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

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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.

Article Highlights

- The study emphasises importance of fluvial stress factors and their effectiveness towards river conservation planning and management.
- Framework for maintenance of minimum water in river to sustain E-flow is highlighted in this study.
- The study highlights the potential riverine habitats for biodiversity conservation in the middle Ganga River.

Keywords River · Fluvial · Stress factor · E-flow · Biodiversity · Habitat

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1 Introduction

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 ecohydrology and geomorphology. The spatial distribution of geomorphological characteristics of river system governs the structure and composition of aquatic biodiversity [1]. The stress factors are forces exerted by flowing water on the river bed and bank as well. These forces play important role in 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 modifies stream habitats [2, 3].

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 hydromorphology and leads towards habitat loss for aquatic biodiversity [4]. The equilibrium between flow, infiltration, and anthropogenic pressure on rivers needs to be maintained for hydrologic cycle. However, due to environmental factors, freshwater scarcity, soil structure and parent material, assessing potential habitat is a significant concern globally [5, 6]. The anthropogenic factors due to human disturbances and dependencies on rivers 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 [7]. Urbanisation along rivers and embankments also increases surface runoff which results in reduced base flows, 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 and seasonal flow. The warming of glaciers has led to changes in river discharge patterns at headwaters in the Himalaya [8]. The riparian areas experience more extreme weather events, including heavy rainfall followed by long droughts because of rising temperatures and decreased precipitation [9].

The alteration of fluvial dynamics disrupts the ecosystem of conservation concerned species [10]. 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 [11]. The reducing flow regime increases sediment loads at the river bed which alters the shape of 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 [12]. 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 finally 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 [13]. 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 [14–16]. 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 [17]. 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 [18] and carries a sediment load of 356 million tonnes per year [19]. The middle Ganga River has very high human dependency in terms of agriculture, human habitations which lead to construction of four barrages in this segment of the Ganga River. The barrages restrict natural flow and free movement of aquatic biodiversity in the Ganga River. 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 [20]. The anthropogenic pressure in sediment water interaction changes the ecosystem functioning of the Ganga River [21]. E-flow is essential to for preserving biodiversity in the Ganga River [22].

The study was carried out using Geographic Information System (GIS) and Analytical Hierarchical Process (AHP) techniques [23] to assess the fluvial stressor, riverine habitat areas in the Ganga River. 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. Various studies were conducted previously using GIS, MCDM and AHP method. The river zones were assessed river zones for water quality management by considering pollution levels, land use, and water flow characteristics using AHP method [24]. In another study, suitable water storage sites were identified based on GIS, and MCDM using AHP method [25]. AHP and Remote Sensing and GIS were used for identifying groundwater zones with varying hydrological characteristics of river systems by considering rainfall, water flow, geological features, and land use as factors [26]. The riparian zones were delineated in data scarce regions and indicated connectivity within riverscape [27]. The Ganga River has been studied to understand impact of stressors in fluvial dynamics, geomorphic diversity and potential habitat of aquatic biodiversity [18, 28]. This study is significant to monitor the impact of fluvial stress factors on river ecohydrology 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.

2 Materials and methods

2.1 Study area

The study was carried out in the stretch of middle Ganga River (MGR), which is a part of Gangetic Plain (7) biogeographic zone and Upper Gangetic Plain (7A) biotic province [29]. The region starts from the downstream of Bhimgoda barrage, at Haridwar, Uttarakhand to the confluence of Gomti River in the Ganga River, at Kaithi, Varanasi, Uttar Pradesh (Fig. 1). This stretch of Ganga River extends from 25° 20′ N to 28° 10′ N and 78° 10′ E to 83° 04′ E. Protected forest areas i.e. Hastinapur Wildlife Sanctuary, Turtle (Kachhua) Wildlife Sanctuary, Dr Bhimrao Ambedkar Bird Sanctuary are located in this segment of the Ganga River. The stretch of MGR is fragmented by four dams and barrages namely, Bhimgoda barrage at Haridwar, Madhya Ganga barrage at Bijnor, Charan Singh Ganga barrage at Narora and Luv Kush barrage at Kanpur. Ramganga, Loni, Duar, Gomti rivers are the major north bank tributaries and Yamuna, Tamas rivers are the major south bank tributaries of the Ganga River in the region. The entire MGR is highly suitable for intensive agriculture practices. Human population growth along the Ganga River has resulted in agricultural development, urbanization and industrialization.

2.2 Data source and methodology

The study was carried out using the GIS and AHP to undergo MCDM analysis [26, 30]. The GIS technique was used for delineating the boundary of the river 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 (Fig. 2).

The Survey of India topographical sheets (Table 1) were used for study area delineation, Land Use Land Cover (LULC) was derived from the Landsat 8 OLI satellite image (Table 2), 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) and Socioeconomic Data and Applications Center (SEDAC) (Table 3).

