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Linking ecological characteristics with fish diversity, assemblage patterns and feeding guilds, and GIS applications along the temporal and spatial gradients in a large subtropical reservoir, India, for sustainable management

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ABSTRACT

The objective of the investigation was to explore the abundance, composition, and diversity patterns of the fish fauna along the temporal and spatial scale and study the influence of environmental parameters on the fish assemblage in the Rihand reservoir, a large sub-tropical Indian reservoir in India. On the temporal scale, the highest abundance was recorded in the summer season and the lowest in the monsoon season, while on the spatial scale, the highest abundance was recorded from the riverine and the minimum from the lacustrine zone. The highest species richness and diversity were recorded from the riverine zone followed by the transitional and lacustrine zones, respectively. The analysis of the variance of fish abundance revealed insignificant differences between the riverine and the transitional zones. The trophic guild analysis indicated the dominance of carnivores. The output of canonical correspondence analysis depicted the significant influence of the physico-chemical traits on the abundance of fish species. The transparency and specific conductivity were found to be the most critical factors affecting fish assemblages in the Rihand reservoir. This study generated important baseline ecological information that would be useful for the monitoring, conservation, and management of the reservoir ecosystem.

Key words: conservation, dam, environmental parameters, habitat–fish association, Rihand reservoir, trophic guilds

HIGHLIGHTS

- This study quantified the abundance and diversity patterns of the fish fauna in the Rihand reservoir.
- The species richness and diversity are arranged in GIS.
- The trophic guild analysis indicated the dominance of carnivores.
- This study suggested the inclusion of the riverine and transitional zones in management and conservation strategies.
- The new information on fisheries and ecological complexity would be useful for sustainable management.

INTRODUCTION

Reservoirs, known as anthropogenic lakes, are created by impounding dams on a river for the generation of hydroelectricity, irrigation, recreation, navigation, and flood control but rarely for fish production (Li & Xu 1995). The subject of water and food security is a global concern because of the unproductive irrigation practices and mismanagement of the available inland water resources (Tayyab *et al.* 2022). India has over 3.42 million ha of reservoirs in which the present level of fish production is far below the potential production (Sarkar *et al.* 2018; Alam *et al.* 2021a). Indian reservoirs are situated, by and large, in warm and nutrient-rich tropical regimes and are conducive to organic productivity (Sarkar *et al.* 2018). Indian reservoirs, however, preserve a relatively rich fish fauna with 117 fish species, of which at least 40 are commercially important (Sarkar *et al.* 2018). Fish culture as culture-based fisheries (CBF) in the reservoir is a recent endeavor in India (Das *et al.* 2009). These potential water resources need to be tapped to produce cheap, quality proteins for safeguarding nutritional security, providing employment opportunities to poor rural youths, and enhancing fish production in the country (Sarkar *et al.* 2018).

The environments in the reservoir, in general, are midway between those that prevail in rivers and in lakes. A typical feature of large reservoirs is the presence of longitudinal gradients that have been categorized into three discrete zones, viz. the riverine (upstream), transitional (midstream), and lacustrine (lower reaches) zones of the reservoir (Thornton *et al.* 1990; Terra *et al.* 2010). The ichthyofaunal diversity in reservoirs is fundamentally shaped by the fish diversity of its parent river and the species stocked after dam construction (Agostinho *et al.* 2010; Sandhya *et al.* 2019). The impact of damming rivers is reflected in physical–chemical, hydrology, and biotic conditions that eventually affect the fishery resources of the reservoir (Agostinho *et al.* 2010; Lianthuamluaia *et al.* 2019; Sandhya *et al.* 2019; Alam *et al.* 2021b). Dams hinder the upstream and downstream migration of fish fauna (Agostinho *et al.* 2010; Pelicice *et al.* 2015). An inherent effect of damming is the alterations in fish species distributions wherein the rheophilic species usually inhabit the upstream riverine and transitional zones, while the lentic species tend to get distributed in the lower lacustrine reaches of the reservoir (Pelicice *et al.* 2015). A sustainable water management plan in reservoirs is vital for maintaining the downstream ecosystems and for managing the rights of other stakeholders (Sari *et al.* 2022; Tayyab *et al.* 2022).

