RESEARCH ARTICLE

Anthropogenic risk assessment of riverine habitat using geospatial modelling tools for conservation and restoration planning: a case study from a tropical river Pranhita, India

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Abstract

The riverine ecosystem provides multiple benefits to human community and contributes to the sustainable development of the ecoregion. The growing dependency on these ecosystems has largely contributed to aggravating the ecological risks, habitat degradation, and loss of ecosystem services. The present study evaluates the ecological risk emanating from nine anthropogenic stressors including river use, hydro-morphology, catchment pollution, and biological stressor on river Pranhita in Godavari Basin of Peninsular India using InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) Habitat Risk Assessment model. The primary field survey, remote sensing, and secondary data-assisted spatial modelling results revealed low ecological risk ($R = 0.65$ of 3) in river Pranhita due to anthropogenic activities. Sediment loading, the inflow of nitrogen, and habitat fragmentation were the major stressors with relatively higher risk score (> 1); influence on a sizeable portion of riverine habitat (29–75% of the total area under high-risk zone) indicates the mounting threat from catchment activities. The low-risk value observed in protected river reaches as compared to unprotected areas is likely to be influenced by the abundant presence of intact riparian vegetation which mitigate the catchment stressors and minimal anthropogenic activity within protected areas. This study demonstrates the application of InVEST HRA model for ecological risk assessment of riverine ecosystems and fish assemblages along with their input data generation framework. This has the potential for prioritization of sensitive habitats based on computed ecological risk and stressor identification based on their exposure and consequences for developing appropriate mitigation measures. This model is spatially explicit and accommodates user-defined criteria for ecosystem-level assessment at a regional and national scale to facilitate the resource managers and policymakers for conservation and restoration planning and implementation of targeted management measures for sustainable development.

Keywords LULC · Habitat risk · Riparian zone · InVEST · Anthropogenic stressor · Protected area

Introduction

Rivers are the lifeline for diverse biota including fishes and ensure the flow of numerous ecosystem services to the human community along its course (Ekka et al. 2020; Pownkumar et al. 2022). However, the unwarranted exploitation of riverine ecosystems by human community has altered their biotic structures and functions, which may lead to the loss of biodiversity and ecosystem services (Zeng et al. 2022) and halt the global sustainable development. The United Nations-Sustainable Development Goal (SDG)-6 deals with "clean water and sanitation," targeting water quality improvement, equitable access, efficient use, protection, and restoration of water-associated ecosystems (https://sdgs.un.org/goals/goal6). Furthermore, achieving this SDG also complies with the 2030 Agenda for Sustainable Development, as this goal is mostly synergistic with other SDGs (UN-Water 2016; Opperman et al. 2018). Generally, the flow, function, habitat status, and biota in the riverine ecosystems are shaped by the characteristics of catchment and riparian zone. The anthropogenic stressors, viz., land use change, habitat degradation, pollution, overexploitation of fishery resources, and

invasive (non-native) fish species, affect the riverine habitats at different spatial and temporal scales (Vass et al. 2011).

India is blessed with 14 major, 44 medium, and numerous minor rivers flowing through diverse eco-regime with a total length of 0.252 million km (https://dof.gov.in/inland-fisheries), which act as a repository for rich fish germplasm (Vass et al. 2011). The recent review on the ichthyofaunal diversity of major rivers of India revealed decreasing fish diversity on a temporal scale, mainly due to the development activities and intensive resource utilization, which probably led to flow change and habitat degradation (Vass et al. 2011; Das et al. 2021b). The "protected areas" (PAs) are considered the cornerstone of biological conservation (https://www.cbd.int/protected/overview/), which maintain the functioning of key habitats and support existing biota. However, such area-based and species-specific conservation measures for fish species' are yet to be implemented for freshwater habitats, especially rivers of India (Gupta et al. 2014; Das et al. 2021a). The management of selected river reaches in each basin, encompassing representative zones or habitats bordering the existing terrestrial PAs, is important for the conservation of critical habitats of indigenous and endemic species in India (Atkore et al. 2011; Sarkar et al. 2013; Gupta et al. 2014, 2015). Even so, the development of a multi-species management framework requires complete habitat and landscape profiling, which is presently lacking in India (Das et al. 2021a).

The understanding of ecological risks associated with anthropogenic activities and their spatial mapping is crucial for the restoration and conservation planning of any ecosystem. Geospatial modelling tools are promising for rapid and accurate environmental risk mapping, which will assist resource managers and policymakers in prioritizing the habitats for conservation and implementing specific management measures for restoration (Raheja 2009; Guerry et al. 2012). InVEST Habitat Risk Assessment (HRA) model is a tool that can quantify the relative risk to habitats by various predefined anthropogenic stressors, through determining the degree of exposure and habitat-specific responses, affecting the delivery of ecosystem services (Arkema et al. 2014; Sharp et al. 2020). This model also accommodates user-defined additional resilience attributes/variables and provides significant results for the customized analysis (Healy and Secchi 2016; Caro et al. 2020). This model helps in spatial habitat zonation in accordance with their risk level and prioritizes the anthropogenic stressors, which stress the habitats for developing specific risk mitigation measures (Zhang et al. 2022). Globally, this model has been applied extensively in coastal (Arkema et al. 2014; Cabral et al. 2015; Elliff and Kikuchi 2017; Wyatt et al. 2017; Zhai et al. 2020; Studwell et al. 2021; Tussadiah et al. 2021), terrestrial habitats (Ghehi et al. 2020; Zhang et al. 2022), and selected species of importance (Duggan et al. 2015) for conservation planning, spatial habitat prioritization, and ecosystem service assessment. However, to the best of our knowledge and according to the InVEST publication database (up

to May 2021) (Lisa and Natural Capital Project 2021), HRA model has not yet been applied to the ecological risk assessment of riverine habitat. The river is a dynamic ecosystem with changing environmental conditions, which is influenced by multiple direct and indirect stressors. Often the non-availability of geo-referenced information on various aspects of the riverine ecosystem has restricted the applications of ecological models at large-scale spatial extent. Risk assessment of stressed riverine habitats can help to explore the influences of human-induced threats to riverine ecosystem services, which had the highest risk to service supply (Culhane et al. 2019).

In the present study, river Pranhita in Peninsular India is taken as a case study to demonstrate the utility of InVEST HRA model for spatial mapping of anthropogenic risk to its habitats and fish communities. This river is the largest tributary of Godavari River and is unique in many ways; it supports rich fish diversity and several endemic and threatened species have been reported (Sheikh 2014; Lal et al. 2016; Prasad et al. 2020; Kantharajan et al. 2022b). The river marks the boundary between the Indian states of Telangana and Maharashtra and the river course borders 3 terrestrial PAs with relatively uninterrupted flow and deep pools (Kantharajan et al. 2022a). Its riparian zone comprises of diverse land use land cover (LULC) and watersheds, which are considered to have undergone a major change in the past (Koneti et al. 2018). The comprehensive study conducted by Kantharajan et al. (2022a, 2022b) in river Pranhita highlighted for a detailed assessment of anthropogenic stressors, viz., the inflow of nutrients and sediments, river flow obstruction, solid waste disposal on river habitats, and fish assemblages, for their conservation and management at spatial scales.

This study aims to (i) assess the LULC pattern of the transitional area between the terrestrial and aquatic habitats and other anthropogenic stressors and (ii) demonstrate the potential of InVEST Habitat Risk Assessment model for evaluating the anthropogenic risk in river Pranhita, as a case study. The spatial quantification and mapping of anthropogenic risk to fish communities of river Pranhita will help in conservation and restoration planning. The impact assessment of anthropogenic stressors on fish communities would facilitate the resource managers and policymakers to implement targeted management measures. Furthermore, the methodology demonstrated in the present study can extend its applications to other inland waterbodies, viz., wetlands, lakes, and brackish water systems.

Materials and methods

Study area

The river Pranhita is one of the major tributaries of the Godavari River, which combines the flow of other

upstream tributaries Wainganga, Penganga, and Wardha from its catchment area of about 109,079 km^2 (Jain et al. 2007; MoWR 2014). This river is considered a "Purāna" (meaning "ancient" in Hindi) basin of cratonic India dating back to the Proterozoic-Mesozoic period (Murkute and Joshi 2014; Amarasinghe et al. 2015) and falls in the South Deccan Plateau physiographic region (http://www.bhoomigeoportal-nbsslup.in/). This river runs up to a total length of 113 km, through undulating terrain with forest cover and rural areas. The average annual rainfall of this river basin is 889–1600 mm and most of which is received during the south-west monsoon season (Jain et al. 2007). This river acts as a boundary for 3 terrestrial PAs, namely, Chaprala Wildlife Sanctuary (WS) and Pranhita WS in Maharashtra and Pranahita WS in Telangana (Fig. 1).

LULC mapping of the riparian zone

To understand the riparian landscape of river Pranhita, LULC mapping was performed for 6 buffer width zones, viz., 0–200 m, 0–500 m, 0–1000 m, 0–1500 m, 0–3000 m, and 0–5000 m, along the sides of the river using Sentinel 2A Multispectral Imager-Level 1C imagery for post-monsoon season-2020 (Table S1). The satellite imageries were classified into 6 LULC classes such as (1) agriculture, irrigated cropland and fallow land; (2) forest vegetation; (3) shrubland, shrubs, bushes, and scrub; (4) bare land, exposed lands devoid of vegetation; (5) waterbody, open water resources like the stream, reservoir, and tanks; and (6) built-up, settlement and roads, based on specific Digital Number (DN) of each pixel. The training sets with a minimum of 100 pixels were generated for each class from different regions (study area) to account for the regional variability (Mishra et al. 2019). The supervised classification was then carried out in ERDAS Imagine-2016, using the maximum likelihood classifier (MLC), which applies a discriminant function based on training set pixel class mean vector and covariance to assign pixel to the LULC class with the highest probability (Ahmad and Quegan 2012; Sisodia et al. 2014).

