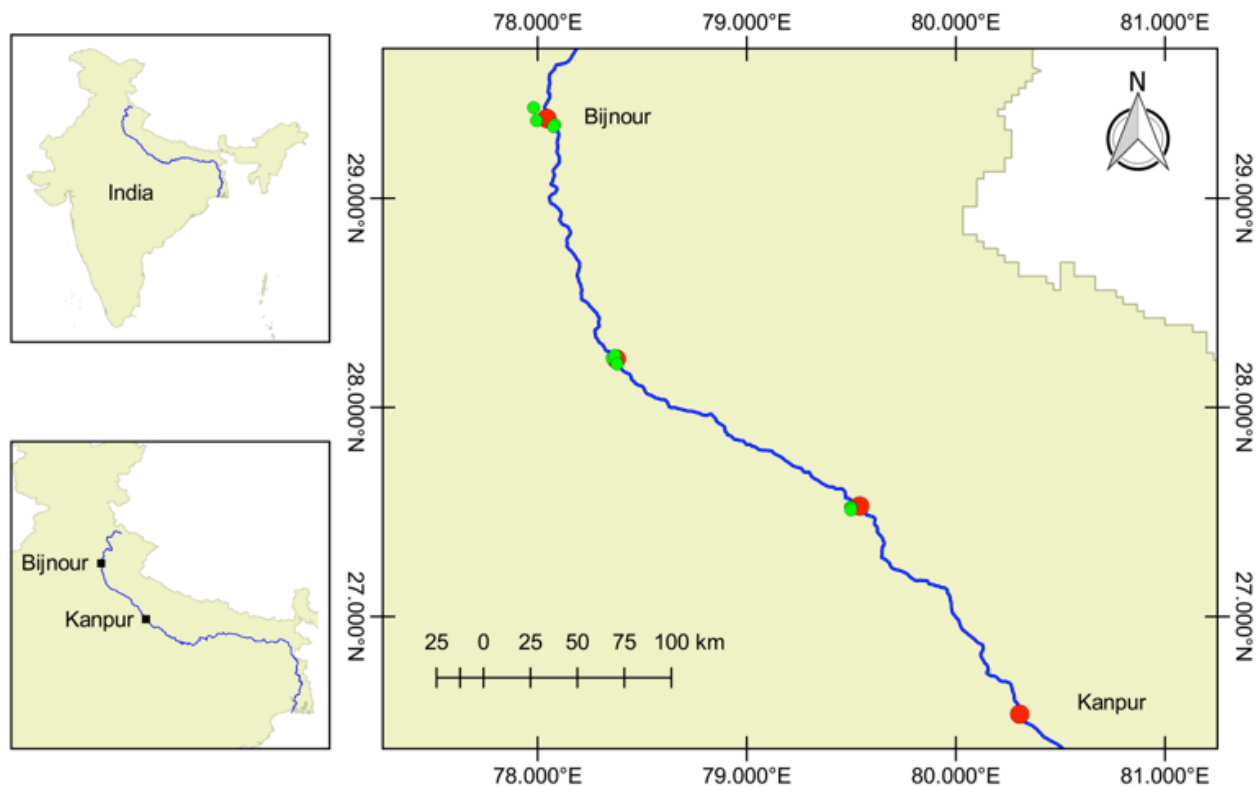


Figure 1. Study area on the river Ganga between Bijour and Kanpur. The red circles represent sampling sites, and green circles represent species sighting locations.

cover type (F.S.I. 2009) from IRS P6 (Linear Imaging Self Scanning Sensor) LISS III with 23.5m spatial resolution using a combined method of digital and on-screen visual image classification and bioclimatic layers from worldclim gridded climatic data (Fick & Hijmans 2017) with 1km spatial resolution. For analysis, we took 2km buffer zones from the river bank and resampled all the layers to 1km spatial resolution.