Water quality parameters have been widely used to monitor and characterize the different ecosystems (Burgan *et al.* 2013; Chakraborty *et al.* 2022; Majhi *et al.* 2023). Fish assemblages in reservoirs are influenced by a range of ecological traits that include abiotic, biotic, and historical features of their ecosystems (Jackson *et al.* 2001; Oliveira *et al.* 2004; Petesse & Petrere 2012; Pelicice *et al.* 2015). As compared with other groups of aquatic biota, fish have higher life-span, which can give insight into the condition of their ecology, and map integrated ecological effects over an extensive period (Plessl *et al.* 2017; Somchuea *et al.* 2022; Tesfaye *et al.* 2022). It is also recognized as a measure of ecosystem productivity, environmental pollution, and habitat deterioration (Gregory *et al.* 2009; Pelicice *et al.* 2015; Sandhya *et al.* 2019). In reservoirs, water quality traits like water temperature, transparency, pH, dissolved oxygen, alkalinity, specific conductivity, and nitrate have been reported to influence the fish faunal assemblage at spatial and temporal scales (Terra *et al.* 2010; Lianthuamluaia *et al.* 2019; Chakraborty *et al.* 2022; Koushlesh *et al.* 2022). Fish assemblage structure in the reservoir shows a longitudinal gradient, viz. from the riverine to the dam zones, resulting in a shift in fish species, abundance, and composition including increase/decrease in the population of some species and disappearance of others (Agostinho *et al.* 2010; Lianthuamluaia *et al.* 2019; Sandhya *et al.* 2019; Alam *et al.* 2021a; Chakraborty *et al.* 2022; Koushlesh *et al.* 2022). The assessment of species diversity in terms of species variability and assemblage patterns can provide important clues for evaluating the influence of habitat on the fish community (Terra *et al.* 2010; Sandhya *et al.* 2019). Fish abundance is also impacted at a temporal scale by seasonal variations of rainfall and temperature, etc., that greatly influence important biological processes like spawning and breeding patterns and feeding behaviors (Das *et al.* 2012; Lianthuamluaia *et al.* 2019; Alam *et al.* 2022). Reservoir ecosystem being dynamic, obtaining baseline information on spatial and temporal fish diversity and assemblage patterns is essential for developing management of its fishery resources, capture, and culture fisheries.

The Rihand reservoir, located in the Sonebhadra district of Uttar Pradesh, India, belongs to the category of large reservoirs (>5,000 ha). It is mainly used for electricity generation, irrigation, and fisheries. Globally, there are several works in the literature available on habitat variations and their impact on fish diversity, abundance, and assemblage patterns. The review of the literature indicates very limited studies so far have been reported from Indian reservoirs (Lianthuamluaia *et al.* 2019; Sandhya *et al.* 2019; Alam *et al.* 2021a; Sajina *et al.* 2021). The Rihand dam is without any fish passes that usually prevent the upstream migration of fish fauna. For this reason, it is assumed that potential changes must have taken place in the fish biota in the past few decades after the dam construction in 1962. Identifying the fish fauna will not only furnish significant clues to understanding the alteration in the fish population after the impoundment but also assist in planning strategies for preserving the fish diversity in the modified ecosystem (Pelicice *et al.* 2015; Ünlü 2021). Also, the development of fisheries in the reservoirs requires the managers to make sound development decisions and planning, which is constrained by the availability of limited data and research in the country. Therefore, the purpose of this investigation was to study the fish diversity, abundance, and structure of assemblage patterns on the temporal and spatial gradients and to determine the important environmental parameters that influence the fish assemblages.

MATERIALS AND METHODS

Study area

The Rihand reservoir (24°–24° 12′ N and 82° 38′–83° 5′ E) was built on the Rihand River, a tributary of the river Sone, in 1962 (Figure 1). The water is used for irrigation, drinking, aquaculture, electricity generation, livestock, and industrial use. The