The classified images were validated through field visits conducted during July–December 2021, and high-resolution images are available in the Google Earth™ platform. The classification results produced an overall accuracy of 95.39% with the kappa value of 0.9269. Furthermore, the LULC datasets were used to generate a floodplain habitat base map of river and stressor input data for habitat risk modelling.
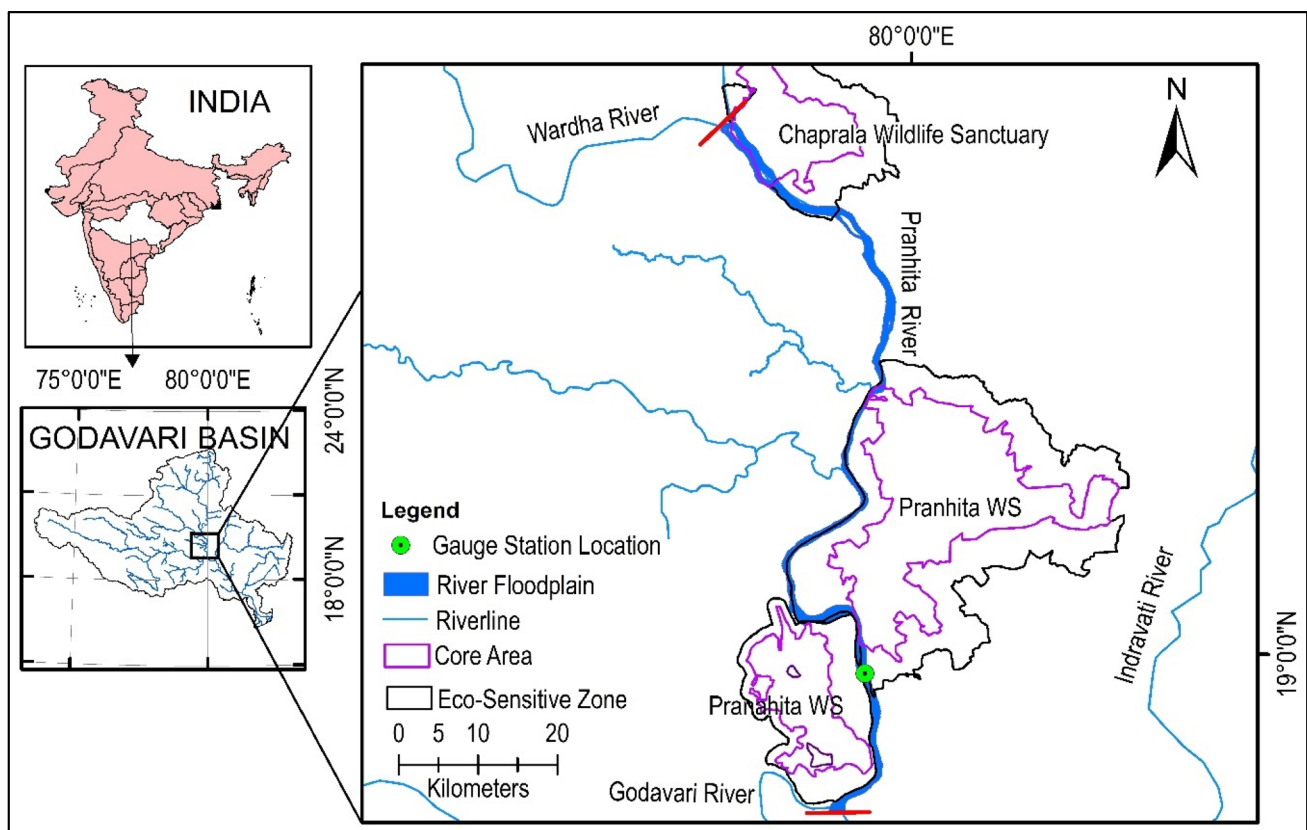
Fig. 1 Map showing the study area: Pranhita River in Godavari Basin, India

Habitat Risk Assessment (HRA) model description

The InVEST Habitat Risk Assessment (HRA) model was developed by Natural Capital Project (https://naturalcapitalproject.stanford.edu/software/invest) to quantify the cumulative risk posed to a particular habitat by anthropogenic activities at current and future scenarios (Guerry et al. 2012; Sharp et al. 2020). This model calculates cumulative habitat risks by incorporating stressor information on exposure and consequence. *Exposure* is the degree to which a habitat experiences stress due to anthropogenic activity which is assessed in terms of its spatiotemporal overlap and intensity. The *consequence* reflects the habitat-specific responses to such anthropogenic stressors, which integrate the *sensitivity* and *resilience* of the habitat to resist an exposed stressor (Arkema et al. 2014; Sharp et al. 2020). The schematic diagram illustrating the overall flow of methodology followed for assessing the anthropogenic risk to the riverine ecosystem is given in Fig. 2.

Anthropogenic stressors: data generation

A total of 9 stressors were identified under river use, hydro-morphology, catchment pollution, and biological stressor category for habitat risk modelling of river Pranhita based on the field survey observations (June 2019–December 2021) and review of literature (McPherson et al. 2008; Gu and Liu 2010; Vörösmarty et al. 2010; Best 2019). The spatial input data of these stressors were obtained from primary data collected through extensive fieldwork, remote sensing approach, and web-based sources. The spatial input datasets were prepared using ArcMap 10.8.1 software (ESRI). The details for the selection of each stressor are given in Table 1 along with the methodology for data generation.

River use stressor

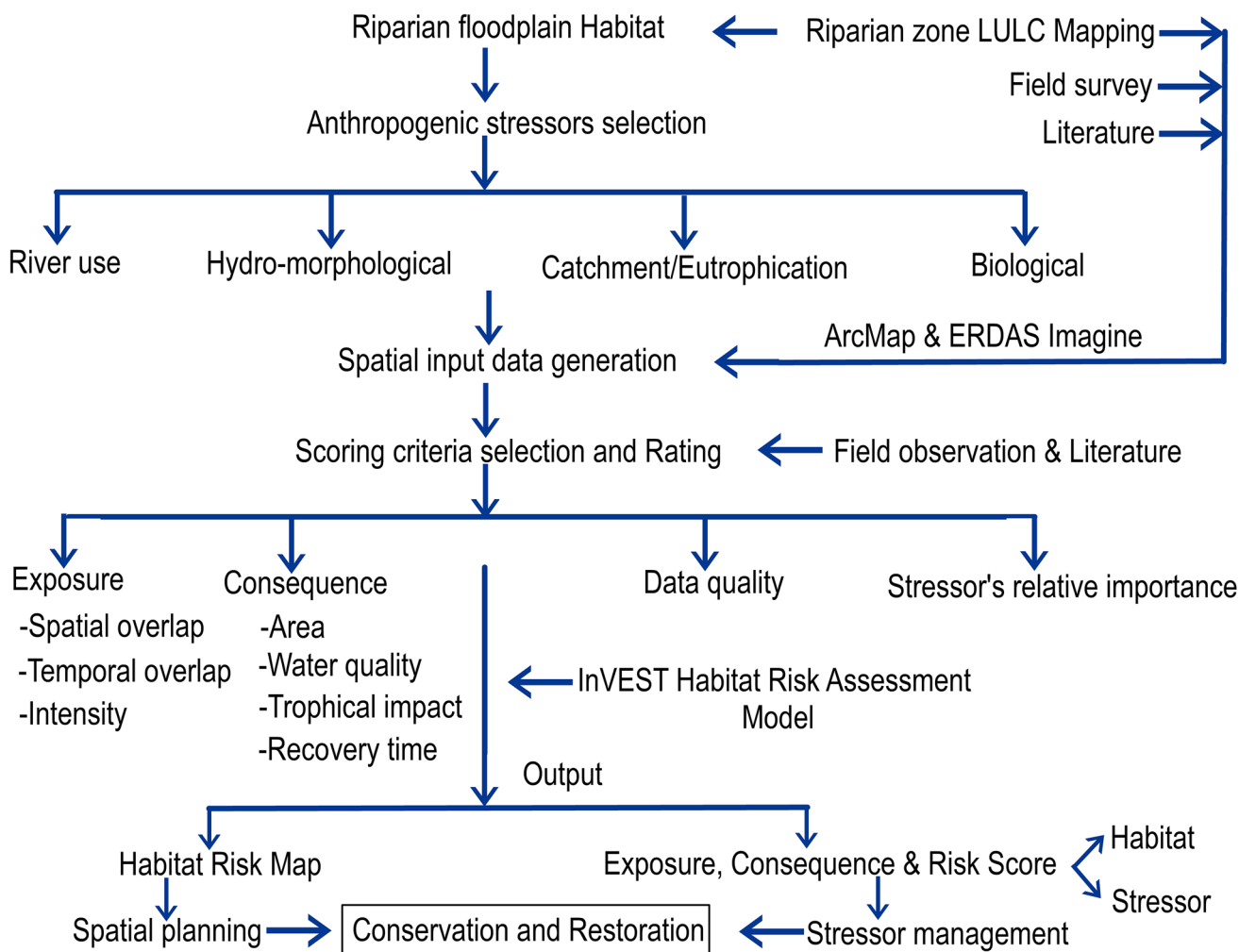**Fishing** The predominant livelihood activity undertaken in the river Pranhita was through the small-scale artisanal

Fig. 2 Schematic diagram illustrating the flow of material, methods, and analysis followed

(subsistence and local trade-oriented) fisheries, which was ascertained through key informant interview and field survey. To represent fishing as a stressor to riverine habitat, a GIS data layer in the form of polygon shapefile of fishing grounds was demarcated through geographical data collected using the handheld Global Positioning System (eTrex Vista HCx, Garmin, USA) and high-resolution imageries available in Google Earth™ platform.

Hydro-morphological stressors

Riverbank structures The spatial data of man-made structures, viz., bridges, erosion control structures, and bathing ghat, located on the riverbed or along the river bank (up to 50 m extent) were delineated in the form of polygon shapefile (high-resolution imageries available in Google Earth™) and verified during the field surveys.

Impact of dam/barrages To account for the impact of dam/barrages located in the upstream of river Pranhita, the vulnerable areas for habitat fragmentation were aggregated based on fortnightly Normalized Difference Water Index (NDWI) map (15 datasets) of post-monsoon and pre-monsoon for water year: 2020–2021 (Kantharajan et al. 2022a). The intensity of the impact of upstream dam/barrages was fixed based on the relative value of water present during the above-mentioned period as no impact, water present in all 15 datasets; low (1), water present in 11–14 datasets; medium (2), water present in 5–10 datasets; and high (3), water present only in 0–4 datasets.

Riparian zone modification To account for the influence of riparian zone modification on riverine habitats, land use class pixels were aggregated up to 200-m buffer width (Xu et al. 2021) and recoded with intensity values assuming the magnitude of its impact as follows: cropland, medium impact (2), and bare land/built-up, high impact (3).

Sand mining The location details of sand ghat identified for mining in Pranhita riverbed during 2018–2019 (Anon 2020) were used, and a downstream buffer distance shapefile of 5000 m was created using analysis tools in ArcMap platform considering its impact along river flow direction (McPherson et al. 2008).

Catchment-associated eutrophication stressors

Point source: sewage and solid waste To represent sewage and solid waste-based surface water pollution, the population density (number/ha) of the villages bordering the river bank on both sides was taken as a proxy (Shen et al. 2017; Milledge et al. 2018). The village shapefiles were delineated

using Bhuvan Geo-portal (https://bhuvan.nrsc.gov.in/), and the spatial data layer was prepared using 2011 Census of India data (https://censusindia.gov.in/). The intensity of this stressor was classified based on its relative population density calculated through quartile method as low (1), < 1.4; medium (2), < 1.4 to < 2.48; and high (3), > 2.48.

Non-point source: sediment loading The data on total suspended solids (TSS) recorded during the field survey-July 2021 (Kantharajan et al. 2022b) and by Central Water Commission ((CWC 2019) at Tekra Water Quality Monitoring Station (WQMS)) along the river Pranhita during the monsoon season was used to represent the sediment loading from its catchment area. The values were interpolated on base shapefile of Pranhita River habitat using "kriging interpolation" method (Murphy et al. 2010; Nagalakshmi et al. 2016). Bilotta and Brazier (2008) reported various effects of suspended solid concentration on salmonids ranging from 20 (altered foraging activity) to 207,000 ppm (100% juvenile mortality). In the present study, the intensity of the stressor was classified as low (1) 42–162, medium (2) 162–295, and high (3) 295–496, based on its relative value (ppm) (Sharp et al. 2020).

Non-point source: nutrient inflow The nutrient inflow to riverine habitat was represented by ammonia-N (nitrogen) and phosphate (phosphorus) value recorded during field survey (Kantharajan et al. 2022b) and by CWC (2019) at Tekra WQMS along the river Pranhita during the monsoon season. These data points were interpolated using "kriging interpolation" method, and the intensity rating for ammonia was fixed based on the critical limit in water as "high" (> 0.4 ppm) and "low" (0.2–0.4 ppm), considering its lethal and sublethal effect to fish species, respectively (Bhatnagar and Devi 2013). Likewise, for good plankton production, the suggested phosphate concentration in pond water is 1 ppm. Hence, a value above this level was considered "high" (Bhatnagar and Devi 2013).