We used 'stack' function of package 'raster' (Hijmans 2019) to stack all the 19 available bioclimatic variable, forest cover and land use land cover (LULC) layers. After that we used 'pairs' function of the package 'raster' (Hijmans 2019) to find the correlation coefficient between stacked layers. Then we selected the variables which had a correlation coefficient less than 0.60 (Pozzobom et al. 2020), and again stacked the selected layers with 'stack' function of package 'raster' (Hijmans 2019). These selected layers were LULC, forest cover and five bioclimatic layers: annual mean temperature (Bio 1), isothermality (Bio 3), temperature seasonality (Bio 4), mean temperature of driest quarter (Bio 9), and precipitation seasonality (Bio 15).

We built four species distribution models: generalized linear model (GLM), maximum entropy (MAXENT)

model, random forest (RF) model, and support vector machines (SVM).

GLM is an extension of classic linear regression modeling, where the iterative weighted linear regression technique is used to estimate maximum-likelihood of the parameters, with observations distributed in terms of an exponential family and systematic effects made linear by the suitable transformation that allow for analysis of non-linear effects among variables and non-normal distributions of the independent variables (McCullagh & Nelder 1989; Chefaoui & Lobo 2008; Shabani et al. 2016).

RF modeling is a machine learning technique which is a bootstrap-based classification and regression trees method (Cutler et al. 2007). It is used to model species distributions from both the abundance and the presence-absence data (Howard et al. 2014). It is insensitive to data distribution (Hill et al. 2017) and also takes a large number of potentially collinear variables; it is robust to over-fitting which makes it very useful for prediction (Prasad et al. 2006; Segal 2004).

MAXENT modeling is a general-purpose machine learning method to estimate a target probability distribution by finding the probability distribution of

maximum entropy and it has several aspects that make it well-suited for species distribution modelling (Phillips et al. 2006). It is relatively less sensitive to the spatial errors associated with location data and needs few locations to build useful models (Baldwin 2009) and it is one of the most accurate and trusted modelling methods for presence-only distribution data (Huerta & Peterson 2008; Srinivasulu & Srinivasulu 2016).

SVM modeling is developed from the theory of statistical learning, in which the error involved with sample size is minimized and the upper limit of the error involved in model generalization is narrowed, which solve the problems of nonlinearity, over-learning and the curse of dimensionality during modelling (Fielding & Bell 1997; Howley & Madden 2005; Huang & Wang 2006). It can be used on small data sets as it is independent of any distributional assumptions or asymptotic arguments (Wilson 2008).

We used 'load_var' function to normalize and load environmental variables, then used 'load_occ' function to load species occurrence data and then used 'modelling' function to build the models with 100 iterations by the package 'SSDM' (Schmitt et al. 2017) to plot the models.

We evaluated and compared four models by comparing values of area under the receiver operating characteristic curve (AUC), Kohen's Kappa, true skill statistic (TSS), model sensitivity, model specificity, and omission error.

The area under the receiver operating characteristic curve or AUC measures the ability of a model to discriminate between the sites where a species is present and the sites where a species is absent (Fielding & Bell 1997; Elith et al. 2006) and it provides a single measure of overall accuracy that is independent of a particular threshold (Fielding & Bell 1997). The evaluation criteria for the AUC statistic are as follows: excellent (0.90–1.00), very good (0.8–0.9), good (0.7–0.8), fair (0.6–0.7), and poor (0.5–0.6) (Swets 1988; Duan et al. 2014).

The Kappa statistic is based on the optimal threshold, measure the performance of the model by using the best of the information in the mixed matrix (Duan et al. 2014) ranges from -1 to +1, where +1 indicates perfect agreement and values of zero or less than zero indicate a performance no better than random (Allouche et al. 2006; Cohen 1960) and the evaluation criteria for the Kappa statistic are as follows: excellent (0.85–1.0), very good (0.7–0.85), good (0.55–0.7), fair (0.4–0.55), and fail (<0.4) (Duan et al. 2014; Monserud & Leemans 1992).

The true skill statistic (TSS) is expressed as Sensitivity + Specificity - 1 (Allouche et al. 2006) and ranges from -1

to +1, where +1 indicates a perfectly performing model with no error, 0 indicates the model with totally random error and -1 indicates the model with total error (Marcot 2012; Ruete & Leynaud 2015).