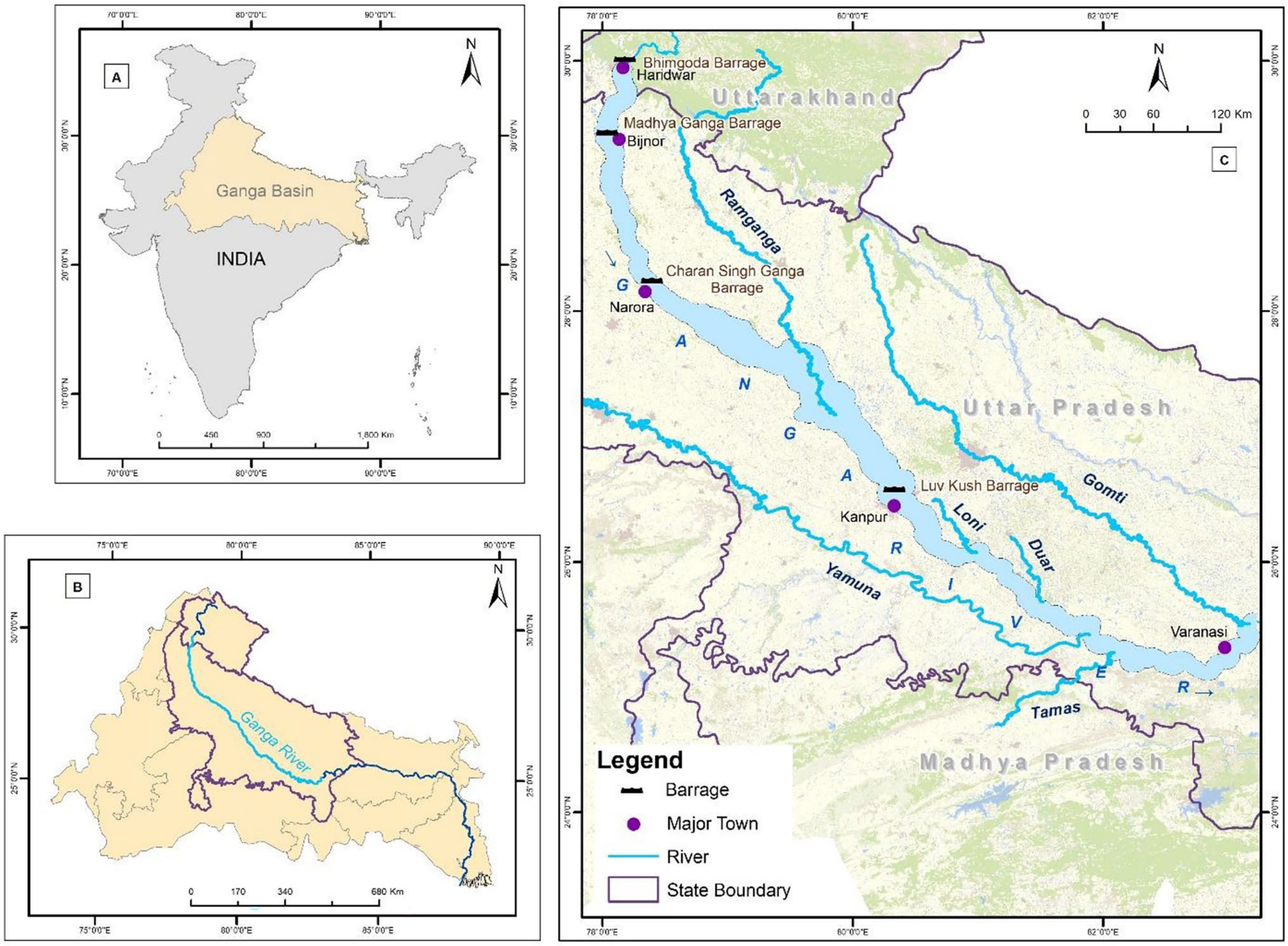

Fig. 1 Study area showing middle Ganga River

2.3 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 [31]. Spatial decision support system, and evaluation of multi criteria factors to address aquatic systems is a globally accepted approach [32]. 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 [33]. 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 [34] 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 [35]. Every factor has

Fig. 2 Methodology flow chart

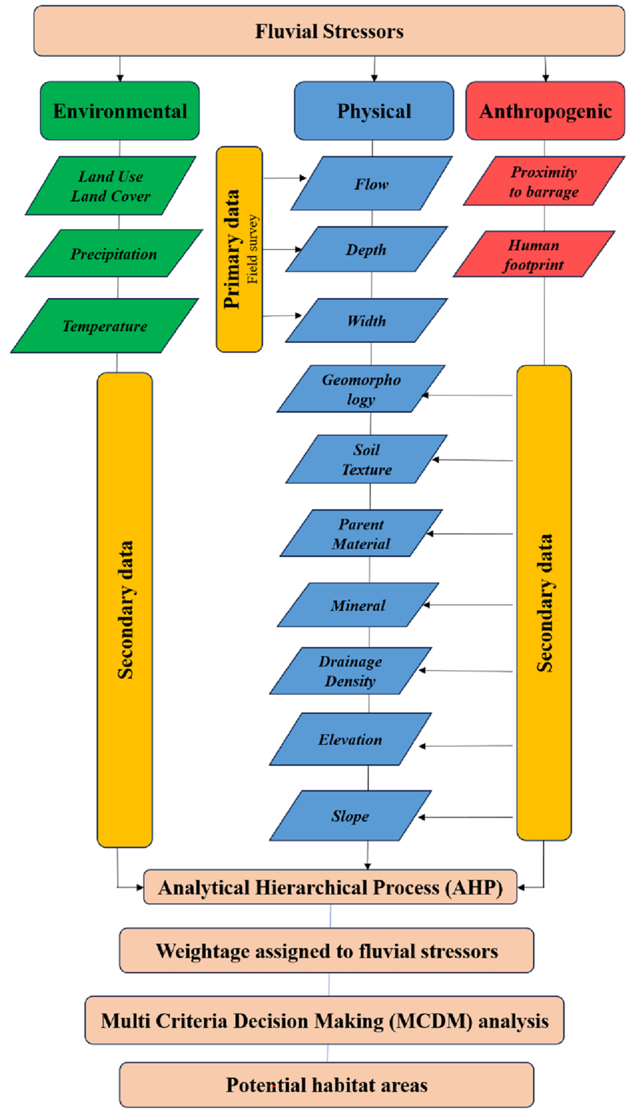

Table 1 List of topographical sheets

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	

been compared with each other in a pairwise comparison matrix (Table 4). The continuous parameters were reclassified using ArcGIS 10.6.1 software for assigning weight.

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

Table 2 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 3 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 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)

$$\lambda_{\max} = \sum\nolimits_{Geometric\ Mean} = 15.614 \tag{1}$$

$$\mathrm{CI} = \left(\lambda_{\max} - \mathrm{n}\right)/\left(\mathrm{n} - 1\right) \tag{2}$$

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

$$\mathrm{CI} = (15.614 - 15)/(15 - 1) = 0.0439$$

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

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RCI} = 0.0439/1.59 = 0.0276 \tag{3}$$

RCI values were obtained from the Saaty's standard (Table 5).

CR of 0.10 or less is acceptable to continue the analysis [32]. 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.

(Eq. 4). The assigned rank and weights to the thematic layers are listed in Table 6.

$$\text{Potential Habitat Area} = \Sigma\left(X_i \times Y_i\right) \tag{4}$$

Table 4 Pairwise comparison matrix

Parameter	Assigned Weight	Flow	Depth	Width	Precipitation	LULC	Geomorphology	Soil texture	Parent material	Mineral	Drainage density	Elevation	Slope	Barrage	Human footprint	Temperature	Geometric Mean	Normalized Weight
Flow	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
Depth	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
Width	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
Precipitation	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
LULC	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
Geomorphology	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
Soil texture	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
Parent material	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
Mineral	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
Drainage density	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
Elevation	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
Slope	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
Proximity to barrage	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
Human footprint	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
Temperature	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

Table 5 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**

The RCI values 1.59 (in bold) is used for calculating the consistency ratio

3 Results

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 [36]. Delineation and mapping of 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 [37]. In this study following 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 [34] for identification of potential habitat areas.