Biological stressor

Exotic fish species The information on exotic fish species distribution was collated through field survey and represented in the form of its associated fishing area polygon to account for its localized impact.

Risk assessment criteria rating and model execution

The present study considers 3 exposure criteria, viz., spatial overlap, temporal overlap, and stressor intensity, and 4 consequence criteria which reflect the habitat sensitivity, viz., change in area, change in water quality and

Table 1 Identified stressors for assessing the habitat risk associated with the river Pranhita, Godavari Basin, India

Sl. no	Stressor	Source	Data type	Justification
I. River use stressors				
1	Fishing	Primary data: filed survey	Polygon	The susceptibility of stream fishes to overfishing in subsistence fisheries reported in Peninsular India by Raghavan et al. (2011) and Keskar et al. (2017)
II. Hydro-morphological stressors				
2	Riverbank modification	Field survey observation, Google Earth, and remote sensing data	Polygon	Man-made structures along the river bank alter its morphology and ecological processes including water quality and fish diversity (Dutta et al. 2018)
3	Impact of dam/barrages: river fragmentation	Remote sensing data results sourced from Kantharajan et al. (2022a)	Polygon	The dams/barrages in the upstream locations are the major reason for the downstream habitat fragmentation and reduced connectivity and water spread (Ward and Stanford 1995) and impacts the aquatic biota (Khedkar et al. 2014)
4	Riparian zone modification	Present study	Polygon	Riparian vegetation enhances bank stability by moderating stream banks and strengthening soil; closely related to water quality or streams (Jontos 2004)
5	Sand mining	Gadchiroli District Survey Report (Anon 2020)	Vector	The riverbed mining disturbs the physical habitat and indirectly influences the channel modification process and affects the water quality (Koehnken et al. 2020)
III. Catchment-associated eutrophication stressors				
6	Point source: sewage and solid waste (proxy: population density)	Census data-2011	Polygon	The population density is one among the most influencing socioeconomic factors determining river impairment (Kim et al. 2021) and is closely associated with the surface water pollution as observed in the Ganga River catchment, India (Milledge et al. 2018) and Songhua River Basin, China (Shen et al. 2017)
7	Non-point source: sediment loading	Primary data: water quality assessment (Kantharajan et al. 2022b) and CWC (2019)	Raster–500 m	The sediment inflow affects the benthic riverine habitats through deposition and clogging fish gills and also hampers the primary productivity (Robertson et al. 2006)
8	Non-point source: nutrient inflow (ammonia-N and phosphate)	Primary data: water quality assessment (Kantharajan et al. 2022b) and CWC (2020)	Raster–500 m	The inflow of nutrients from the catchment area affects the aquatic ecosystem structure and functions through eutrophication (Smith et al. 1999)
IV. Biological stressors				
9	Exotic fish species	Primary data	Polygon	These species compete with native fish species for food and habitat and disturb key ecological functions (Joshi et al. 2021)

trophic impact, and time needed for the recovery of habitat after the stressor exposure for the risk assessment. The criteria "change in water quality" and "trophic impact" (Wyatt et al. 2017) were included to evaluate the degree of water quality alteration and the effect on life forms by a stressor. The index scores of the mentioned criteria ranged between 1 and 3 (lowest-highest) (Table 2), which was determined by field survey observations and relevant literatures. The HRA model calculates a cumulative risk score of a habitat considering the spatial overlapping with stressors; hence, the buffer distance was assigned to non-overlapping stressors, i.e., riverbank structures (200 m), riparian zone modification (500 m), and population density (1000 m). The Pranhita River habitats were assigned a score of 2 for "recovery time," a habitat-based resilience attributes considering the time required for the lotic ecosystem to recover from any intense stressors (Verdonschot et al. 2013).

Additionally, uncertainties in scoring exposure and consequence criteria of the stressors and quality of the datasets were eliminated by assigning a data quality (DQ) score as 1, 2, and 3 for best, adequate, and limited datasets used for the assessment, respectively. The highest DQ score (1) was assigned for datasets and scores based on primary field surveys and literature from the study area. The scoring of exposure and consequence criteria of the stressors, based on the datasets of the outside study area with moderate statistical relationship, was assigned a medium DQ score (2) while the scoring based on limited datasets was assigned a low DQ score (3). Likewise, each criterion was weighted based on its relative importance in determining the impact of the stressor to habitat as most important (1), moderately important (2), and least important (3) (Sharp et al. 2020).

The resolution of analysis for the model run was fixed as "200 m" to reflect the input data resolution of the habitat and stressor which ranged between 30 and 500 m. The present study applied "Euclidean" risk equation distance for habitat-stressor risk plots (Arkema et al. 2014; Sharp et al. 2020), where mean exposure and the mean consequence score are located on different axes. Furthermore, "linear" decay equation was chosen, where the effects of a stressor in the specified buffer area decrease linearly with distance from the stressor. Additionally, the river habitats bordering terrestrial PAs located along the river Pranhita were given as area of interest (AoI) vector shapefile during the model run to get the summary statistics of exposure, consequence, and risk values averaged within each zone.

## Results

LULC mapping of Pranhita riparian zone

The LULC map of Pranhita riparian landscape prepared using Sentinel 2 imagery of post-monsoon season-2020 is depicted in Fig. 3. The map shows that the dominant LULC classes were agriculture, forest, and shrubland though the proportion of area (%) varied between the river bank and buffer width zone (Fig. 4). For instance, the proportion of agricultural land to total area varied between 38 and 61% along the left bank, while it ranged between 27 and 45% on the right bank. Similarly, the proportion of forest area reported on the left bank was 8–36%, whereas it ranged between 21 and 48% along the right bank. The built-up area contributed to 3–3.6% of the total area along the river banks (Table S2).

The proportion of LULC classes (%) at different buffer widths revealed distinct patterns in the Pranhita riparian zone. The proportion (%) of agriculture and shrubland was found to decrease with the increase in buffer width, while forest and built-up land showed an increasing trend with the buffer width. The highest proportion of agricultural land was

Table 2 Exposure and consequence criteria and its rating framework used in the Habitat Risk Assessment model

Sl. no	Criteria	Low (1)	Medium (2)	High (3)
Exposure criteria				
1	Spatial overlap	Yes	-	-
2	Temporal overlap	Habitat and stressor co-occur for 0–4 months/year	Habitat and stressor co-occur for 4–8 months/year	Habitat and stressor co-occur for 8–12 months/year
3	Intensity	Low	Medium	High
Consequence criteria				
4	Change in area*	Low loss in area (0–20%)	Medium loss in area (20–50%)	High loss in area (50–100%)
5	Change in water quality*	Little to no change	Partial/multiple parameters	Entire ecosystem impairment
6	Trophic impact*	Single species/trophic level	Multiple species/trophic level	Entire ecosystem
7	Recovery time#	Less than 1 year	1–10 years	More than 10 years

* Is a sensitivity attribute of consequence criteria; # is a resilience attribute of consequence criteria pertaining to habitat
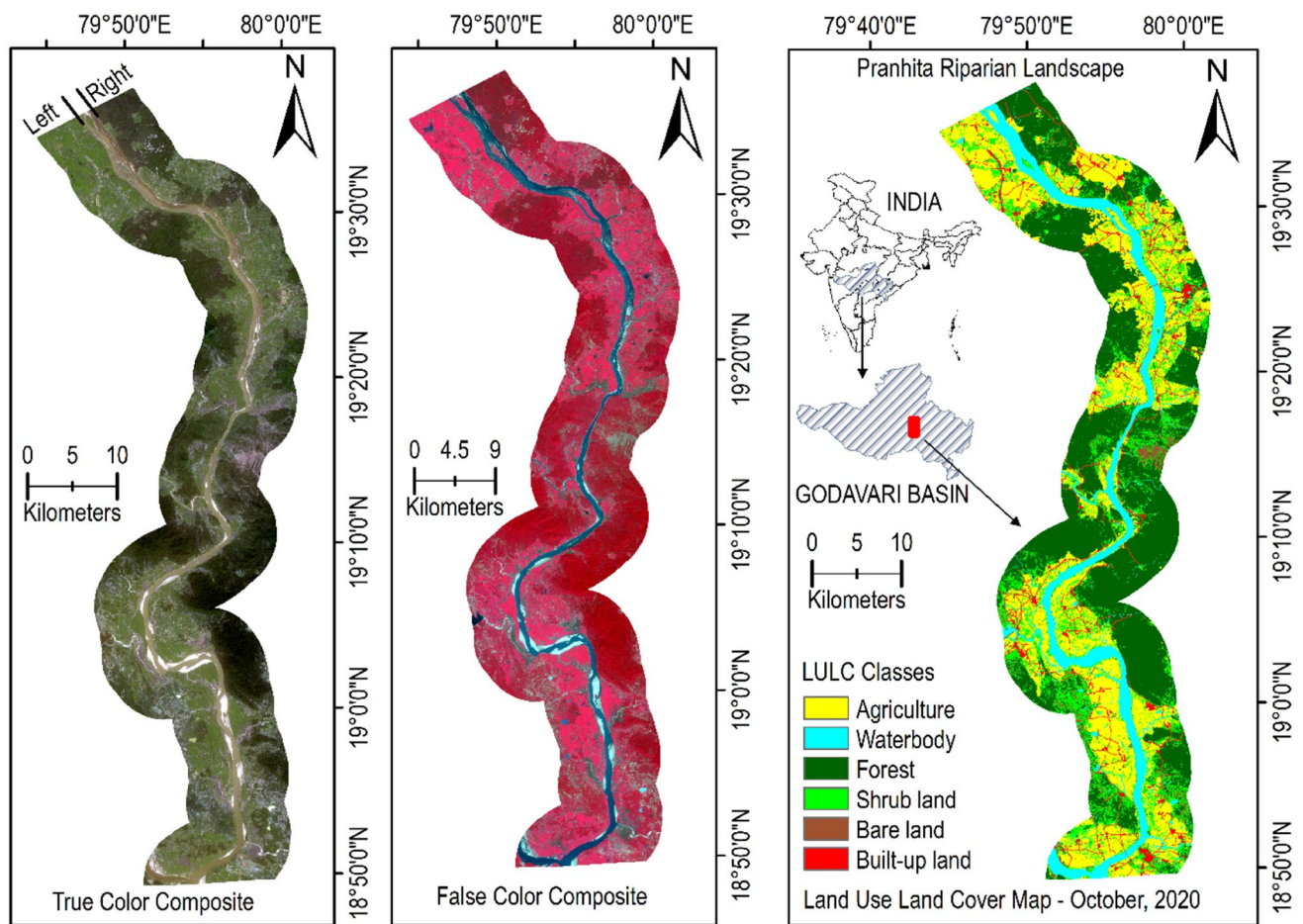
Fig. 3 True color satellite image, false color satellite image, and classified land use land cover map of Pranhita riparian habitat (October, 2020)

reported in the 500-m buffer width zone along both sides, i.e., left, 61%, and right, 45% of the river.

Anthropogenic stressors and criteria rating

Exposure criteria

The spatial extent of overlapping and non-overlapping stressors in the Pranhita riverine ecosystem is depicted in Fig. 5. For all the selected stressors, a uniform rating of 1 was assigned for its overlapping pixels (Table 3). The ecological risks of non-overlapping stressors, viz., river bank and riparian zone modification and population density of bordering villages (proxy for solid waste disposal) on the Pranhita riverine ecosystem were included in the present study, considering the influence zone of 200–1000 m.