The model sensitivity denotes the proportion of correctly predicted presences, thus quantifying omission errors (Ward 2007; Shabani et al. 2016) and model specificity denotes the proportion of correctly predicted presences, thus quantifying commission errors (Shabani et al. 2016).

Omission error (1- sensitivity) is the under-prediction or false-negative result in areas being classified as unsuitable when they are not and commission error (1-specificity) is the over-prediction or false-positive result in areas being classified as suitable when they are not (Ward 2007) and for a good SDM, both of the omission error and commission error should be low.

For evaluation of model performance and variable importance we used 'knitr::kable(Modelname@evaluation)' function and 'knitr::kable(Modelname@variable.importance)' function of the package 'SSDM' (Schmitt et al. 2017), respectively.

We chose five probability classes (0 to <0.20, 0.20 to <0.40, 0.40 to <0.60, 0.60 to <0.80 and 0.80 to 1.00) to know what percentage of the area is being declared the best and worst by each of the models by 'ratify' function of package 'raster' (Hijmans 2019)

We performed all the analysis in the ArcMap 10.3.1, QGIS 2.14.7 and in R language and environment for statistical computing (R Core Team 2019).

RESULT

The plot for each of the four models is given in Fig. 2. We found that the AUC value was highest for GLM (0.983), followed by RF (0.833), MAXENT (0.829) and SVM (0.667); the value of Kappa statistic was highest for RF (0.667), followed by GLM (0.356), SVM (0.333) and MAXENT (0.049); the value of TSS was highest for GLM (0.965), followed by RF (0.666), MAXENT (0.658) and SVM (0.334); the value of model sensitivity was 1 for GLM, 0.833 for both MAXENT and RF and 0.667 for SVM; the value of model specificity was maximum for GLM (0.965), followed by RF (0.833), MAXENT (0.825) and SVM (0.667); the omission error was lowest for GLM (0.00), for both MAXENT and RF models it was 0.167 and for SVM it was 0.333; the commission error was lowest for GLM (0.035), followed by RF model (0.167), MAXENT (0.175) and SVM (0.333) (Table 1, Fig. 3)