3.1 Flow

Flow is a critical factor for structure and function of river systems that influence the habitat availability. The natural flow regime of the river, including variations in temporal discharge impacts the physical, environmental, and biological factors that augment to maintain E-flow to sustain aquatic biodiversity in river system. Seasonal flow variations support ecological processes such as 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 [38]. Flow measurement using Acoustic Doppler Current Profiler (ADCP) is a widely accepted method for assessing discharge and water velocity in rivers [39]. The flow was measured in field using ADCP in selected locations and interpolated the result in the study area. The continuous layer was reclassified in seven thematic classes (Table 7, Appendix 1). The Ganga River from downstream of Jhilmil Jheel 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 (≤ 220 m^3/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 m^3/s) covering 1799.59 km^2 and 9.95% of the area (Figure 3, Appendix 2).

3.2 Depth

Depth is important as it influence the habitat structure, biodiversity, and availability of water resource for aquatic organisms in the river system. Freshwater biodiversity is threatened by overexploitation, water pollution, flow modification, habitat destruction, and invasion by exotic species [4]. Stretches with deeper sections provide refuge for species during low flow conditions and support habitat pockets for aquatic organisms, whereas shallow areas play a key role for spawning and nutrient cycling. Change in water depth disrupts the river geomorphological features that acts as habitat for aquatic biodiversity. It also impacts species survival and river ecosystem [38, 40]. Depth was measured in the field. The continuous layer was reclassified in seven thematic classes (Table 8, Appendix 1). The Ganga River from downstream of Jhilmil Jheel CR to Brijghat is observed with low depth (≤ 4 m) covering 1706.90 km^2 and

Table 6 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

Table 6 (continued)

Weightage Category	Factor	Assigned weight (*X*)	Class Name	Rank (*Y*)
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

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 km^2 and 2.59% of the area. The Ganga River downstream of 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 km^2 which is 35.66% of the MGR (Figure 4, Appendix 2).

3.3 Width

The width of river plays a critical role in shaping the habitat structure and biodiversity within the ecosystem. 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, particularly the faunal species used to bask and floral species of riparian vegetation. Channelization of rivers reduces nutrient flow and macroinvertebrate diversity in the transition zone between the river and riparian floodplain [41]. Width was measured in field. The continuous layer was reclassified in six thematic classes (Table 9, Appendix 1). 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 km^2 and 8.03% of the total area. Whereas, from Turtle (Kachhua) Wildlife Sanctuary to Gomti River confluence near Kaithi is observed with highest channel width (> 400 m) covering 2463.98 km^2 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 km^2 which is 26.06% of the MGR (Fig. 5, Appendix 2).

3.4 Precipitation

Precipitation is a fundamental driver of river habitat dynamics, as it directly influences streamflow, water levels, and sediment transport [42]. Rainfall leads to maximize river discharge, resulting in flooding events that alter channel morphology, expand floodplain areas, and connect the fragmented habitats into single stretch of habitat areas. However, excessive precipitation also leads to rapid erosion and higher sediment loads, 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 significantly impact the health of river ecosystems, affecting species composition, migration patterns, and food availability [43]. Precipitation was derived from the Worldclim. The continuous layer was reclassified in five thematic classes (Table 10, Appendix 1). 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 km^2 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 km^2 and 4.17% of the area. The Ganga River downstream Charan Singh Ganga barrage at Narora to Farrukhabad having precipitation 1000 to 1200 mm, that covers maximum area of 8129.28 km^2 which is 44.93% of the MGR (Fig. 6, Appendix 2).

3.5 Land use land cover

The flooding, erosion, landslides, runoff, and sedimentation are prevalent as a resultant of Land Use Land Cover (LULC) changes that alter aquatic habitats [2, 3, 44]. LULC changes are important for the environment's changing dynamics that impact hydrology and morphology of the river [45]. The derived LULC summarized in Table 11 (Appendix 1) and Fig. 7 (Appendix 2). Satellite images were rectified radiometrically and geometrically to undergo object based image classification for categorizing pixels from the Landsat images into different LULC classes [46] by supervised image classification method using Maximum Likelihood Classifier (MLC) [47]. The area was classified in nine attributes, i.e., River, Sandbar, and Island, Barrenland, Waterbody, Forest, Agriculture, Builtup, and Grassland. It is observed that 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 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.

3.6 Geomorphology

Geomorphological factors are essential in the hydrological system process on the earth surface. It significantly influences river habitat systems by physical features of river channels and floodplains. Geomorphological processes result dynamic and diverse habitats in river and floodplain ecotones [48]. 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 12, Appendix 1). 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 Bhimgoda barrage at Haridwar to Ramganga River confluence at Kannauj (Fig. 8, Appendix 2).

3.7 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 [49]. 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 [50]. Soil texture was derived from the Bhoomi portal, NBSS&LUP. The continuous layer was reclassified in four thematic classes (Table 13, Appendix 1). The loamy soil is predominant throughout the study region near water channels from Haridwar to Varanasi, particularly in segment between Farrukhabad and Kanpur. The loamy soil texture covers 9231.88 km^2 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 km^2 and 44.67% of the area. Other soil textures present in the region are clayey and loamy skeletal (Fig. 9, Appendix 2).

3.8 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 [51]. Parent material was derived from the Bhoomi portal, NBSS&LUP. The continuous layer was reclassified in three thematic classes (Table 14, Appendix 1). The alluvium is dominant throughout the study region. It is extended from Jhilmil Jheel CR to Varanasi covering 17260.65 km^2 and 95.39% of the MGR. Colluvium is present in 193.61 km^2 near Haridwar which is approximately 1.07% whereas, sandstone is present in 639.80 km^2 area at Chunar, approximately 3.54% of the area (Fig. 10, Appendix 2).

3.9 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 [52]. Mineral was derived from the Bhoomi portal, NBSS&LUP. The continuous layer was reclassified in three thematic classes (Table 15, Appendix 1). The Smectite mixed mineral is dominant throughout the MGR, it covers a major part i.e. 17524.99 km^2 and 96.85% of the total area. Montmorillonite covers 20.77 km^2 and 0.11% of the total area. Illite minerals are present near lateral sandbars (Fig. 11, Appendix 2).