The field survey observation and interaction with fishermen revealed that the fishing is carried out the entire year (except peak flood days) particularly during the post-monsoon and pre-monsoon season, when reduced flow results in fragmentation

of floodplain habitat. In addition to fishing, the temporal impact of other stressors, viz., population, riverbank and riparian zone modification, and presence of exotic fish species on the riverine ecosystem were accounted for the entire year and assigned a score of 3 (Table 3). A temporal overlap score of 2 (8 months/ year) was assigned for major catchment-associated non-point source eutrophication stressors, i.e., sediment and nutrient inflow (NH_3-N and P) to account for their seasonal influence.

The intensity rating for most of the stressors was generated as a spatially explicit dataset and classified into three categories: low (1), medium (2), and high (3) (Fig. 5). The intensity of nutrient inflow, i.e., NH_3-N and P, was decided based on the optimum value for fishes, while it was based on relative values recorded for sediment loading and quartile based for population density stressor. The results revealed that Pranhita riverine ecosystem was exposed predominantly to high-intensity fragmentation, while the degree of intensity was medium–high for sediment loading and nutrient inflow (NH_3-N) stressors. For other stressors, viz., fishing, riverbank structure, and exotic species, a "low" intensity score (1) was assigned.
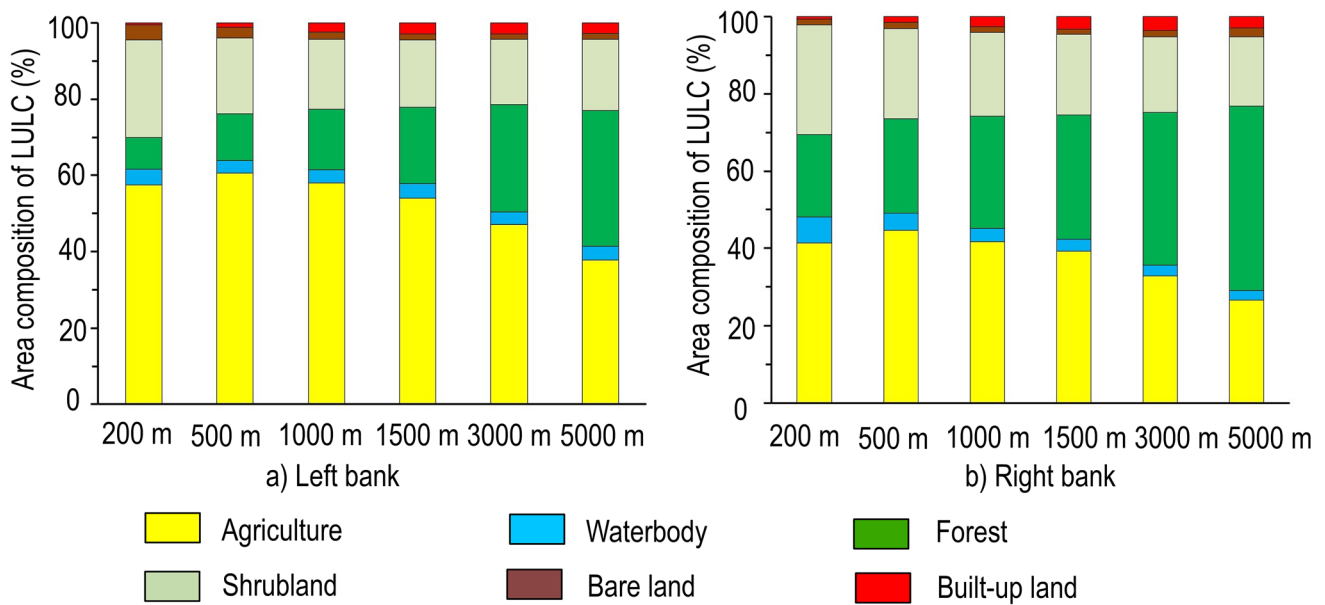
Fig. 4 Variations in LULC area composition (%) proportion at buffer scales from 0-200 to 0-5000 m along **a** left and **b** right bank of river Pranhita, India

Consequence criteria

Among the stressors listed for the risk assessment, the impact of upstream barrage on habitat change by area has been assigned a high score (3) followed by riparian zone modification and sediment loading (2). The remaining stressors were assigned a low score (1). Likewise, the negative consequences of anthropogenic activities, viz., riparian zone modification, sewage and solid waste dumping, sand mining, sediment loading, and nutrient runoff, on water quality deterioration of the Pranhita riverine ecosystem were assigned a score of 3. The trophic impact of the identified stressors is concerned; a score of 2–3 was assigned considering their effect on multiple fish species and biota belonging to different trophic levels in the ecological niche.
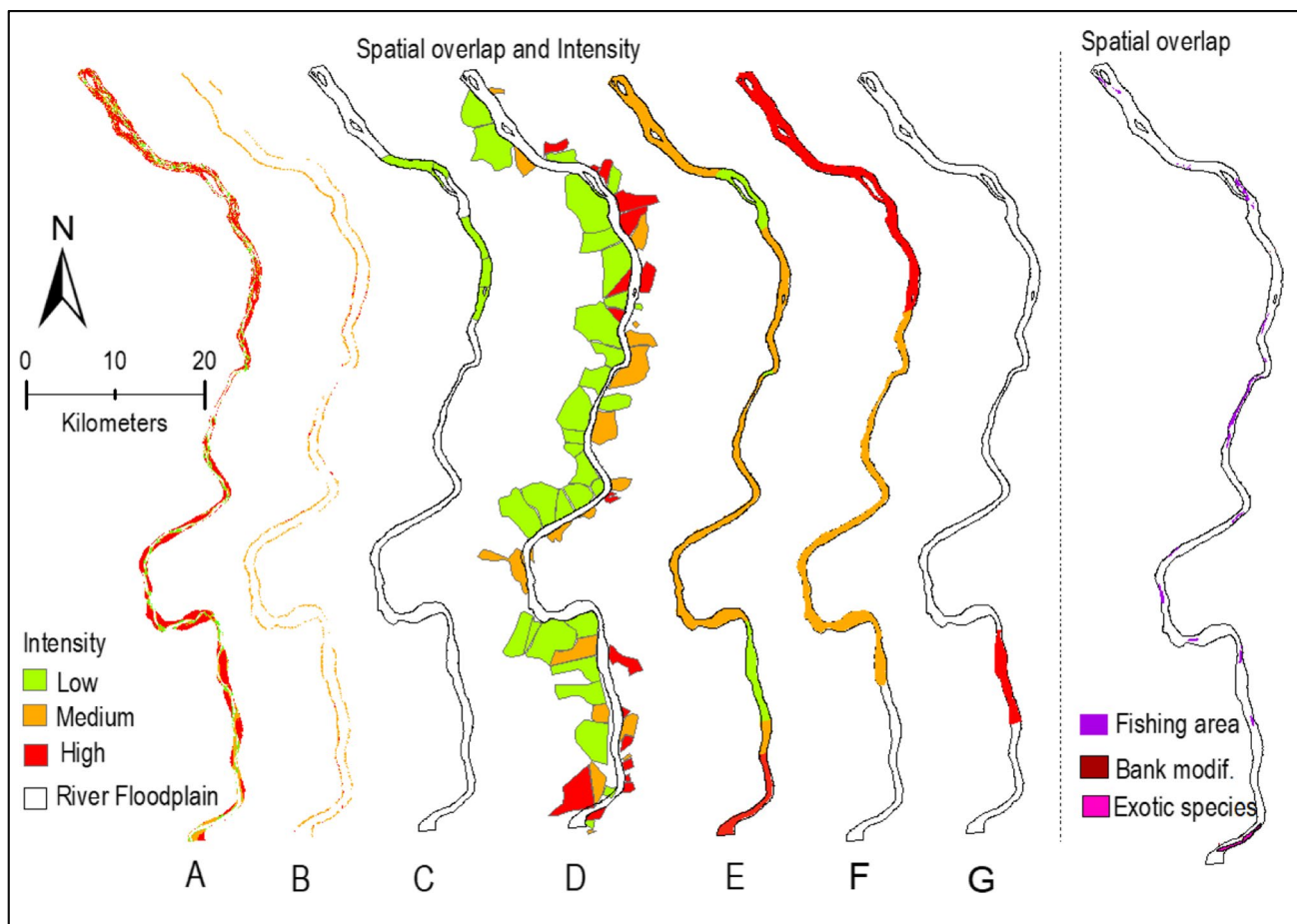
Risk assessment

The extent of exposure to various anthropogenic stressors and their negative consequences on Pranhita riverine ecosystem is depicted in the risk plot (Fig. 6) based on HRA model results. The overall mean exposure, consequence, and risk score of Pranhita riverine ecosystem to anthropogenic activities were 0.78, 1.01, and 0.65, respectively. The anthropogenic stressors which have the highest exposure on Pranhita riverine ecosystem include sediment loading and river fragmentation followed by

inflow of nitrogen (NH_3-N), population density, and riparian zone modification. In terms of consequences, threats such as sediment loading, inflow of nitrogen (NH_3-N), and river fragmentation were observed to be the topmost factors (Table 4). These threats also received the highest value for overall risk score (> 1.25) in Pranhita riverine ecosystem.

The spatial distribution of ecological risks due to anthropogenic activities in Pranhita riverine ecosystem and proportion of area (%) under various risk zone categories are depicted in Figs. 7 and 8, respectively. This study defines a particular grid into "high," "medium," and "low" risk when the cumulative risk scores are 66–100%, 33–66%, and 0–33% of the total possible cumulative risk score, respectively. The modelled results portrayed that majority of the Pranhita habitats (95.86% of the total area) fell under low-risk zone, while 4.14% area was under medium-risk zone.

In terms of individual stressor-habitat specific ecological risk, predominant area (> 90%) of Pranhita riverine ecosystem was classified under low-risk zone for anthropogenic threats, viz., mining, riverbank modification, exotic species, and phosphate inflow. Most of the habitats were classified under a high-risk zone (29–75%) due to stressors such as sediment loading, fragmentation due to the upstream barrage, and nitrogen inflow (NH_3-N). Fishing, as an anthropogenic activity considered in the present study, revealed that 87% of the Pranhita riverine habitat is under low-risk, while 13% is under high-risk zone.