For GLM, RF, and SVM models the forest had

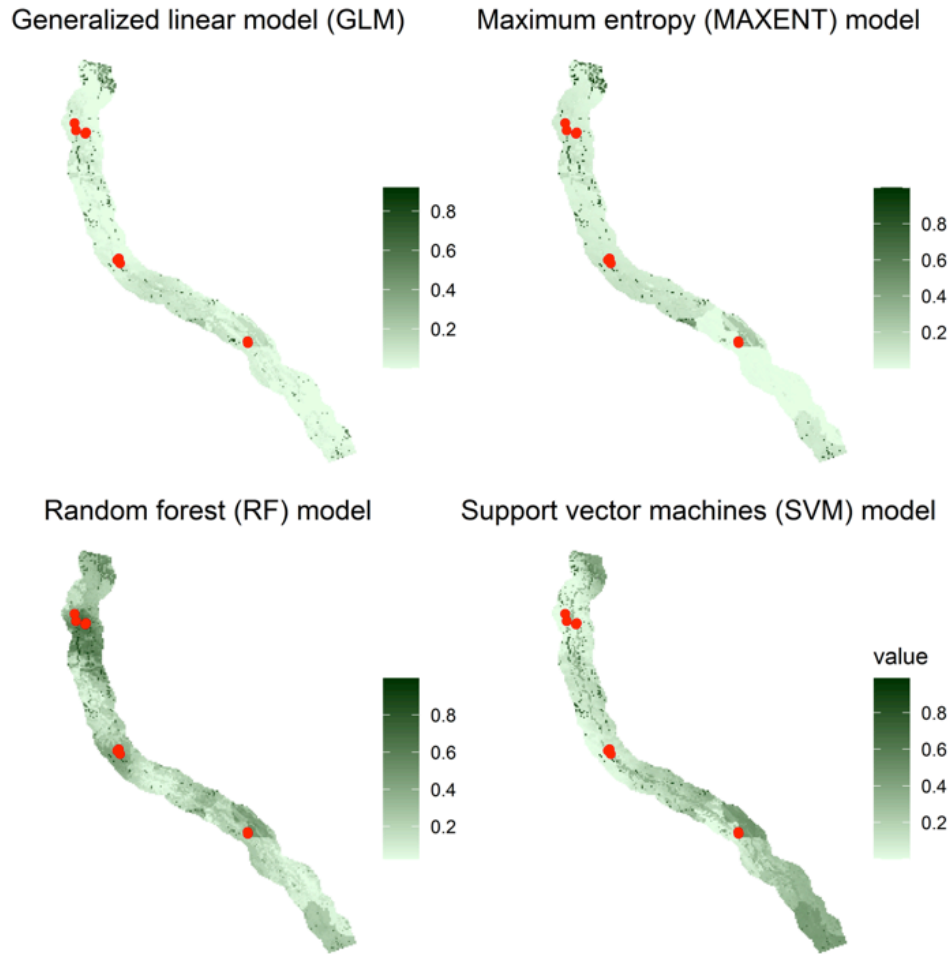


Figure 2. Comparative account of four species distribution models – generalized linear model (GLM), maximum entropy (MAXENT), random forest (RF), and support vector machines (SVM). The legend in each model shows probability of occurrence and the red dots represents the occurrence location of the species.

the highest importance but for MAXENT model the Precipitation seasonality (Bio 15) had the highest importance (Table 2, Fig. 4). For GLM and SVM models the Precipitation seasonality (Bio 15) had lowest importance, for MAXENT forest had lowest importance, while for RF model Isothermality (Bio 3) had lowest importance (Table 2, Fig. 4). Overall, the variation in the variable importance was lowest in MAXENT model (SD = 3.367), followed by GLM (SD = 24.344), RF (SD = 30.868) and SVM (SD = 37.071) (Fig. 5).

By comparative analysis, we found that GLM showed 1.62% of total area as the best (occurrence probability, 0.80 to 1) and 65.50% of total area as the worst (occurrence probability, 0 to 0.20) for suitable habitat. MAXENT model showed 10.08% of total area as the best and 77.70% of total area as the worst for suitable habitat. RF model showed 5.39% of total area as the best and 23.79% of total area as the worst for suitable habitat. SVM model showed 4.53% of total area as the

Table 1. Values of AUC, Kappa statistic, TSS, sensitivity, specificity, omission error, and commission error generated by generalized linear model (GLM), maximum entropy (MAXENT) model, random forest (RF) model, and support vector machines (SVM) model.

	GLM	MAXENT	RF	SVM
AUC	0.983	0.829	0.833	0.667
Kappa statistic	0.356	0.049	0.667	0.333
True skill statistic	0.965	0.658	0.666	0.334
Sensitivity	1	0.833	0.833	0.667
Specificity	0.965	0.825	0.833	0.667
Omission error	0	0.167	0.167	0.333
Commission error	0.035	0.175	0.167	0.333

best and 27.68% of total area as the worst for suitable habitat (Table 3, Fig. 6).

Table 2. Comparative importance (%) of seven variables from generalized linear model (GLM), maximum entropy (MAXENT) model, random forest (RF) model, and support vector machines (SVM) model.

	GLM	MAXENT	RF	SVM
Annual mean temperature (Bio 1)	11.831	16.352	2.254	0.198
Isothermality (Bio 3)	8.062	14.789	0.513	0.337
Temperature seasonality) (Bio 4)	5.709	15.405	4.076	0.239
Mean temperature of driest quarter (Bio 9)	3.241	13.638	0.907	0.069
Precipitation seasonality (Bio 15)	1.103	16.417	2.817	0.019
Forest	68.799	7.014	84.186	98.353
Land use land cover	1.252	16.384	5.247	0.785