3.10 Drainage density

Water availability is the primary determinant of ecological processes in most drainage networks, with hydrologic connectivity and geomorphic change [53]. 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 16, Appendix 1). The Ganga River at Haridwar, Bijnor, Kannauj and Kanpur barrage and Farrukhabad (> 1.5) covering 6959.56 km^2 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 km^2 which is 38.46% of the MGR (Fig. 12, Appendix 2).

3.11 Elevation

Elevation plays important role in hydrological processes and structures by influencing the gradient, velocity, and erosion processes within river course [54]. 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 17, Appendix 1). 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 (Fig. 13, Appendix 2).

3.12 Slope

Slopes strongly influence interrill erosion processes, with time to runoff, flow velocity, runoff rate, and interrill erosion rate decreasing with increasing gradients [55]. Slope was derived from the ALOS DEM with 30 m resolution. The continuous layer was reclassified in seven thematic classes (Table 18, Appendix 1). The Ganga River at Prayagraj and Varanasi has lower slope (≤ 0.5 degree) covering 3707.91 km^2 and 20.49% of the MGR. Whereas, higher slope (> 5 degree) has the coverage of 348.43 km^2 and 1.93% of the area that lies near Bhimgoda barrage at Haridwar (Fig. 14, Appendix 2).

3.13 Proximity to barrage

The dams and barrages are major driving forces behind the alteration of fluvial environment at downstream flows [56]. Alteration takes place particularly in aquatic and riparian habitat by affecting river hydrology at downstream [57]. The proximity to barrage governs species movement which was measured in field. The continuous layer was reclassified in five thematic classes (Table 19, Appendix 1). The Ganga River ≤ 20 km from the dams and barrages are covered by 2457.56 km^2 and 13.58% of the total area. Whereas, the stretch > 200 km from the dams and barrages are covered by 3335.83 km^2 and 18.44% of the MGR (Fig. 15, Appendix 2).

3.14 Human footprint

Human activities have profoundly altered river systems, often leading to significant ecological and hydrological changes. The human driven modifications exacerbates the vulnerability of river systems towards alteration of flow regimes compromising the resilience system of river to extreme weather events [38]. The human footprint was derived from Earthdata, NASA and Socioeconomic Data and Applications Center (SEDAC) [58]. The continuous layer was reclassified in five thematic classes (Table 20, Appendix 1). The Ganga River channels are minimum human footprint areas (≤ 30) covering 2048.29 km^2 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 km^2 area and 4.07% of the MGR. The largest area of 7859.55 km^2 which is 43.44% of the total study area is covered under human footprint range 31 to 40 (Fig. 16, Appendix 2).

3.15 Temperature

Warming temperatures, along with changes in precipitation contribute to the effects on aquatic systems [59]. 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. The continuous layer was reclassified in four thematic classes (Table 21, Appendix 1). The Ganga River from upstream of Farrukhabad to Gomti River confluence at Kaithi having higher temperature (> 26 °C) covering 12,434.57 km^2 and 68.72% of the total area. The Ganga River near Bhimgoda barrage at Haridwar having temperature ≤ 24 °C covers 29.52 km^2 area and 0.16% of the MGR (Fig. 17, Appendix 2).

3.16 Potential habitat areas

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 supports the spatial analysis of riverscape by integrating environmental, physical, biological and anthropogenic factors that influences ecological pattern and process in rivers [60]. The decision making tool 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 [61].

Table 7 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

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 [62]. The derived potential habitat area was classified in four thematic classes (Table 7) and (Fig. 3).

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 km^2 floodplain area, which is 21% of length and 16.66% of floodplain in the MGR. Turtle (Kachhua) 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 km^2 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 km^2 floodplain area, which is 37% of length and 34.87% of floodplain in the MGR. Hydromorphological status of the Ganga River between downstream of Jhilmil Jheel 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 km^2 floodplain area, which is 31% of length and 39.92% of floodplain in the MGR (Fig. 4). The restoration area has maximum coverage in MGR, where natural flow need to be maintained to sustain aquatic biodiversity.

4 Discussion

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 amalgamating 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 crucial 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 [40]. E-flow regime is required in river to achieve desired ecological objectives [63] that result in ecological recovery in regulated rivers, with 30% of taxa increasing in frequency at regulated sites following the implementation of the flows [64]. Ecologically relevant environmental flows are essential for restoring the floodplain of rivers impacted by flow regulation and guiding flow restoration measures [65]. River management design must restore natural flow variability and achieve hydrological connectivity between a river and its surroundings for successful restoration [66]. E-flow was assessed to understand challenges and opportunities for implementation, which requires enhancement of water in the Ganga River [67]. E-flow can be maintained in the MGR by allocation of minimum water to