Fig. 5 Spatial overlap and intensity of the selected stressors along the river Pranhita, India, included in the habitat risk assessment. Note: A, river fragmentation; B, riparian zone modification; C, sand mining; D, population density; E, sediment loading; F, nutrient inflow (NH₃-N); G, nutrient inflow (phosphate)

Table 3 Rating of anthropogenic stressors–exposure and consequence criteria for Habitat Risk Assessment modelling of river Pranhita, Godavari Basin, India

Sl. no	Stressors	Exposure criteria	Consequence criteria		
		Temporal overlap	Change in area	Change in water quality	Trophic impact
1	Fishing	3	1	1	2
2	River bank structure	3	1	1	2
3	Impact of barrage	2	3	2	3
4	Riparian zone modification	3	2	3	3
5	Sand mining	2	1	2	2
6	Sewage and solid waste (population density)	3	1	3	3
7	Sediment loading	2	2	3	3
8	Nutrient inflow (ammonia-N)	2	1	3	3
9	Nutrient inflow (phosphate)	2	1	3	3
10	Exotic fish species	3	1	1	3

Rating score: 1, low; 2, medium; and 3, high

Fig. 6 Risk plot showing the consequence and exposure scores for selected stressors in Pranhita riverine ecosystem
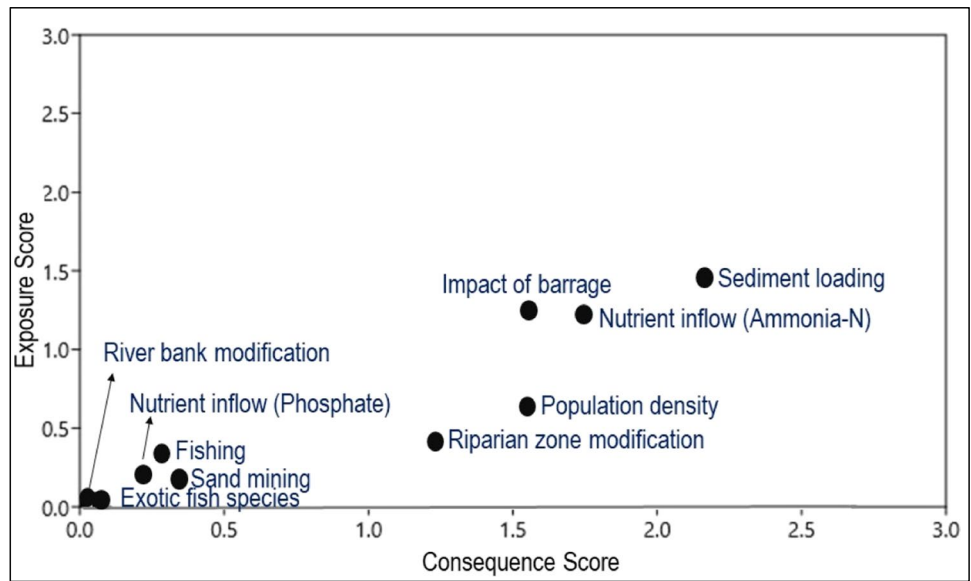
Table 4 Exposure, consequence, and total risk scores developed from the HRA model for river Pranhita, Godavari Basin, India

Sl. no		Exposure	Consequence	Risk
Stressor				
1	Fishing	0.34	0.27	0.27
2	River bank modification	0.02	0.01	0.02
3	Impact of barrage	1.26	1.54	1.25
4	Riparian zone modification	0.42	1.22	0.57
5	Sand mining	0.18	0.34	0.17
6	Sewage and solid waste (population density)	0.64	1.54	0.92
7	Sediment loading	1.46	2.15	1.68
8	Nutrient inflow (ammonia-N)	1.23	1.74	1.38
9	Nutrient inflow (phosphate)	0.21	0.21	0.20
10	Exotic fish species	0.04	0.05	0.03
Habitat sub-region: Pranhita riverine ecosystem				
1	Over all riverine habitat	0.78	1.01	0.65
2	Riverine habitat bordering protected areas (PAs)	0.88	1.14	0.71
3	Unprotected habitats	0.94	1.19	0.76

Spatial conservation measures vis a vis ecological habitat risk

The ecological risk of defined habitat areas based on their existing spatial conservation measures, i.e., wildlife sanctuaries, in Pranhita riverine ecosystem was assessed for the selected anthropogenic stressors in terms of exposure, consequence, and risk scores. The results showed that the mean values of these scores were higher for habitats located along the unprotected river stretch ($E=0.94$; $C=1.19$; $R=0.76$) compared to those bordering the protected area (PA) ($E=0.88$; $C=1.14$; $R=0.71$)

(Table 4). Furthermore, the proportion of habitats under low-risk zone was higher for PA category (96%) compared to unprotected river stretch (92%) (Table S4).

Discussion

LULC mapping of Pranhita riparian zone

The riparian zone supports the river ecosystem functions through bank stabilization, water quality maintenance by

Fig. 7 Radar chart depicting the % of riverine habitat area under different risk categories for selected stressors in Pranhita riverine ecosystem
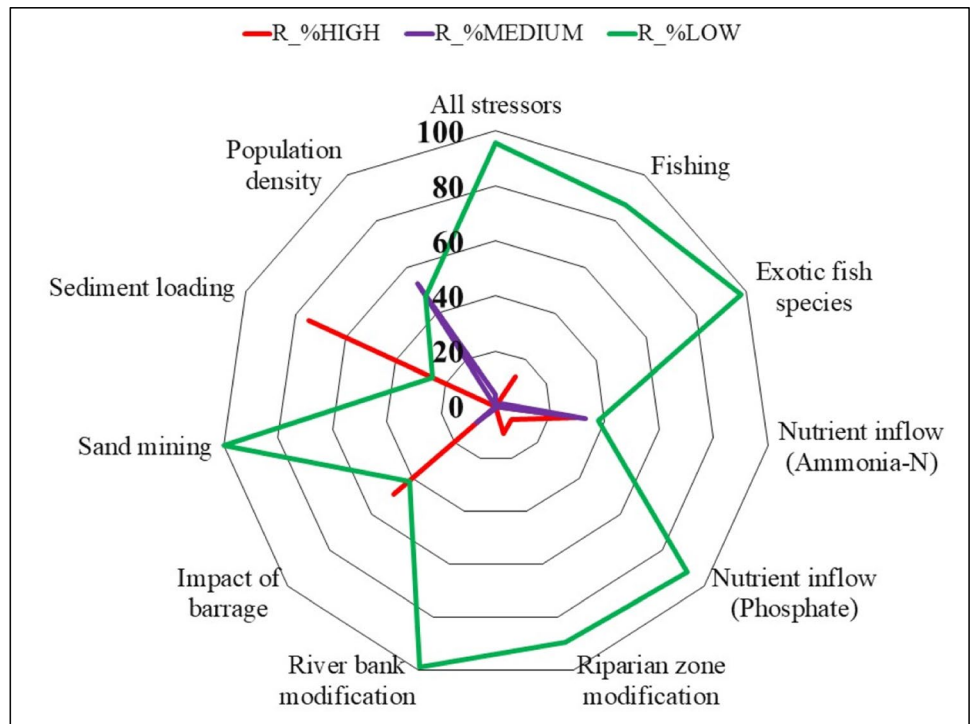
Fig. 8 Ecological risk due to anthropogenic activities in Pranhita riverine ecosystem
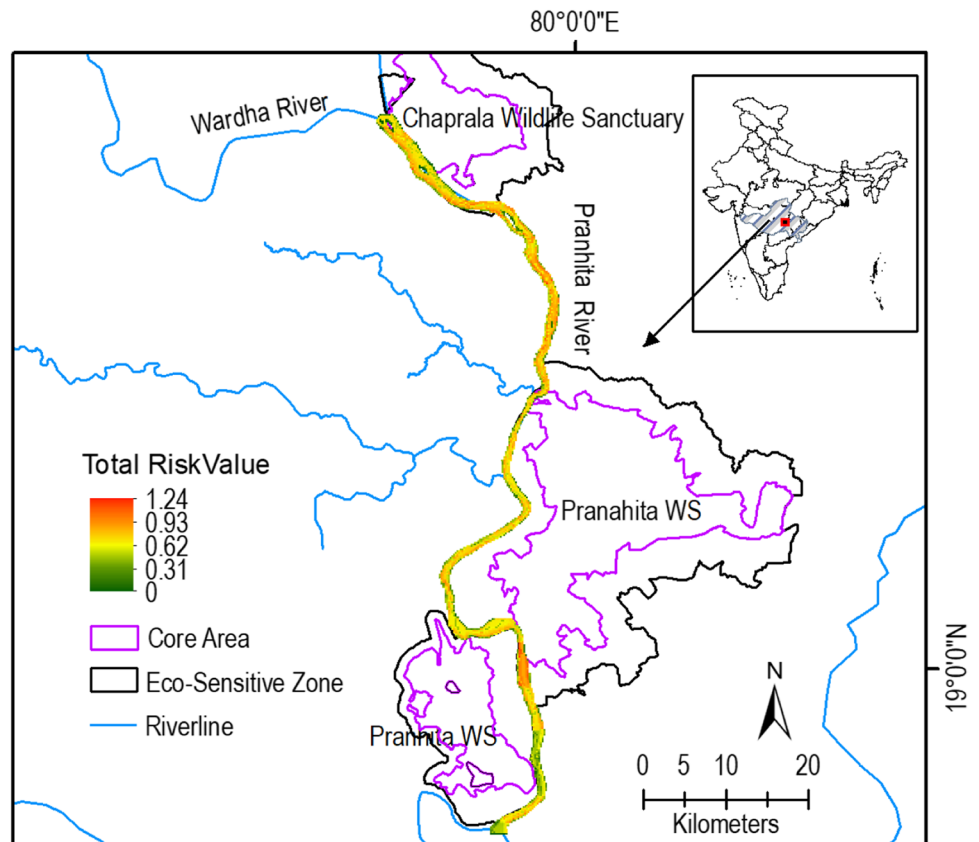
sediment/nutrient retention, and sustenance biodiversity (Décamps et al. 2009; Dosskey et al. 2010). The information on land use pattern of riparian area is essential for planning restoration and management activities to maintain the optimum water quality and habitat conditions to sustain the aquatic biodiversity (Gu and Liu 2010; Choudhary et al. 2021). The LULC map generated in the present study (Fig. 4) and field survey observations indicated that apart from agricultural land, selected section of the river Pranhita is bordered by contiguous and dense vegetation on either or both sides of the river banks, which are notified as wildlife sanctuaries under the Wildlife Protection Act 1972 by Govt. of India. The comparatively low proportion of area under agriculture and a high proportion of area under forest land cover reported along the right bank of river Pranhita (than the left bank) are attributed to the presence of two wildlife sanctuaries (Chaprala WS and Pranhita WS) (Fig. 1) in its riparian zone.

The dominant LULC classes in 0–200-m buffer zone along the river Pranhita are agriculture and shrubland, and the proportion of these classes decreases with an increase in riparian buffer width. This is attributed to the diverse LULC of Pranhita riparian landscape, where the spread of rich forest vegetation is evident along the river. On the contrary, Gu and Liu (2010) reported a linear relationship between an increase in cultivated land and buffer width in an agricultural landscape. A similar study conducted along the river Ganga near Varanasi, for a buffer width of 1000 m along a 20-km stretch, revealed settlement and agriculture as the major land use classes with negligible riparian vegetation (Sharma et al. 2016). Generally, LULC change and difference in its proportion between the river banks and buffer width category are attributed to the topography, soil characteristics, and socio-economic and demographic characteristics of a region (Bansal et al. 2016; Birhane et al. 2019).

Xu et al. (2021) reported the positive effect of forest vegetation of 200-m buffer width on the removal of non-point source pollutants, viz., total phosphorus, total nitrogen, and NH_3-N, while agricultural land along the riparian zone was significantly correlated to an elevated level of such components in Huangpu River, China. The agricultural land located in Pranhita riparian landscape is generally a rainfed system, which poses a huge risk to the aquatic biota, especially during the monsoon season through sediment export and nutrient runoff. The intensive or poorly managed agricultural land in undulating terrain amplify the inflow of agriculture inputs such as nutrients, pesticides, organic matter, and eroded soil to river (Chattopadhyay et al. 2005; Sharma et al. 2016).