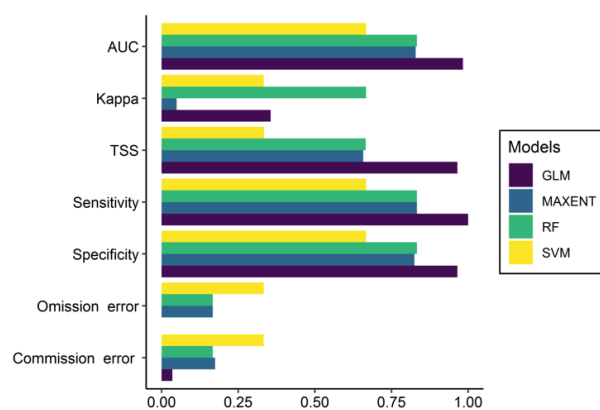


Figure 3. Bar diagram showing comparative account of values of AUC, Kappa statistic, TSS, sensitivity, specificity, omission error and commission error for four models – generalized linear model (GLM), maximum entropy (MAXENT) model, random forest (RF) model, and support vector machines (SVM) model.

DISCUSSION

Freshwater ecosystems, which include rivers, lakes, peat lands, swamps, fens, and springs, are highly dynamic and host a great diversity of life forms, particularly freshwater endemic species (He et al. 2019; Tickner et al. 2020). They are among the most threatened ecosystems (He et al. 2019), as globally wetlands are vanishing more rapidly than forests and freshwater species are declining faster than terrestrial or marine populations (Tickner et al. 2020). Therefore, for proper conservation management, we should understand the distribution of plants and animals inhabiting aquatic ecosystems. Species distribution models can play an important role on such efforts, because they can produce credible, defensible and repeatable information and provide tools for mapping habitats to inform decisions (Sofaer et al. 2019). Species distribution models can forecast the potential impacts of future environmental changes (Howard et al. 2014) and predict how species

Table 3. Comparison of percentage of total area obtained from each model for five occurrence probability classes,

Occurrence probability class	Models			
	GLM	MAXENT	RF	SVM
0 to <0.20	65.50	77.70	23.79	27.68
0.20 to <0.40	7.94	3.93	35.61	42.55
0.40 to <0.60	19.58	4.04	17.97	18.04
0.60 to <0.80	5.35	4.24	17.24	7.19
0.80 to 1.00	1.62	10.08	5.39	4.53

will respond (Buckley et al. 2010). Yet debate remains over the most robust species distribution modelling approaches for making projections (Howard et al. 2014), because these models have sensitivity to data inputs and methodological choices. This makes it important to assess the reliability and utility of the model predictions (Sofaer et al. 2019).

In the present study we compared the GLM, MAXENT, RF, and SVM approaches. We found that GLM generated the highest values for AUC, TSS, specificity and sensitivity, and the lowest values for omission error and commission error. The value of Kappa statistic was highest for RF modelling. The MAXENT model used roughly all variables equally, which is not true of the other models which put more emphasis on forest cover.

The success of a model depends on many factors, such as sample size, spatial extent of the study area, and number of ecological and statistical significant variables which affect the distribution of species of interest. We acknowledge that there were some limitations to the current work, such as that our sample size was small (only 10 presence locations), we used only seven variables, we tested only four species distribution models, and we selected a species whose distribution depends on other factors, such as the physiochemical parameters of water and availability of resources. We did not include such