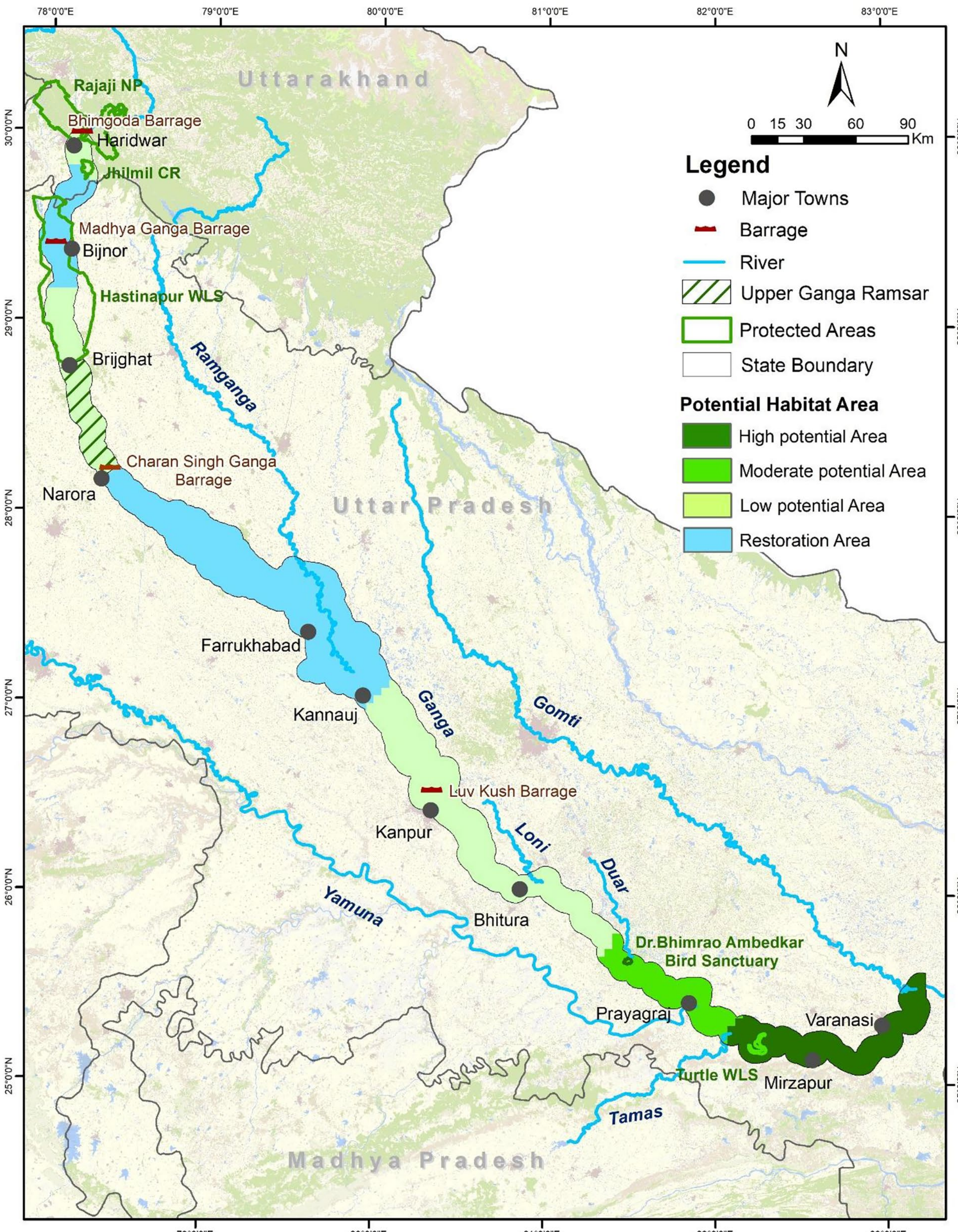

Fig. 3 Map showing distribution of potential habitat areas

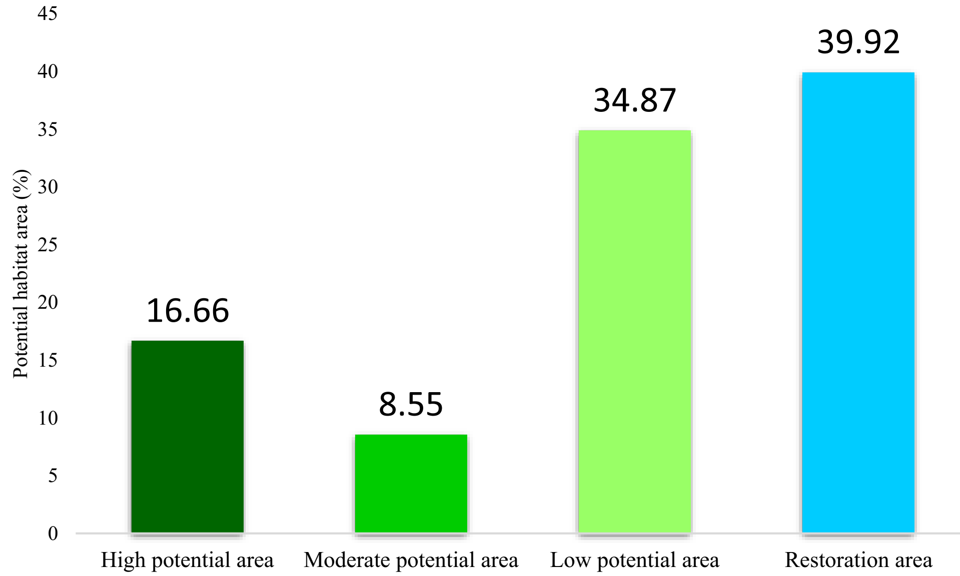

Fig. 4 Potential habitat areas (%)

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 [68]. 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 [69]. Climate change and socioeconomic 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 [70, 71]. In another study suggested that climate change will increases river flows in India, but socioeconomic 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 [72]. 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 [73]. 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 [74]. 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 [73, 75]. Ecohydrological approach can enhance the sustainability and human well-being of the Ganga River by managing water, biodiversity, ecosystem services, and resilience [74, 76]. Conservation measures should focus on maintaining minimum flow for ecosystem processes as Gharial (*Gavialis gangeticus*) prefer sandy river banks and sand bars for basking [77], alteration in flow regime of the Ganga River has resulted in the isolation and fragmentation of turtle populations [78], 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 [79]. 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 [80]. 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 [81]. The river modifications for human need is 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. Maintaining natural flow variability is crucial for sustaining river ecosystems and ensuring the resilience of freshwater habitats [4]. The flow in the Ganga River is highly regulated which needs to be maintained for the natural connectivity of potential habitat and restoration areas.

5 Conclusion

Assessment of stress factors in river ecology is important for sustainability of freshwater ecosystems. 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 hydromorphology, 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 sand bars and islands are a very important habitat for mammals like Smooth coated otter (*Lutrogale perspicillata*), reptiles like Gharial (*Gavialis gangeticus*), Turtles and birds, as they bask and lay eggs on the sandy areas. Whereas, deep pools are suitable habitats for Gangetic dolphin (*Platanista gangetica*) and ichthyofauna species in the Ganga River. 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 Jheel 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. This study is important for policymakers to step forward in the Ganga River rejuvenation.