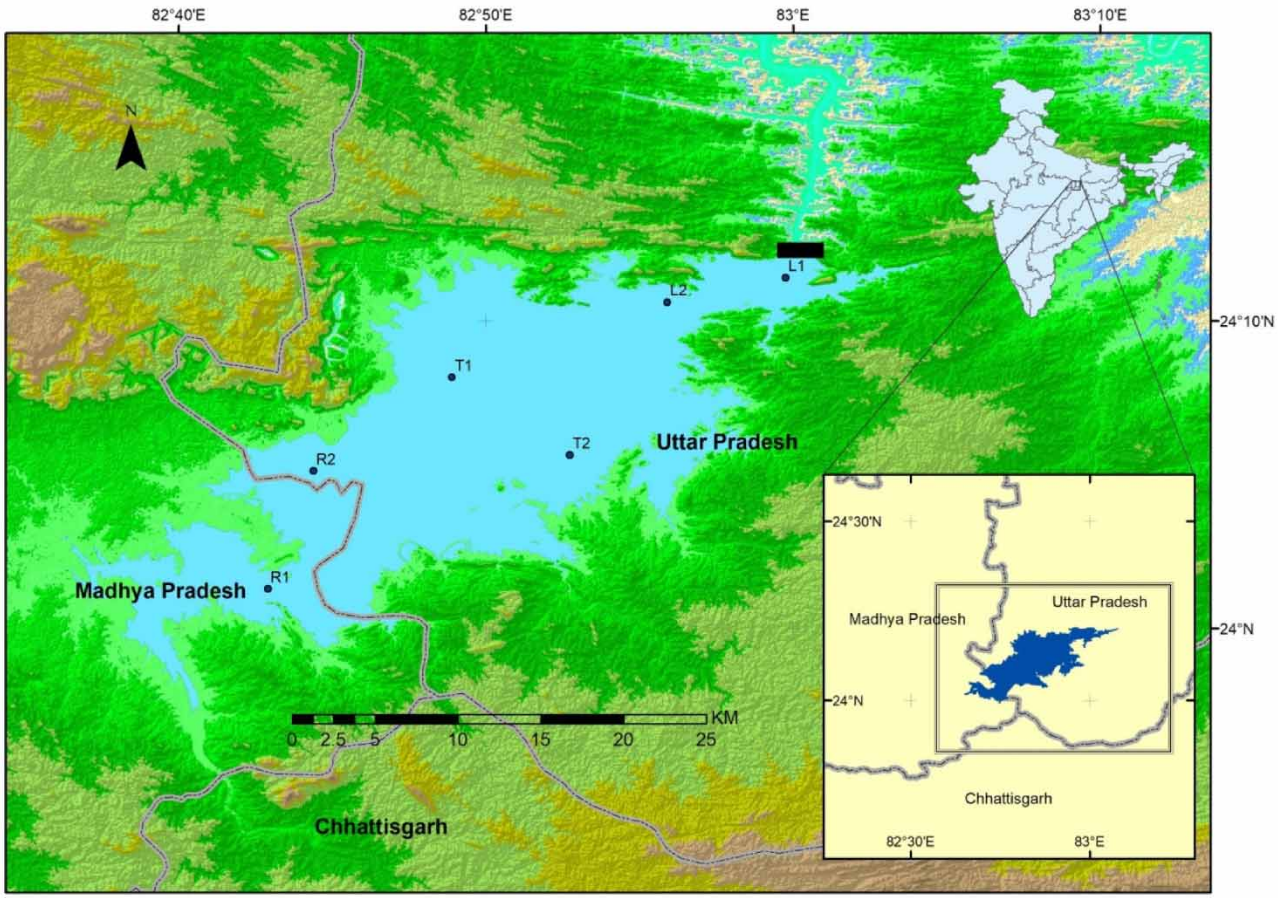

Figure 1 | Location of the Rihand reservoir depicting sampling stations (L – lacustrine, T – transitional, R – riverine).

reservoir has a drainage area of 13,411 km^2, a perimeter of 461 km, and a water spread area of 466 km^2 with a storage capacity of 10.6 km^3. The length of the reservoir is around 48 km. According to Alam *et al.* (2021b), the reservoir is oligotrophic. The mean inflow is 162.7 $m^3\ s^{-1}$. The climate in this watershed is sub-tropical monsoon with an average annual rainfall of 1,048 mm, which is mainly concentrated between July and September (Alam *et al.* 2021b). Around the reservoir, forest land (27.7%), scrubland (27.1%), cultivated land (21.7%), and barren land (7.9%) are presently under tremendous anthropogenic pressure (Vishwakarma *et al.* 2016).