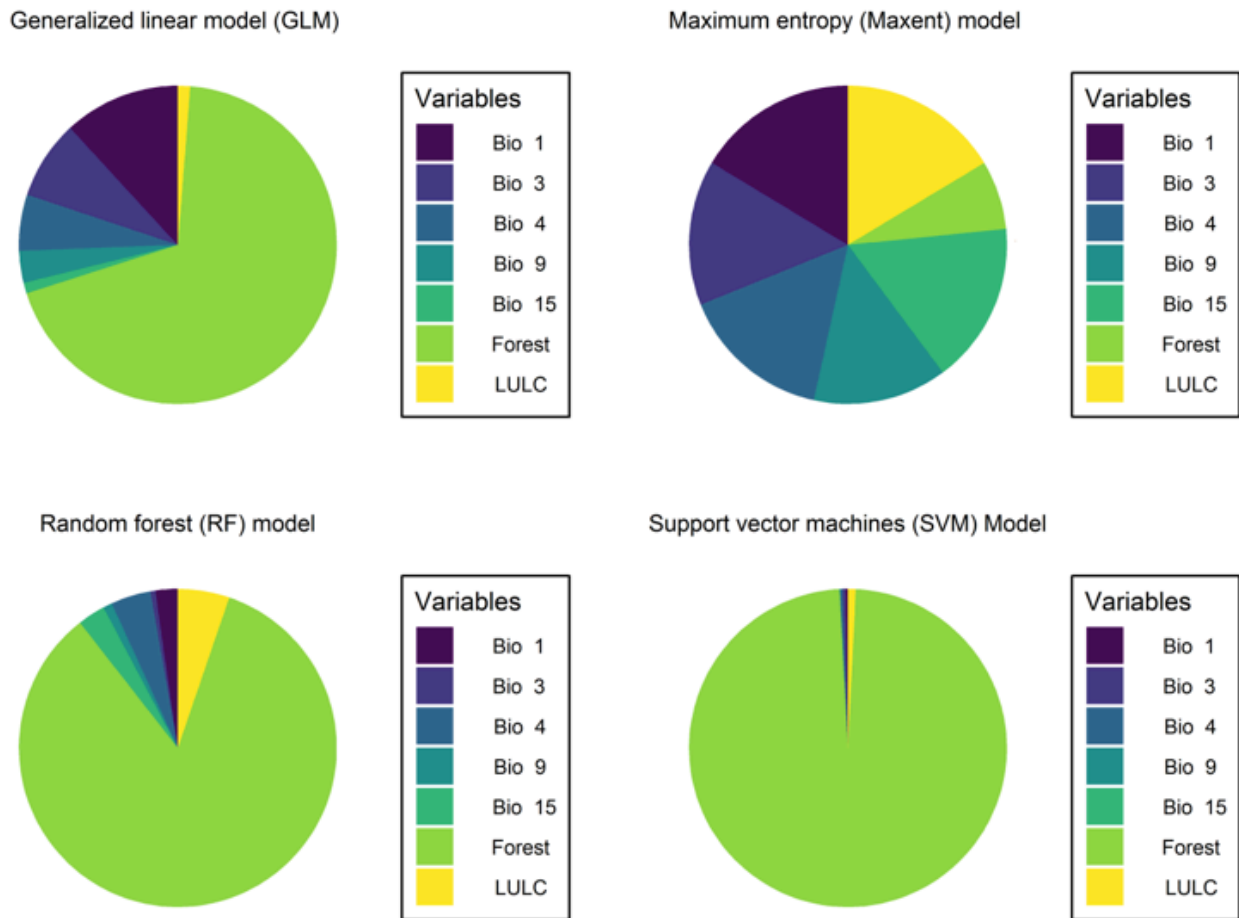


Figure 4. Pie diagram showing percentage importance for seven variables for four models – generalized linear model (GLM), maximum entropy (MAXENT) model, random forest (RF) model, and support vector machines (SVM) model.

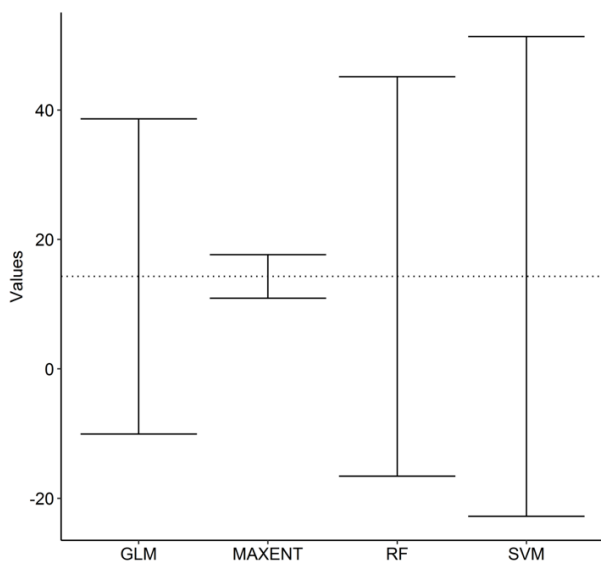
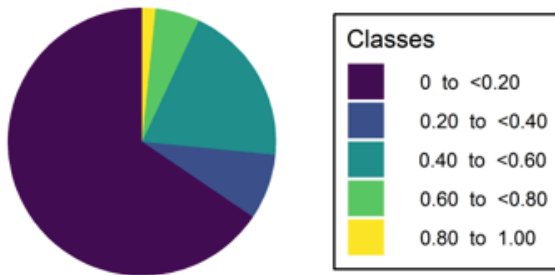


Figure 5. Comparison of standard deviation of variable importance for generalized linear model (GLM), maximum entropy (MAXENT) model, random forest (RF) model, and support vector machines (SVM) model. The black dotted line represents the mean value.