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Declarations

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References

1. Belmar O, Booker D, Álvarez-Cabria M, Peñas F, Barquín J. Modelling physical characteristics of river habitats. River Res Appl. 2019;35:804–17. https://doi.org/10.1002/rra.3456.
2. Jacobson RB, Femmer SR, McKenney RA. Land-use changes and the physical habitat of streams: a review with emphasis on studies within the US Geological Survey Federal-State Cooperative Program/USGS. 2001; Circular No. 1175.
3. Mandal S, Mani A, Lall AR, Kumar D. Slope stability assessment and landslide susceptibility mapping in the Lesser Himalaya, Mussoorie. Uttarakhand Discov Geosci. 2024;2:51. https://doi.org/10.1007/s44288-024-00055-9.
4. Dudgeon D, Arthington AH, Gessner MO, Kawabata Z, Knowler DJ, Leveque C, Naiman RJ, Prieur-Richard AH, Soto D, Stiassny MLJ, Sullivan CA. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev. 2006;81(2):163–82. https://doi.org/10.1017/S1464793105006950.
5. Rai PK, Mishra VN, Singh P. Geospatial technology for landscape and environment management: sustainable assessment & planning. Singapore: Springer Nature; 2022.
6. Mishra VN, Rai PK, Singh P. Geo-information technology in earth resources monitoring and management. USA: Nova Science Publishers; 2021.
7. Hoang L, Van Vliet M, Kummu M, Lauri H, Koponen J, Supit I, Leemans R, Kabat P, Ludwig F. The Mekong's future flows under multiple drivers: How climate change, hydropower developments and irrigation expansions drive hydrological changes. Sci Total Environ. 2019;649:601–9. https://doi.org/10.1016/j.scitotenv.2018.08.160.
8. Hasnain S. Himalayan glaciers meltdown: impact on south Asian rivers. IAHS-AISH Public. 2002. https://doi.org/10.1371/journal.pone.0278605.
9. Zhang X, Yu G, Li Z, Li P. Experimental study on slope runoff, erosion and sediment under different vegetation types. Water Resour Manage. 2014;28:2415–33. https://doi.org/10.1007/s11269-014-0603-5.
10. Kondolf GM. PROFILE: hungry water: effects of dams and gravel mining on river channels. Environ Manage. 1997;21:533–51. https://doi.org/10.1007/S002679900048.
11. Filho L, Alam G, Nagy G, Rahman M, Roy S, Wolf F, Kovaleva M, Saroar M, Li C. Climate change adaptation responses among riparian settlements: a case study from Bangladesh. PLoS ONE. 2022;17(12):2786.
12. Juracek K, Fitzpatrick F. Geomorphic responses of fluvial systems to climate change: a habitat perspective. River Res Appl. 2022;38:757–75. https://doi.org/10.1002/rra.3938.
13. Bower L, Peoples B, Eddy M, Scott M. Quantifying flow-ecology relationships across flow regime class and ecoregions in South Carolina. Sci Total Environ. 2021;802: 149721. https://doi.org/10.1016/j.scitotenv.2021.149721.
14. Paudel S, Koprowski J, Thakuri U, Sigdel R, Gautam R. Ecological responses to flow variation inform river dolphin conservation. Sci Rep. 2020. https://doi.org/10.1038/s41598-020-79532-3.
15. Vashistha G, Mungi N, Lang J, Ranjan V, Dhakate P, Khudsar F, Kothamasi D. Gharial nesting in a reservoir is limited by reduced river flow and by increased bank vegetation. Sci Rep. 2021. https://doi.org/10.1038/s41598-021-84143-7.
16. Alam A, Kumar J, Sarkar U, Jha D, Das S, Srivastava S, Kumar V, Das B. Assessing the influence of environmental factors on fish assemblage and spatial diversity in an unexplored subtropical Jargo reservoir of the Ganga River basin. Aquatic Ecosyst Health Manag. 2021;24:46–53. https://doi.org/10.14321/aehm.024.04.07.
17. Walton C, Zak D, Audet J, Petersen R, Lange J, Oehmke C, Wichtmann W, Kreyling J, Grygoruk M, Jabłońska E, Kotowski W, Wiśniewska M, Ziegler R, Hoffmann C. Wetland buffer zones for nitrogen and phosphorus retention: impacts of soil type, hydrology and vegetation. Sci Total Environ. 2020;727: 138709. https://doi.org/10.1016/j.scitotenv.2020.138709.
18. Sinha R, Mohanta H, Jain V, Tandon SK. Geomorphic diversity as a river management tool and its application to the Ganga River India. River Res Applic. 2017. https://doi.org/10.1002/rra.3154.
19. Khan S, Sinha R, Whitehead P, Sarkar S, Jin L, Futter MN. Flows and sediment dynamics in the Ganga River under present and future climate scenarios. Hydrol Sci J. 2018. https://doi.org/10.1080/02626667.2018.1447113.
20. Zarfl C, Dunn F. The delicate balance of river sediments. Science. 2022;376:1385–6. https://doi.org/10.1126/science.abq6986.
21. Jaiswal D, Pandey J. Human-driven changes in sediment-water interactions may increase the degradation of ecosystem functioning in the Ganga River. J Hydrol. 2021. https://doi.org/10.1016/J.JHYDROL.2021.126261.
22. Nale J, Gosain A, Khosa R. Environmental flow assessment of river ganga - importance of habitat analysis as a means to understand hydrodynamic imperatives for a sustainable ganga biodiversity. Curr Sci. 2017. https://doi.org/10.18520/CS/V112/I11/2187-2188.
23. Saaty TL. The Analytic Hierarchy Process. New York: McGraw-Hill; 1980.
24. Das A. Surface water potential zones delineation and spatiotemporal variation characteristics of water pollution and the cause of pollution formation in Brahmani River Basin Odisha. Hydro Res. 2025. https://doi.org/10.1016/j.hydres.2024.10.002.
25. Ahmad I, Verma M. Application of analytic hierarchy process in water resources planning: a GIS based approach in the identification of suitable site for water storage. Water Resour Manage. 2018;32:5093–114. https://doi.org/10.1007/s11269-018-2135-x.
26. Achu A, Thomas J, Reghunath R. Multi-criteria decision analysis for delineation of groundwater potential zones in a tropical river basin using remote sensing, GIS and analytical hierarchy process (AHP). Groundw Sustain Dev. 2020;10: 100365. https://doi.org/10.1016/j.gsd.2020.100365.