Data collection

The data were collected seasonally during the rainy (July–October), winter (November and February), and summer (March–June) seasons at three sampling zones from February 2018 to January 2020 at a close date during each season. In each zone, samples were gathered from two sampling points (Figure 1). The reservoir was longitudinally divided into the lacustrine, transitional, and riverine zones, respectively. The area close to the dam (12 km) was designated as the lacustrine zone. The middle zone of the reservoir (22 km) which had the maximum width was selected as the transitional zone, while the tail region of the reservoir, usually narrow (similar to the river), covering a length of 14 km was designated as the riverine zone. The two sampling points in each zone were significantly apart by almost 7 km. The fish data were collected employing gillnets (300 m long × 4.5–5 m deep) of different mesh sizes (15–150 mm) that were set for 14 h (17: 00–07: 00). The sampling effort along with a combination of mesh sizes was always kept the same across space and time. The data on fish abundance, diversity, and physico-chemical parameters were pooled by season and zones, respectively. The specimens were collected and identified at the species level using specialized literature (Talwar & Jhingran 1991; Jayaram 2010). The water quality parameters, viz. water temperature, pH, dissolved oxygen, chloride, specific conductivity, total dissolved solids, total hardness, alkalinity, dissolved organic matter, phosphate, nitrate, silicate, and chlorophyll-a were examined following standard methodologies (Jhingran *et al.* 1969; APHA 2017). According to the IUCN Red List, the conservation status of fish species in the reservoir was documented (IUCN 2022). Based on the feeding habits, the trophic guilds of fishes were categorized as planktivores (PL), omnivores (OM), detritivores (DE), and carnivores (CA) (Das & Moitra 1963).

Statistical analysis

The PAleontological STatistics (PAST) software, version 2.6 (Hammer *et al.* 2001) was employed to evaluate diversity indices, viz. the species richness, Shannon–Wiener diversity index (Shannon & Weaver 1964), and Pleiou's index of equitability (Pielou 1966). A comparison of the species richness was made employing an individual-based refractive curve among zones using the R add-on package 'Vegan'. To typify the various zones/seasons with indicator species, the indicator species analysis was employed (Dufrêne & Legendre 1997). This analysis gives the output between 0% and 100%, wherein, 0% signifies that it is not an indicator species and 100% indicates it to be an indicator species for that season/zone, the statistical significance of which was tested using a permutation test. The dissimilarity in fish composition across zones and seasons was performed using the Bray–Curtis dissimilarity analysis through R software (Vegan package) for the most abundant species. The significant differences in fish abundance and the physico-chemical parameters at spatial (zones) and temporal (seasons) scales were determined using ANOVA (analysis of variance) following Tukey's HSD (honestly significant difference) test (Fisher 1925, 1992). In this analysis, the monthly water volume and rainfall data used were obtained from the Irrigation & Water Resources Department, Sonebhadra, Uttar Pradesh. The canonical correspondence analysis (CCA) was done to recognize the main environmental parameters (ter Braak & Verdonschot 1995) affecting the fish abundance of the top 15 commercially important fishes of the reservoir using R software (Vegan package). Out of 14 environmental variables, only five variables were selected based on their VIF (variance inflation factor) value (<10) for CCA. Environmental parameters were log-transformed $\log(x + 1)$ except the pH which itself is on a log scale. To identify the commercially important fishes of the reservoir, the fish catch data were collected by species for the last three decades (1998–2018) from the Department of Fisheries, Sonebhadra, Uttar Pradesh, India.

In this study, ArcGIS ver. 10.2.2 developed by Environment Systems Research Institute (ESRI) was used for constructing the maps of various parameters. The GPS coordinates of the sampling points in the reservoir were gathered. A table with data on different biological parameters was prepared and ascribed to the layers of those parameters. Firstly, the Landsat 8 OL1 satellite image (<10% cloud coverage) was downloaded for extracting the water spread area of the Rihand reservoir. In the following step of image processing, correction of the data involving layer stacking and radiometric modification was carried out. The 'Kriging' interpolation technique was employed for the geostatistical investigation in ArcGIS software within its spatial forecaster extension module with different sets of biological data acquired from the various locations of the reservoir (Isaaks & Srivastava 1989; ESRI 2001; Chakraborty *et al.* 2022). The most suitable thematic maps were generated based on the field surveys to represent the various biological parameters, viz. species richness, species diversity (Shannon–Wiener diversity), species evenness (Pleiou's index of equitability), and trophic guild of the fish fauna at the spatial scale (zone-wise) as choropleth maps. A flow chart for the methodology for investigating fish–habitat association and assemblage pattern is depicted in Figure 2.