Anthropogenic stressors and criteria rating

The InVEST HRA model is widely used to assess the impact of ecological stressors associated with anthropogenic activities in coastal and terrestrial habitats around the world. The application of this model for any ecosystem is linked with the use of input source data of land use and anthropogenic activities (Zhai et al. 2020). This study assessed the ecological risk of Pranhita riverine ecosystem due to anthropogenically induced hydro-morphological alterations, eutrophication, and exotic fish species based on their spatial data availability. The dependable data on inland fishery are not readily available, both in developing and developed countries, due to the artisanal nature of fisheries, lack of infrastructure capacity, remote and widely spread nature of resources, and seasonal influence (Bartley et al. 2015; Cooke et al. 2016). The spatial input data used for the modelling work were obtained through primary field surveys, remote sensing applications, and published literature/reports pertaining to the study area.

Exposure criteria

This study assigned a buffer distance for non-overlapping stressors, viz., riverbank modification, riparian zone, and population density, considering their "zones of influence." The buffer distance value is fixed based on the stressor type, ecosystem under study, and local conditions. For instance, Tussadiah et al. (2021) assigned a stressor buffer width of 1000 m (cruise line) to 10,000 m (sea level rise) for the risk assessment of coastal ecosystems, such as mangrove, seagrass, and coral reefs, in East Nusa Tenggara, Indonesia. The man-made structures on the river bank are known to impact the water quality and associated local biodiversity (Dutta et al. 2018) and thus are likely to contribute to the habitat modification of river Pranhita as observed during the field survey (Fig. S1).

This study considers year-round exposure for stressors, viz., population, riverbank and riparian zone modification, fishing, and exotic fish species. The river Pranhita is the largest tributary of river Godavari in terms of flow and upstream catchment area (MoWR 2014). The river is known to be in spate during the monsoon months, and hence most of the anthropogenic activities (sand mining, impact of dam) are limited to a non-monsoon season, though fishing is carried out around the year. On the other hand, the inflow of sediments and nutrients from the catchment area is reported to be higher during the monsoon months, as 99.96% of the sediment export (1969–2019) in river Pranhita (at Tekra WQMS) was reported to occur during the monsoon months, i.e., June–November (CWC 2020). Hence, the temporal exposure of catchment area stressors, such as the inflow of sediments and nutrients, was considered for 8 months which includes monsoon and post-monsoon season.

The majority of the floodplain habitats in Pranhita riverine ecosystem are exposed to high-intensity fragmentation. A recent study on habitat fragmentation assessment of river

Pranhita (Kantharajan et al. 2022a) based on satellite imageries and gauge data measurements revealed the contiguous flow of water only through narrow channels and the formation of isolated water pools during non-monsoon months. Fishing in river Pranhita is classified as a "low"-intensity activity due to its subsistence nature and fishermen using passive fishing gears and fishing crafts without any mechanical propulsion. However, constant fishing efforts are being implied over a particular area (along the village); hence, a plausible impact on biotic integrity (Raghavan et al. 2011; Keskar et al. 2017) is expected, especially during the non-monsoon season accompanied with habitat fragmentation. Habitat fragmentation can divide large populations into smaller subpopulations and subsequently regulate their level and patterns of genetic diversity (Poff and Schmidt 2016). These resultant smaller sub-populations exhibit reduced genetic diversity (Junker et al. 2012), which enhances the risk of losing rare alleles from the populations. Such fragmented populations are believed to exhibit higher levels of genetic differentiation (Habib et al. 2012) in order to adapt to environment challenges and are more prone to sudden expansion along with the emergence of low frequency new haplotypes.

A correlation investigation of habitat fragmentation and population genetic diversity of European grayling (*Thymallus thymallus*) in south-eastern Norway (Van-Leeuwen et al. 2017) was done by genotyping and radio-tracking of adult fish throughout the river section. The findings confirmed the evidences of declining genetic diversity due to major migration barriers that restrict the gene flow. Similarly, considerable effects of habitat fragmentation on genetic diversity levels were also observed in *Silonia silondia* (Mandal et al. 2021), *Chitala chitala* (Dutta et al. 2020), and *Tor tor* (Sah et al. 2021).

Consequence criteria

Two among the four consequence criteria, viz., change in water quality and trophic impact, are specifically included in the study to assess the impact of selected anthropogenic stressors on Pranhita riverine ecosystem and its aquatic biota. Among the stressors listed, the impact of upstream barrages, riparian zone modification, and subsequent sediment loading causes habitat loss (change in area) by reducing the actual water spread, channel width, and depth of water pools (Ward and Stanford 1995; Robertson et al. 2006; Kantharajan et al. 2020a).

The present study evaluated the habitat risk of river Pranhita on its aquatic biota. The stressors selected had consequences on water quality and therefore its impact on fish species at various trophic levels was also inevitable (Table 3). Hence, a maximum score was assigned for most of the stressors, such as riparian zone modification, sewage, solid waste dumping, sand mining, sediment loading, and nutrient runoff.

Risk assessment

The riverine ecosystem is extremely dynamic and its interactions with catchment stressors are convoluted at a spatiotemporal scale with fluctuating physical and chemical setting, which impacts the associated biota (Yamani et al. 2011). Hence, impact assessment of land use/catchment stressors on the riverine ecosystem is essential for conservation and restoration planning (Gupta et al. 2014; Lemm et al. 2021). The lower overall risk score (0.64) and occurrence of the major portion of Pranhita habitat under the "low" risk zone attributed to the negligible influence of anthropogenic activities on riverine ecology, presence of intact forest vegetation (Fig. 4), and contiguous water flow (Kantharajan et al. 2022a). These findings are also supported by the recent fish diversity assessment in the Pranhita River, wherein they reported rich fish diversity compared to other adjacent tributaries (Kantharajan et al. 2022b). Furthermore, the low overall score reported may also be due to the dilution of spatial averaging of exposure and consequence criteria score of stressors (Arkema et al. 2014; Studwell et al. 2021).

Regarding individual stressors, a relatively higher risk score (> 1) was estimated for stressors such as sediment loading, inflow of nitrogen, habitat fragmentation, and their influence on a sizeable portion of Pranhita riverine habitat (29–75% of the total area under high-risk zone), which indicated the mounting threat from catchment activities. The high-risk zone habitats may experience habitat degradation and ecosystem health deterioration which may lead to the loss in ecosystem services (Ghehi et al. 2020). The non-point source pollutants including sediment and nutrients are widespread. Their management requires effective source control through public participation (Weiner and Matthews 2003). The sediment export from agriculture and degraded landscape causes damage to fish species and deterioration in water and stream bed quality (Robertson et al. 2006; Mateo-Sagasta et al. 2017). Likewise, the inflow of nitrogen-based nutrients to the riverine ecosystem may lead to eutrophication and subsequently loss to native resources (Sarkar and Islam 2021). Though the influence of sand mining, fishing, and phosphate inflow was reported to be very low in the Pranhita riverine ecosystem, regular monitoring of their impact at the micro-scale level is needed for sustainability.

Arkema et al. (2014) emphasized that the HRA model results can be used in consultation with stakeholders and resource managers to reduce the spatial extent of high-risk activities overlapping with sensitive habitats and also to reduce its consequences by moderating stressor intensity. For instance, the impact of sediment loading on riverine habitats of Pranhita can be reduced by deploying effective

agronomic measures and management practices in its catchment area (Rejani et al. 2016). Likewise, maintaining the intactness of forest cover and riparian vegetation in the catchment reduces the impact of non-point source pollutants on riverine ecosystem health (Jontos 2004; Xu et al. 2019). Furthermore, awareness of waste management and proper sewage treatment in villages with high-intensity exposure will help in moderating the impact of point source pollution.

Applications in spatial prioritization of riverine ecosystem

The sub-regional level assessment of riverine habitats according to their existing spatial conservation measures revealed comparatively higher anthropogenic risk to river reaches bordering the unprotected area ($R = 0.76$) as compared to PAs ($R = 0.71$), though the difference in risk value was reported to be low. The LULC map of the Pranhita riparian zone revealed the presence of intact riparian vegetation (Fig. 3) and minimal direct influence of anthropogenic stressors on river reaches bordering the terrestrial PAs. This is also supported by the rich fish diversity reported in the river stretch bordering the PAs over the unprotected area in Pranhita River (Kantharajan et al. 2022b). Gupta et al. (2015) reported the effectiveness of terrestrial PAs and managed river reaches over unprotected sites in conserving fish species against anthropogenic stressors, viz., over-fishing, river fragmentation, and pollution, in the Shivalik ranges, India. However, the contribution of terrestrial PAs to safeguard freshwater biodiversity depends on their location and the appropriate management measures undertaken (Acreman et al. 2020).

Furthermore, the targeted management of representative river zones in each river basin yields an overall positive benefit to the entire ecosystem (Gupta et al. 2014). The river basin-wise habitat risk assessment through InVEST HRA model will aid in the process of science-driven conservation planning and certainly improve the efficacy of proposed environmental management schemes. Additionally, the incorporation of fish diversity at spatial scales will help resource managers and policymakers to prioritize the areas for conservation (low risk; high diversity) and restoration (high risk; high species diversity). The HRA model results are spatially explicit (Arkema et al. 2014; Huang et al. 2020), which provide a risk-based classification of habitats and ranking of the stressors based on their exposure and consequence (Zhang et al. 2022), which will facilitate the basin scale approach to river ecosystem management.

Limitations

A few stressors listed in the present study, viz., fishing and agriculture, are contributing to food, livelihood, and other benefits to the local communities residing along the river.

However, this study acknowledges that activities that are associated with the ecosystem benefits are expected to affect the structure and function of the same habitats upon which their livelihood depend (Wyatt et al. 2017). The calculated risk score is relative (Sharp et al. 2020), which does not reflect the influence of past activities (Arkema et al. 2014), and low-risk score does not necessarily mean that the particular area is free from anthropogenic activities. Furthermore, the indirect effects and synergistic interaction between the stressors selected are not captured by this model (Wyatt et al. 2017; Tussadiah et al. 2021).

Conclusion

This study demonstrates the potential use of InVEST Habitat Risk Assessment model to assess the ecological risk to riverine habitats due to anthropogenic activities, which will be useful for conservation and restoration planning. The methodology framework followed for spatial ecological risk assessment of riverine ecosystem can be replicable in other inland waterbodies in India and elsewhere. The study results conclude the overall healthy state of the ecosystem with initial indications of the mounting threats due to the influence of sediment export, nutrient runoff, and habitat fragmentation. Thus, the model results help in the moderating of anthropogenic activities, which pose a high ecological risk and provide a scope for developing an appropriate mitigation measure. Furthermore, using this model, the role of spatial conservation measures and the efficacy of various environmental management schemes on ecosystem health and species conservation can be assessed. The case study demonstrated in a tropical river Pranhita in Godavari Basin proves its potential for utilization in conservation and restoration planning at regional and national scales to ensure global sustainable development.