27. Betz F, Lauermann M, Cyffka B. Delineation of the riparian zone in data-scarce regions using fuzzy membership functions: an evaluation based on the case of the Naryn River in Kyrgyzstan. Geomorphology. 2018;306:170–81. https://doi.org/10.1016/J.GEOMORPH.2018.01.024.
28. Rao R. Biological resources of the Ganga River India. Hydrobiologia. 2001;458:159–68. https://doi.org/10.1023/A:1013173204091.
29. Rodgers WA, Panwar HS, Mathur VB. Wildlife Protected Areas in India: A Review (Executive Summary). Wildlife Institute of India, Dehradun. 2002.
30. Canco I, Kruja D, Iancu T. AHP, a reliable method for quality decision making: a case study in business. Sustainability. 2021. https://doi.org/10.3390/su132413932.
31. Sinha S. Crisp and Fuzzy AHP in GIS-MCDM for wildlife habitat suitability analysis. Spat Inf Sci Nat Res Manage. 2020. https://doi.org/10.4018/978-1-7998-5027-4.ch001.
32. Rousta B, Araghinejad S. Development of a multi criteria decision making tool for a water resources decision support system. Water Resour Manage. 2015;29:5713–27. https://doi.org/10.1007/s11269-015-1142-4.
33. Malczewski J. GIS-based multicriteria decision analysis: a survey of the literature. Int J Geogr Inf Sci. 2006;20(7):703–26. https://doi.org/10.1080/13658810600661508.
34. Saaty TL. How to make a decision: the analytic hierarchy process. Euro J Operat Res. 1990. https://doi.org/10.1016/0377-2217(90)90057-I.
35. Arulbalaji P, Padmalal D, Sreelash K. GIS and AHP Techniques based delineation of groundwater potential zones: a case study from southern Western Ghats India. Sci Rep. 2019;9:2082. https://doi.org/10.1038/s41598-019-38567-x.
36. Mcmanamay RA, Griffiths NA, DeRolph CR, Pracheil BM. A synopsis of global mapping of freshwater habitats and biodiversity: implications for conservation. Pure Appl Biogeography. 2017. https://doi.org/10.5772/intechopen.70296.
37. Pande CB, Moharir K. GIS based quantitative morphometric analysis and its consequences: a case study from Shanur River Basin Maharashtra India. Appl Water Sci. 2017;7:861–71. https://doi.org/10.1007/s13201-015-0298-7.
38. Bunn SE, Arthington AH. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ Manage. 2002;30(4):492–507. https://doi.org/10.1007/s00267-002-2737-0.
39. Gao J, Yang Q, Yuan M, Zhu Y, Ma Y, Wang F. A review of ADCP river flow measurement method based on bio-visual mechanism. Proc of SPIE. 2023. https://doi.org/10.1117/12.2686363.
40. Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg J. The natural flow regime: a paradigm for river conservation and restoration. Bioscience. 1997;47(11):769–84. https://doi.org/10.2307/1313099.
41. Kennedy T, Turner T. River channelization reduces nutrient flow and macroinvertebrate diversity at the aquatic terrestrial transition zone. Ecosphere. 2011;2:1–13. https://doi.org/10.1890/ES11-00047.1.
42. Das S. Dynamics of streamflow and sediment load in Peninsular Indian rivers (1965–2015). Sci Total Environ. 2021;799: 149372. https://doi.org/10.1016/j.scitotenv.2021.149372.
43. Shousha S, Maranger R, Lapierre J. Decadal changes in anthropogenic inputs and precipitation influence riverine exports of carbon, nitrogen, and phosphorus, and alter ecosystem level stoichiometry. Global Biogeochem Cycles. 2023. https://doi.org/10.1029/2023GB007820.
44. Mani A, Kumari M, Badola R. Landslide hazard zonation (LHZ) mapping of Doon Valley using multi-criteria analysis method based on remote sensing and GIS techniques. Discov Geosci. 2024;2:35. https://doi.org/10.1007/s44288-024-00044-y.
45. Mani A, Kumari M, Badola R. Morphometric analysis of suswa river basin using geospatial techniques. Eng Proc. 2022;27(1):65. https://doi.org/10.3390/ecsa-9-13225.
46. Bansal S, Srivastav SK, Roy PS, Krishnamurthy YVN. An analysis of land use and land cover dynamics and causative drivers in a thickly populated Yamuna River basin of India. Appl Ecol Environ Res. 2016;14(3):773–92. https://doi.org/10.15666/aeer/1403_773792.
47. Sisodia P, Tiwari V, Kumar A. Analysis of supervised maximum likelihood classification for remote sensing image. Int Conf Recent Adv Innov Eng. 2014. https://doi.org/10.1109/ICRAIE.2014.6909319.
48. Sear D, Newson M. Environmental change in river channels: a neglected element towards geomorphological typologies, standards and monitoring. Sci Total Environ. 2003. https://doi.org/10.1016/S0048-9697(02)00619-8.
49. Liu Y, Yang Z, Wang X. Numerical simulation of slope–gully–stream sediment transport process with water and gravity erosion. Front Earth Sci. 2022;10: 913243. https://doi.org/10.3389/feart.2022.913243.
50. Allan JD. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annu Rev Ecol Evol Syst. 2004;35:257–84. https://doi.org/10.1146/annurev.ecolsys.35.120202.110122.
51. Tucker GE, Slingerland R. Drainage basin responses to climate change. Water Resources Res. 1997;33(8):2031–47. https://doi.org/10.1029/97WR00409.
52. Zegers G, Navarro-Valdivia L, Lagos-Zúñiga M, Navarrete-Calvo Á, Caraballo M, Niño Y, McPhee J, Montserrat S. An integrated modeling approach for mineral and metal transport in acidic rivers at high mountainous porphyry Cu systems. J Hydrol. 2021;1: 126718. https://doi.org/10.1016/J.JHYDROL.2021.126718.
53. Sponseller R, Heffernan J, Fisher S. On the multiple ecological roles of water in river networks. Ecosphere. 2013;4:1–14. https://doi.org/10.1890/ES12-00225.1.
54. Loritz R, Kleidon A, Jackisch C, Westhoff M, Ehret U, Gupta H, Zehe E. A topographic index explaining hydrological similarity by accounting for the joint controls of runoff formation. 2019. Hydrol Earth Syst Sci. https://doi.org/10.5194/HESS-23-3807-2019.
55. Wu B, Li L, Xu L, Wei X, Li X. The influence of slopes on interrill erosion processes using loessial soil. J Soils Sediments. 2021;21:3672–81. https://doi.org/10.1007/s11368-021-03018-6.
56. Aguiar FC, Martins MJ, Silva PC, Fernandes MR. Riverscapes downstream of hydropower dams: Effects of altered flows and historical land-use change. Landsc Urban Plan. 2016;153:83–98. https://doi.org/10.1016/j.landurbplan.2016.04.009.
57. Alldredge B, Moore G. Assessment of riparian vegetation sensitivity to river hydrology downstream of a major Texas dam. River Res Applic. 2014. https://doi.org/10.1002/rra.2625.
58. Sanderson EW, Jaiteh M, Levy MA, Redford KH, Wannebo AV, Woolmer G. The human footprint and the last of the wild. Bioscience. 2002;52(10):891. https://doi.org/10.1641/00063568(2002)052[0891:THFATL]2.0.CO;2.
59. Gleick P. Climate Change and Water. Berkeley: University of California Press; 2009.