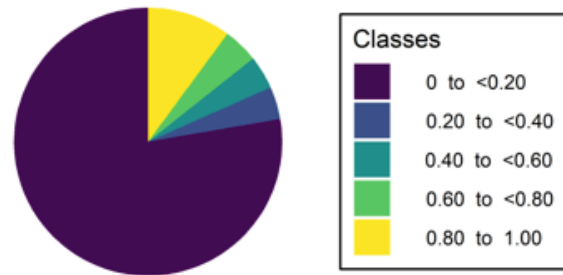
variables as this study was preliminary.

Collins & McIntyre (2015) reviewed 30 studies on species distribution modelling of odonates across the world, and found that 43% used GLM, 33% MAXENT and 20% RF models. Other models used were BIOMOD, general additive model (GAM), generalized boosted model (GBM), artificial neural networks (ANN), multivariate adaptive regression splines (MARS), classified tree analysis (CTA), flexible discriminant analysis (FDA), boosted regression trees (BRT), surface range envelopes (SRE), and mixture discriminant analysis (MDA). Different species distribution models produce different results (Shabani et al. 2016), and the same model can give different results for different species and areas. We urge researchers not to rely on just one model, rather they should compare different available species distribution models and select the best one. Our study was in India where an insect was used for comparative evaluation of species distribution models in a riverine riparian zone. We recommend that further

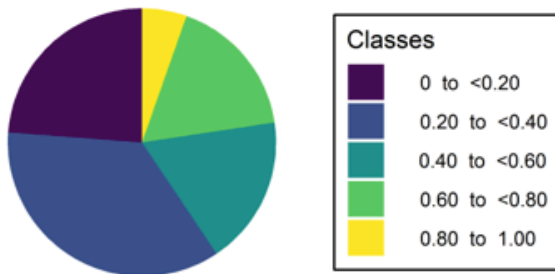
Generalized linear model (GLM)



Maximum entropy (Maxent) model



Random forest (RF) model



Support vector machines (SVM) Model

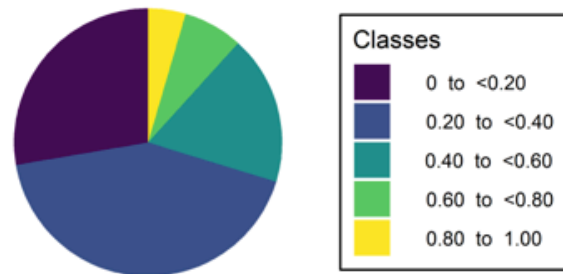


Figure 6. Pie diagram showing percentage area for five occurrence probability classes for four models – generalized linear model (GLM), maximum entropy (MAXENT) model, random forest (RF) model, and support vector machines (SVM) model.

studies on different species distribution models using different animals and ecological variables should be carried out in the riparian zones of Indian river systems for proper design and implementation of ecological habitat management plans.

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Assessment of Riverine Habitat Vulnerability to Climate Change in the Middle Ganga River

in NEC-2024 Organized by

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From February 15th to 17th, 2024

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This is to certify that Mr./Dr./Ms./Mrs, **SK ZEESHAN ALI, PRINCIPAL PROJECT ASSOCIATE, WILDLIFE INSTITUTE OF INDIA** has participated in International Conference on “*Emerging Issues of Biodiversity and Environment for Sustainable Development*” organized by the Department of Zoology and Environmental Science, VGC Mandi on 14th & 15th February 2024.

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Coordinator ICCON 2023
Scientist - F,
Wildlife Institute of India

Virendra Tiwari

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