Author contribution GK: methodology, formal analysis, investigation, visualization, writing-original draft; PMG: methodology, validation, writing-review and editing; RC: methodology, writing-review and

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Acreman M, Hughes KA, Arthington AH, Tickner D, Dueñas MA (2020) Protected areas and freshwater biodiversity: a novel systematic review distils eight lessons for effective conservation. Conserv Lett 13:e12684. https://doi.org/10.1111/conl.12684

Ahmad A, Quegan S (2012) Analysis of maximum likelihood classification on multispectral data. Appl Math Sci 6:6425–6436

Amarasinghe U, Chaudhuri A, Collins AS, Deb G, Patranabis S (2015) Evolving provenance in the Proterozoic Pranhita-Godavari Basin, India. Geosci Front 6(3):453–463. https://doi.org/10.1016/j.gsf.2014.03.009

Anon (2020) District survey report for sand mining including other minor mineral. Prepared by District Mining Officer, Gadchiroli District, Maharashtra

Arkema KK, Verutes G, Bernhardt JR, Clarke C, Rosado S, Canto M, ... De Zegher J (2014) Assessing habitat risk from human activities to inform coastal and marine spatial planning: a demonstration in Belize. Environ Res Lett 9:114016. https://doi.org/10.1088/1748-9326/9/11/114016

Atkore VM, Sivakumar K, Johnsingh AJT (2011) Patterns of diversity and conservation status of freshwater fishes in the tributaries of River Ramganga in the Shiwaliks of the Western Himalaya. Curr Sci 100:731–736

Bansal S, Srivastav SK, Roy PS, Krishnamurthy YVN (2016) 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 14:773–792

Bartley DM, De Graaf GJ, Valbo-Jørgensen J, Marmulla G (2015) Inland capture fisheries: status and data issues. Fish Manag Ecol 22:71–77. https://doi.org/10.1111/fme.12104

Best J (2019) Anthropogenic stresses on the world's big rivers. Nat Geosci 12:7–21. https://doi.org/10.1038/s41561-018-0262-x

Bhatnagar A, Devi P (2013) Water quality guidelines for the management of pond fish culture. Int J Environ Sci 3:1980–2009

Bilotta GS, Brazier RE (2008) Understanding the influence of suspended solids on water quality and aquatic biota. Water Res 42:2849–2861. https://doi.org/10.1016/j.watres.2008.03.018

Birhane E, Ashfare H, Fenta AA, Hishe H, Gebremedhin MA, Solomon N (2019) Land use land cover changes along topographic gradients in Hugumburda national forest priority area, Northern Ethiopia. Remote Sens Appl: Soc Environ 13:61–68. https://doi.org/10.1016/j.rsase.2018.10.017

Cabral P, Levrel H, Schoenn J, Thiébaut E, Le Mao P, Mongruel R, Daures F (2015) Marine habitats ecosystem service potential: a vulnerability approach in the Normand-Breton (Saint Malo) Gulf, France. Ecosyst Serv 16:306–318. https://doi.org/10.1016/j.ecoser.2014.09.007

Caro C, Marques JC, Cunha PP, Teixeira Z (2020) Ecosystem services as a resilience descriptor in habitat risk assessment using the InVEST model. Ecol Indic 115:106426. https://doi.org/10.1016/j.ecolind.2020.106426

Chattopadhyay S, Rani LA, Sangeetha PV (2005) Water quality variations as linked to landuse pattern: a case study in Chalakudy river basin, Kerala. Curr Sci 89:2163–2169

Choudhary A, Deval K, Joshi PK (2021) Study of habitat quality assessment using geospatial techniques in Keoladeo National Park, India. Environ Sci Pollut Res 28(11):14105–14114. https://doi.org/10.1007/s11356-020-11666-3

Cooke SJ, Allison EH, Beard TD, Arlinghaus R, Arthington AH, Bartley DM, ... Welcomme RL (2016) On the sustainability of inland fisheries: finding a future for the forgotten. Ambio 45:753–764. https://doi.org/10.1007/s13280-016-0787-4

Culhane F, Teixeira H, Nogueira AJ, Borgwardt F, Trauner D, Lillebø A, ... Robinson LA (2019) Risk to the supply of ecosystem services across aquatic ecosystems. Sci Total Environ 660:611–621. https://doi.org/10.1016/j.scitotenv.2018.12.346

CWC (2019) Godavari basin–suspended sediment year book: June 2018–May 2019. Central Water Commission-Godavari Basin, Hyderabad, Ministry of Water Resources, River Development and Ganga Rejuvenation, Govt. of India

CWC (2020) Godavari basin–water quality year book: June 2018–May 2019. Central Water Commission-Godavari Basin, Hyderabad, Ministry of Water Resources, River Development and Ganga Rejuvenation, Govt. of India.

Das BK, Bhakta D, Kumar L, Sangeetha MN, Koushlesh SK, Sajina AM, Roshith CM, Samanta S (2021a) Ichthyofaunal diversity of the major Indian rivers: a review. J Inland Fish Soc India 53:22–35

Das BK, Ray A, Johnson C, Verma SK, Alam A, Baitha R, ... Sarkar UK (2021b) The present status of ichthyofaunal diversity of river Ganga India: synthesis of present v/s past. Acta Ecol Sin. https://doi.org/10.1016/j.chnaes.2021.10.008

Décamps H, Naiman RJ, McClain ME (2009) Riparian zones. In: Likens GE (ed) The encyclopaedia of inland waters. Cary Institute of Ecosystem Studies Millbrook, New York. https://doi.org/10.1016/B978-012370626-3.00053-3

Dosskey MG, Vidon P, Gurwick NP, Allan CJ, Duval TP, Lowrance R (2010) The role of riparian vegetation in protecting and improving chemical water quality in streams. J Am Water Resour Assoc 46:261–277. https://doi.org/10.1111/j.1752-1688.2010.00419.x

Duggan JM, Eichelberger BA, Ma S, Lawler JJ, Ziv G (2015) Informing management of rare species with an approach combining scenario modeling and spatially explicit risk assessment. Ecosyst Health Sustain 1:1–18. https://doi.org/10.1890/EHS14-0009.1

Dutta N, Singh RK, Pathak A, Mohindra V, Mandal S, Kaur G, Lal KK (2020) Mitochondrial DNA markers reveal genetic connectivity among populations of Osteoglossiform fish *Chitala chitala*. Mol Biol Rep 47:8579–8592. https://doi.org/10.1007/s11033-020-05901-w

Dutta V, Sharma U, Iqbal K, Kumar R, Pathak AK (2018) Impact of river channelization and riverfront development on fluvial habitat: evidence from Gomti River, a tributary of Ganges, India. Environ Sustain 1:167–184. https://doi.org/10.1007/s42398-018-0016-0

Ekka A, Pande S, Jiang Y, der Zaag PV (2020) Anthropogenic modifications and river ecosystem services: a landscape perspective. Water 12:2706. https://doi.org/10.3390/w12102706

Elliff CI, Kikuchi RKP (2017) Ecosystem services provided by coral reefs in a Southwestern Atlantic Archipelago. Ocean Coast Manag 136:49–55. https://doi.org/10.1016/j.ocecoaman.2016.11.021

Gu F, Liu W (2010) Applications of remote sensing and GIS to the assessment of riparian zones for environmental restoration in agricultural watersheds. Geo Spat Inf Sci 13:263–268. https://doi.org/10.1007/s11806-010-0368-9

Ghehi NK, MalekMohammadi B, Jafari H (2020) Integrating habitat risk assessment and connectivity analysis in ranking habitat patches for conservation in protected areas. J Nat Conserv 56:125867. https://doi.org/10.1016/j.jnc.2020.125867

Guerry AD, Ruckelshaus MH, Arkema KK, Bernhardt JR, Guannel G, Kim CK, ... Spencer J (2012) Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning. Int J Biodivers Sci Ecosyst Serv Manag 8:107–121. https://doi.org/10.1080/21513732.2011.647835

Gupta N, Raghavan R, Sivakumar K, Mathur VB (2014) Freshwater fish safe zones: a prospective conservation strategy for river ecosystems in India. Curr Sci 107:949–950

Gupta N, Sivakumar K, Mathur VB, Chadwick MA (2015) Terrestrial protected areas and managed reaches conserve threatened freshwater fish in Uttarakhand, India. Parks 21:89–101

Habib M, Lakra WS, Mohindra LKK, Punia P, Singh RK, Khan AA (2012) Assessment of ATPase 8 and 6 mtDNA sequences in genetic diversity studies of *Channa marulius* (Channidae: Perciformes). Proc Natl Acad Sci India Sect B Biol Sci 82:497–501. https://doi.org/10.1007/s40011-012-0061-x

Healy M., Secchi S (2016) A comparative analysis of ecosystem service valuation decision support tools for wetland restoration. Association of State Wetland Managers, Windham, Maine

Huang C, Zhang C, Liu Q, Wang Z, Li H, Liu G (2020) Land reclamation and risk assessment in the coastal zone of China from 2000 to 2010. Reg Stud Mar Sci 39:101422. https://doi.org/10.1016/j.rsma.2020.101422

Jain SK, Agarwal PK, Singh VP (2007) Krishna and Godavari basins, In Hydrology and water resources of India. Water Science and Technology Library. Springer, Dordrecht. https://doi.org/10.1007/1-4020-5180-8_14

Jontos R (2004) Vegetative buffers for water quality protection: an introduction and guidance document. Connecticut Association of Wetland Scientists White Paper on Vegetative Buffers: Draft version-1

Joshi KD, Basheer VS, Kumar A, Srivastava SM, Sahu V, Lal KK (2021) Alien fish species in open waters of India: appearance, establishment and impacts. Indian J Anim Sci 91:167–173

Junker J, Peter A, Wagner CE, Mwaiko S, Germann B, Seehausen O, Keller I (2012) River fragmentation increases localized population genetic structure and enhances asymmetry of dispersal in bullhead (*Cottus gobio*). Conserv Genet 13:545–556. https://doi.org/10.1007/s10592-011-0306-x

Kantharajan G, Anand A, Krishnan P, Singh RK, Kumar K, Yadav AK, Mohindra V, Shukla SP, Lal KK (2022a) Applications of Sentinel-2 satellite data for spatio-temporal mapping of deep pools for monitoring the riverine connectivity and assessment of ecological dynamics: a case from Godavari, a tropical river in India (2016–2021). Environ Monit Assess 194(8):1–21. https://doi.org/10.1007/s10661-022-10089-6

Kantharajan G, Yadav AK, Chandran R, Singh RK, Mohindra V, Krishnan P, Kumar K, Shukla SP, Lal KK (2022b) Impact of terrestrial protected areas on the fish diversity and habitat quality: evidence from tropical river Pranhita, India. J Nat Conserv 68:126187. https://doi.org/10.1016/j.jnc.2022.126187

Keskar A, Raghavan R, Kumkar P, Padhye A, Dahanukar N (2017) Assessing the sustainability of subsistence fisheries of small indigenous fish species: fishing mortality and exploitation of hill stream loaches in India. Aquat Living Resour 30:13. https://doi.org/10.1051/alr/2016036

Khedkar GD, Lutzky S, Rathod S, Kalyankar A, David L (2014) A dual role of dams in fragmentation and support of fish diversity across the Godavari River basin in India. Ecohydrology 7(6):1560–1573. https://doi.org/10.1002/eco.1470

Kim S, Lee SW, Park SR, Shin Y, An K (2021) Socioeconomic risks and their impacts on ecological river health in South Korea: an application of the analytic hierarchy process. Sustainability 13:6287. https://doi.org/10.3390/su13116287

Koehnken L, Rintoul MS, Goichot M, Tickner D, Loftus AC, Acreman MC (2020) Impacts of riverine sand mining on freshwater ecosystems: a review of the scientific evidence and guidance for future research. River Res Appl 36:362–370. https://doi.org/10.1002/rra.3586

Koneti S, Sunkara SL, Roy PS (2018) Hydrological modeling with respect to impact of land-use and land-cover change on the runoff dynamics in Godavari River Basin using the HEC-HMS model. ISPRS Int J Geo-Inf 7:206. https://doi.org/10.3390/ijgi7060206