60. Erős T, Lowe W. The landscape ecology of rivers: from patch-based to spatial network analyses. Curr Landscape Ecol Rep. 2019;4:103–12. https://doi.org/10.1007/s40823-019-00044-6.
61. Zhang X, Du H, Zhao Z, Wu Y, Cao Z, Zhou Y, Sun Y. Risk assessment model system for aquatic animal introduction based on analytic hierarchy process (AHP). Animals Open Access J MDPI. 2023. https://doi.org/10.3390/ani13122035.
62. Store R, Jokimäki J. A GIS-based multi-scale approach to habitat suitability modeling. Ecol Model. 2003;169:1–15. https://doi.org/10.1016/S0304-3800(03)00203-5.
63. Acreman M, Dunbar M. Defining environmental river flow requirements, a review. Hydrol Earth Syst Sci. 2004;8:861–76. https://doi.org/10.5194/HESS-8-861-2004.
64. Growns I. The implementation of an environmental flow regime results in ecological recovery of regulated rivers. Rest Ecol. 2016. https://doi.org/10.1111/rec.12330.
65. Hayes D, Brändle J, Seliger C, Zeiringer B, Ferreira T, Schmutz S. Advancing towards functional environmental flows for temperate floodplain rivers. Sci Total Environ. 2018;633:1089–104. https://doi.org/10.1016/j.scitotenv.2018.03.221.
66. Palmer M, Ruhí A. Linkages between flow regime, biota, and ecosystem processes: implications for river restoration. Science. 2019. https://doi.org/10.1126/science.aaw2087.
67. Kaushal N, Babu S, Mishra A, Ghosh N, Tare V, Kumar R, Sinha P, Verma R. Towards a healthy ganga improving river flows through understanding trade offs. Front Environ Sci. 2019. https://doi.org/10.3389/fenvs.2019.00083.
68. Hanus S, Hrachowitz M, Zekollari H, Schoups G, Vizcaíno M, Kaitna R. Future changes in annual, seasonal and monthly runoff signatures in contrasting Alpine catchments in Austria. 2021. Hydrol Earth Syst Sci. https://doi.org/10.5194/hess-25-3429-2021.
69. Anand J, Gosain A, Khosa R. Prediction of land use changes based on Land Change Modeler and attribution of changes in the water balance of Ganga basin to land use change using the SWAT model. Sci Total Environ. 2018. https://doi.org/10.1016/j.scitotenv.2018.07.017.
70. Jin L, Whitehead P, Sarkar S, Sinha R, Futter M, Butterfield D, Caesar J, Crossman J, Crossman J. Assessing the impacts of climate change and socio-economic changes on flow and phosphorus flux in the Ganga river system. Environ Sci Process Impacts. 2015;17(6):1098–110. https://doi.org/10.1039/c5em00092k.
71. Whitehead P, Jin L, Macadam I, Janes T, Sarkar S, Rodda H, Sinha R, Nicholls R. Modelling impacts of climate change and socio-economic change on the Ganga, Brahmaputra, Meghna, Hooghly and Mahanadi river systems in India and Bangladesh. Sci Total Environ. 2018;636:1362–72. https://doi.org/10.1016/j.scitotenv.2018.04.362.
72. Jana B, Lahiri S, Ghosh D, Bhakta J, Mandal S, Bag S. Understanding the soil-water interactions for sustainable ecosystem services in aquatic environments. Waste Water Manage Through Aquacul. 2018. https://doi.org/10.1007/978-981-10-7248-2_1.
73. Wang X, Zhou J, Wu Y, Bol R, Wu Y, Sun H, Bing H. Fine sediment particle microscopic characteristics, bioavailable phosphorus and environmental effects in the world largest reservoir. Environ Pollut. 2020. https://doi.org/10.1016/j.envpol.2020.114917.
74. Dynesius M, Nilsson C. Fragmentation and flow regulation of river systems in the northern third of the world. Science. 1994;266(5186):753–62. https://doi.org/10.1126/science.266.5186.753.
75. Kumar D, Kumar A, Malik D, Sharma R, Gupta V, Kumar P. Effect of barrages and anthropogenic activities on ecological integrity of the Ganga River: a review on current issues and restoration efforts. Agro Environ Sustain. 2023. https://doi.org/10.59983/s2023010109.
76. Singh R, Singh G. Integrated management of the Ganga River: An ecohydrological approach. Ecohydrol Hydrobiol. 2020;20:153–74. https://doi.org/10.1016/j.ecohyd.2019.10.007.
77. Hussain S. Basking site and water depth selection by gharial *Gavialis gangeticus* Gmelin 1789 (Crocodylia, Reptilia) in National Chambal Sanctuary, India and its implication for river conservation. Aquatic Conservation-marine Freshwater Ecosyst. 2009;19:127–33. https://doi.org/10.1002/AQC.960.
78. Bajaj A, Chauhan R, Sathiaseelan S. Turtle rescue centre Bhagalpur (Bihar) India. Reptiles & Amphibians. 2021. https://doi.org/10.17161/RANDA.V28I2.15502.
79. Choudhary S, Dey S, Dey S, Sagar V, Nair T, Kelkar N. River dolphin distribution in regulated river systems: implications for dry-season flow regimes in the Gangetic basin. Aquatic Conserv-Marine Freshwater Ecosyst. 2012;22:11–25. https://doi.org/10.1002/AQC.1240.
80. Mani A, Kumari M, Badola R. GIS and AHP-based methods for river risk zone (RRZ) assessment: a case study of the Himalayan rivers in Doon Valley, Uttarakhand India. Environ Sci Pollution Research. 2025. https://doi.org/10.1007/s11356-025-36136-6.
81. Sonkar G, Gaurav K. Assessing the impact of large barrages on habitat of the Ganga River dolphin. River Res Appl. 2020;36:1916–31. https://doi.org/10.1002/rra.3715.