RESULTS

The study documented a total of 3,397 individuals, 53 species representing 40 genera, 16 families, and eight orders (Table 1, Figure 3). Cypriniformes was the most dominant order with 24 species followed by Siluriformes (14). The family Cyprinidae had the highest number of species, representing 15 species, followed by Danionidae ($n = 6$), and Schilbeidae ($n = 5$), respectively. The family Cyprinidae contributed the highest number of individuals, representing 1,085 individuals (31.9%) of total fish samples collected followed by Ambassidae (26.5%) and Danionidae (19.7%), respectively (Figure 3). Four exotic fishes, namely *Hypophthalmichthys molitrix, Ctenopharyngodon idella, Cyprinus carpio,* and *Oreochromis niloticus* were observed. Among the exotics, *O. niloticus* (1.18%) was the most abundant. Data on fish species collected during the investigation comprising their order, family, distribution, conservation status, and trophic status are presented in Table 1. This study revealed that small-sized fish, for example, *Parambassis ranga* (24.55%) followed by *Salmostoma phulo* (17.02%), *Puntius chola* (9.7%), and *Osteobrama cotio* (3.3%) were the most abundant fishes based on their numbers. In the spatial gradient, the analyses of data showed that the highest abundance of fish was available from the riverine (1,347) followed by the transitional (1,336) and lacustrine (714) zones of the reservoir. Among the 53 fish species documented, 12 species (*L. boggut, T. khudree, G. annandalei, S. bacaila, B. barila, L. guntea, A. coila, B. bagarius, G. viridescens, M. bleekeri, H. fossilis, C. marulius,* and *C. gachua*) were noted only from the riverine zone, which signified the distinct form of fish assemblages