Lal KK, Dwivedi AK, Singh RK, Mohindra V, Chandra S, Gupta BK, Dhawan S, Jena J (2016) A new Bagrid catfish species, *Rita bakalu* (Siluriformes: Bagridae), from the Godavari River basin. India Hydrobiologia 790(1):67–81. https://doi.org/10.1007/s10750-016-3019-9

Lemm JU, Venohr M, Globevnik L, Stefanidis K, Panagopoulos Y, van Gils J, ... Birk S (2021) Multiple stressors determine river ecological status at the European scale: towards an integrated understanding of river status deterioration. Glob Chang Biol 27(9):1962–1975. https://doi.org/10.1111/gcb.15504

Lisa M, Natural Capital Project (2021) Database of publications using InVEST and other Natural Capital Project software – May 2021. Stanford Digital Repository. Available at: https://purl.stanford.edu/bb284rg5424. Accessed 14 Nov 2022

Mandal S, Singh A, Sah P, Singh RK, Kumar R, Lal KK, Mohindra V (2021) Genetic and morphological assessment of a vulnerable large catfish, *Silonia silondia* (Hamilton, 1822), in natural populations from India. J Fish Biol 98:430–444. https://doi.org/10.1111/jfb.14587

Mateo-Sagasta J, Zadeh SM, Turral H, Burke J (2017) Water pollution from agriculture: a global review. Executive summary. Published by the Food and Agriculture Organization of the United Nations, Rome and the International Water Management Institute, Colombo

McPherson M, Schill S, Raber G, John K, Zenny N, Thurlow K, Sutton AH (2008) GIS-based modeling of environmental risk surfaces (ERS) for conservation planning in Jamaica. J Conservat Plann 4:60–89

Milledge DG, Gurjar SK, Bunce JT, Tare V, Sinha R, Carbonneau PE (2018) Population density controls on microbial pollution across the Ganga catchment. Water Res 128:82–91. https://doi.org/10.1016/j.watres.2017.10.033

Mishra PK, Rai A, Rai SC (2019) Land use and land cover change detection using geospatial techniques in the Sikkim Himalaya, India. Egypt J Remote Sens Space Sci 23:133–143. https://doi.org/10.1016/j.ejrs.2019.02.001

MoWR (2014) Godavari basin. Retrieved from http://india-wris.nrsc.gov.in/Publications/BasinReports/Godavari%20Basin.pdf. Accessed 18 Apr 2021

Murkute YA, Joshi SP (2014) Neoproterozoic siliciclastic sedimentation around Kampa-Tenpa area, Pranhita Godavari Graben (PGG), Central India: facies analysis, petrography and depositional environment. J Geol Soc India 83:423–432. https://doi.org/10.1007/s12594-014-0059-5

Murphy RR, Curriero FC, Ball WP (2010) Comparison of spatial interpolation methods for water quality evaluation in the Chesapeake Bay. J Environ Eng 136:160–171. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000121

Nagalakshmi R, Prasanna K, Chandar PS (2016) Water quality analysis using GIS interpolation method in Serthalaikadu Lagoon, East coast of India. Rasayan J Chem 9:634–640

Opperman JJ, Orr S, Baleta H, Dailey M, Garrick D, Goichot M, McCoy A, Morgan A, Turley L, Vermeulen A (2018) Valuing rivers: how the diverse benefits of healthy rivers underpin economies. World Wildlife Fund

Poff NL, Schmidt JC (2016) How dams can go with the flow. Science 353:1099–1100. https://doi.org/10.1126/science.aah4926

Pownkumar V, Ananthan PS, Ekka A, Qureshi NW, Velumani T (2022) Fisheries as ecosystem services: a case study of the Cauvery river basin, India. Front Environ Sci 10:892012. https://doi.org/10.3389/fenvs.2022.892012

Prasad KK, Younus M, Srinivasulu C (2020) Occurrence of Corica soborna Hamilton, 1822 (Clupeiformes: Clupeidae) in the Godavari basin, India. J Threat Taxa 12:17361–17365. https://doi.org/10.11609/jott.5983.12.17.17361-17365

Raghavan R, Ali A, Dahanukar N, Rosser A (2011) Is the Deccan Mahseer, *Tor khudree* (Sykes, 1839) (Pisces: Cyprinidae) fishery in the Western Ghats hotspot sustainable? A participatory approach to stock assessment. Fish Res 110:29–38. https://doi.org/10.1016/j.fishres.2011.03.008

Raheja N (2009) GIS-based software applications for environmental risk management. Geospatial World. https://www.geospatialworld.net/article/gis-based-software-applications-for-environmental-risk-management/. Accessed 13 Mar 2022

Rejani R, Rao KV, Osman M, Rao S, Reddy KS, Chary GR, Samuel J (2016) Spatial and temporal estimation of soil loss for the sustainable management of a wet semi-arid watershed cluster. Environ Monit Assess 188:1–16. https://doi.org/10.1007/s10661-016-5143-4

Robertson MJ, Scruton DA, Gregory RS, Clarke KD (2006) Effect of suspended sediment on freshwater fish and fish habitat. Canadian Technical Report of Fisheries and Aquatic Sciences-2644.

Sah P, Mandal S, Singh RK, Dutta N, Sah R, Pathak A, Mohindra V (2021) Development of novel microsatellite marker panel in threatened tetraploid mahseer, *Tor tor* (Hamilton 1822) for insights into its genetic diversity and population structure. Meta Gene 28:100880. https://doi.org/10.1016/j.mgene.2021.100880

Sarkar UK, Pathak AK, Tyagi LK, Srivastava SM, Singh SP, Dubey VK (2013) Biodiversity of freshwater fish of a protected river in India: comparison with unprotected habitat. Rev Biol Trop 61:161–172. https://doi.org/10.15517/rbt.v61i1.10942

Sarkar B, Islam A (2021) Assessing poverty and livelihood vulnerability of the fishing communities in the context of pollution of the Churni River, India. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-17719-5

Sharma S, Roy A, Agrawal M (2016) Spatial variations in water quality of river Ganga with respect to land uses in Varanasi. Environ Sci Pollut Res 23:21872–21882. https://doi.org/10.1007/s11356-016-7411-9

Sharp R, Douglass J, Wolny S, Arkema K, Bernhardt J et al (2020) InVEST user's guide - V3.10.0. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund

Sheikh SR (2014) Studies on ichthyofaunal diversity of Pranhita River, Sironcha, Dist: Gadchiroli, Maharashtra, India. Int J Fish Aquat Stud 1:144–147

Shen Y, Cao H, Tang M, Deng H (2017) The human threat to river ecosystems at the watershed scale: an ecological security assessment

of the Songhua River Basin, Northeast China. Water 9:219. https://doi.org/10.3390/w9030219

Sisodia PS, Tiwari V, Kumar A (2014) Analysis of supervised maximum likelihood classification for remote sensing image. In International conference on recent advances and innovations in engineering (ICRAIE-2014), pp.1–4. https://doi.org/10.1109/ICRAIE.2014.6909319

Smith VH, Tilman GD, Nekola JC (1999) Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environ Pollut 100:179–196. https://doi.org/10.1016/S0269-7491(99)00091-3

Studwell A, Hines E, Nur N, Jahncke J (2021) Using habitat risk assessment to assess disturbance from maritime activities to inform seabird conservation in a coastal marine ecosystem. Ocean Coast Manag 199:105431. https://doi.org/10.1016/j.ocecoaman.2020.105431

Tussadiah A, Sujiwo AS, Andesta I, Daeli W (2021) Assessment of coastal ecosystem services and its condition for policy management plan in East Nusa Tenggara, Indonesia. Reg Stud Mar Sci 47:101941. https://doi.org/10.1016/j.rsma.2021.101941

UN-Water (2016) Water and sanitation interlinkages across the 2030 agenda for sustainable development. UN Water: Geneva, Switzerland. Available: https://www.unwater.org/app/uploads/2016/08/Water-and-Sanitation-Interlinkages.pdf. Accessed 17 Feb 2022

Van-Leeuwen CHA, Dokk T, Haugen TO, Kiffney PM, Museth J (2017) Small larvae in large rivers: observations on downstream movement of European grayling *Thymallus thymallus* during early life stages. J Fish Biol 90:2412–2424. https://doi.org/10.1111/jfb.13326

Vass KK, Das MK, Tyagi RK, Katiha PK, Samanta S, Srivastava NP, Bhattacharjya BK, Suresh VR, Pathak V, Chandra G, Debnath D, Gopal B (2011) Strategies for sustainable fisheries in the Indian part of the Ganga Brahmaputra River Basins. Int J Ecol Environ Sci 37:157–218

Verdonschot PFM, Spears BM, Feld CK, Brucet S, Keizer-Vlek H, Borja A, Johnson RK (2013) A comparative review of recovery processes in rivers, lakes, estuarine and coastal waters. Hydrobiologia 704:453–474. https://doi.org/10.1007/s10750-012-1294-7

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, ... Davies PM (2010) Global threats to human water security and river biodiversity. Nature 467(7315):555–561. https://doi.org/10.1038/nature09440

Ward JV, Stanford JA (1995) Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regul River 11:105–119. https://doi.org/10.1002/rrr.3450110109

Weiner RF, Matthews RA (2003) Nonpoint Source Water Pollution. In: Weiner, RF, Matthews RA (eds) Environmental Engineering, 4th edn. Butterworth-Heinemann, pp 233–249. https://doi.org/10.1016/B978-075067294-8/50011-7

Wyatt KH, Griffin R, Guerry AD, Ruckelshaus M, Fogarty M, Arkema KK (2017) Habitat risk assessment for regional ocean planning in the US Northeast and Mid-Atlantic. PLoS ONE 12:e0188776. https://doi.org/10.1371/journal.pone.0188776

Xu H, Cai C, Du H, Guo Y (2021) Responses of water quality to land use in riparian buffers: a case study of Huangpu River, China. GeoJournal 86:1657–1669. https://doi.org/10.1007/s10708-020-10150-2

Xu K, Mo L, Zhang Z, Zhang M (2019) Water quantity and quality changes from forested riparian buffer in Beijing. Environ Sci Pollut Res 26(28):29041–29051. https://doi.org/10.1007/s11356-019-05991-5

Yamani M, Goorabi A, Dowlati J (2011) The effect of human activities on river bank stability (case study). Am J Environ Sci 7:244. https://doi.org/10.3844/ajessp.2011.244.247

Zeng C, Wen Y, Liu X, Yu J, Jin B, Li D (2022) Impact of anthropogenic activities on changes of ichthyofauna in the middle and lower Xiang River. Aquac Fish 7(6):693–702. https://doi.org/10.1016/j.aaf.2021.06.007

Zhai T, Wang J, Fang Y, Qin Y, Huang L, Chen Y (2020) Assessing ecological risks caused by human activities in rapid urbanization coastal areas: towards an integrated approach to determining key areas of terrestrial-oceanic ecosystems preservation and restoration. Sci Total Environ 708:135153. https://doi.org/10.1016/j.scitotenv.2019.135153

Zhang J, Cao Y, Ding F, Wu J, Chang IS (2022) Regional ecological security pattern construction based on ecological barriers: a case study of the Bohai Bay terrestrial ecosystem. Sustainability 14(9):5384

Web references

https://naturalcapitalproject.stanford.edu/software/invest

Google earth. https://earth.google.com/web/

https://sdgs.un.org/goals/goal6. Accessed 17 Feb 2022

Census of India, 2011. https://censusindia.gov.in/. Accessed 11 Feb 2022

Inland Fisheries in India https://dof.gov.in/inland-fisheries. Accessed 9 Mar 2022

https://scihub.copernicus.eu/

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