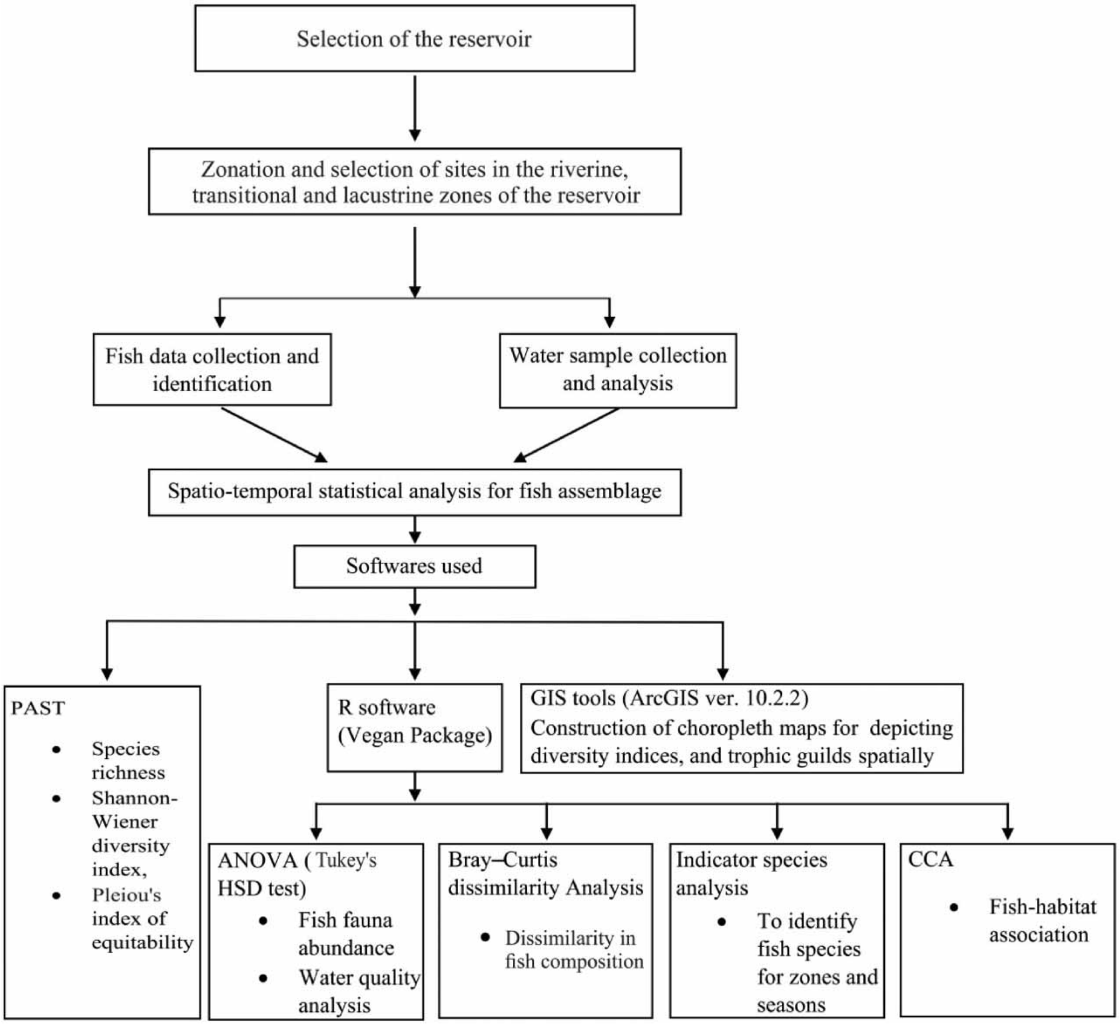

Figure 2 | A flow chart for the methodology for investigating assemblage pattern, fish–habitat association, and feeding guilds and GIS application at spatio-temporal scale in Rihand reservoir, India.

in the reservoir. The analyses of variance showed that the abundance of the fish assemblage was significant at a 5% level of significance between the riverine and lacustrine and between the transitional and lacustrine zones ($p < 0.05$), while it was insignificant between the riverine and the transitional zones ($p > 0.05$). Likewise, on the temporal scale, the fish abundance differed significantly between the summer and winter and between the summer and monsoon seasons ($p < 0.05$), while it did not differ significantly between the monsoon and winter seasons ($p > 0.05$).

According to the refractive curve, the expected species richness was 24, 32, and 42 fish species for a sample size of 714 specimens for riverine, transitional, and lacustrine zones of the reservoir (Figure 4). The biodiversity blueprint based on diversity indices, viz. species richness, Shannon–Weiner diversity, and evenness index, was depicted using the GIS tool at spatial scale (Figures 5–7). At the spatial scale, the highest species richness was recorded in the riverine ($n = 44$) followed by transitional ($n = 36$) and lacustrine ($n = 24$) zones of the reservoir (Figure 5) and diversity analyses indicated that the highest Shannon diversity (H) and evenness index (J) was observed from the riverine zones ($H = 3.096$; $J = 0.820$) trailed by the transitional ($H = 2.594$; $J = 0.741$) and lacustrine zones ($H = 2.431$; $J = 0.765$) of the reservoir (Figures 6 and 7).

The temporal analyses of data showed the highest abundance in the summer (1,635) followed by monsoon (938) and winter (824). The maximum number of fish species was documented during the monsoon (44) followed by summer (40) and winter (30) seasons. The diversity analyses along the temporal scale revealed that the highest diversity was noted in the monsoon season ($H = 3.129$; $J = 0.827$) followed by the summer ($H = 2.837$; $J = 0.769$) and winter season ($H = 2.32$; $J = 0.656$)

Table 1 | Fish species and their conservation status, distribution, and trophic guilds in the Rihand reservoir

Fish species	IUCN status	Riverine zone	Transitional zone	Lacustrine zone	Trophic guild
Order – Osteoglossiformes					
Family – Notopteridae					
Notopterus notopterus (Pallas, 1769)	LC	+	+	–	CA
Chitala chitala (Hamilton, 1822)	NT	+	+	–	CA
Order – Cypriniformes					
Family – Cyprinidae					
Gibelion catla (Hamilton, 1822)	LC	+	+	+	PL
Labeo rohita (Hamilton, 1822)	LC	+	+	+	PL
Labeo calbasu (Hamilton, 1822)	LC	+	+	+	PL
Labeo gonius (Hamilton, 1822)	LC	+	+	+	PL
Labeo boggut (Sykes, 1839)	LC	+	–	–	PL
Cirrhinus mrigala (Hamilton, 1822)	LC	+	+	+	DE
Cirrhinus reba (Hamilton, 1822)	LC	+	+	+	PL
Puntius sophore (Hamilton, 1822)	LC	+	–	+	PL
Puntius chola (Hamilton, 1822)	LC	+	+	+	OM
Pethia ticto (Hamilton, 1822)	LC	+	+	+	PL
Pethia conchonius (Hamilton, 1822)	LC	+	+	+	CA
Tor khudree (Sykes, 1839)	NE	+	–	–	OM
[a]*Cyprinus carpio* (Linnaeus, 1758)	VU	–	+	+	OM
Osteobrama cotio (Hamilton, 1822)	LC	+	+	+	OM
Garra mullya (Sykes, 1839)	LC	+	–	–	PL
Family – Danionidae					
Amblypharyngodon mola (Hamilton, 1822)	LC	+	–	–	PL
Salmostoma phulo (Hamilton, 1822)	LC	+	+	+	OM
Salmostoma bacaila (Hamilton, 1822)	LC	+	–	–	OM
Barilius barila (Hamilton, 1822)	LC	+	–	+	PL
Securicula gora (Hamilton, 1822)	LC	–	+	–	OM
Esomus danrica (Hamilton, 1822)	LC	–	–	+	CA
Family – Xenocyprididae					
[a]*Hypophthalmichthys molitrix* (Valenciennes, 1844)	NT	–	+	–	PL
[a]*Ctenopharyngodon idella* (Valenciennes, 1844)	NE	+	+	–	PL
Family – Cobitidae					
Lepidocephalichthys guntea (Hamilton, 1822)	LC	+	–	–	PL
Order – Siluriformes					
Family – Siluridae					
Wallago attu (Bloch & Schneider, 1801)	VU	+	+	+	CA
Ompok bimaculatus (Bloch, 1794)	NT	+	–	–	CA
Family – Schilbeidae					
Silonia silondia (Hamilton, 1822)	LC	+	+	+	CA
Eutropiichthys vacha (Hamilton, 1822)	LC	+	+	–	CA
Eutropiichthys murius (Hamilton, 1822)	LC	+	+	–	CA
Clupisoma garua (Hamilton, 1822)	LC	+	+	–	CA
Ailia coila (Hamilton, 1822)	NT	+	–	–	OM

(*Continued*.)

Table 1 | Continued

Fish species	IUCN status	Riverine zone	Transitional zone	Lacustrine zone	Trophic guild
Family – Sisoridae					
Bagarius bagarius (Hamilton, 1822)	NT	+	–	–	CA
Gogangra viridescens (Hamilton, 1822)	LC	+	–	–	CA
Family – Bagridae					
Sperata seenghala (Sykes, 1839)	LC	+	+	+	CA
Sperata aor (Hamilton, 1822)	LC	+	+	–	CA
Mystus bleekeri (Day, 1877)	LC	+	–	–	CA
Mystus cavasius (Hamilton, 1822)	LC	–	+	–	CA
Family – Heteropneustidae					
Heteropneustes fossilis (Bloch, 1794)	LC	+	–	–	CA
Order – Perciformes Family – Ambassidae					
Chanda nama (Hamilton, 1822)	LC	+	+	+	CA
Parambassis ranga (Hamilton, 1822)	LC	+	+	+	CA
Order – Anabantiformes Family – Channidae					
Channa marulius (Hamilton, 1822)	LC	+	–	–	CA
Channa striata (Bloch, 1793)	LC	+	+	–	CA
Channa punctata (Bloch, 1793)	LC	–	+	–	CA
Channa gachua (Hamilton, 1822)	LC	+	–	–	CA
Family – Osphronemidae					
Trichogaster fasciata (Bloch & Schneider, 1801)	LC	–	+	+	OM
Order – Gobiiformes Family – Gobiidae					
Glossogobius giuris (Hamilton, 1822)	LC	–	+	–	CA
Order – Cichliformes Family – Cichlidae					
[a]*Oreochromis niloticus* (Linnaeus, 1758)	LC	+	+	+	OM
Order – Mugiliformes Family – Mugilidae					
Minimugil cascasia (Hamilton, 1822)	LC	+	+	+	OM
Rhinomugil corsula (Hamilton, 1822)	LC	+	+	–	OM
Order – Synbranchiformes Family – Mastacembelidae					
Mastacembelus armatus (Lacepède, 1800)	LC	+	+	+	CA
Macrognathus pancalus (Hamilton, 1822)	LC	–	+	–	CA

Note: LC, least concern; EN, endangered; NT, near threatened; VU, vulnerable; NE, not evaluated; CA, carnivorous; PL, planktivorous; OM, omnivorous.
[a]Exotic fishes.

(Figure 8). Based on the dietary preference, the trophic guilds of the fishes showed that the carnivorous fish species dominated, followed by OM and DE in all the zones of the reservoir (Figure 5).

According to the dissimilarity analysis, the average dissimilarity between riverine and transitional zones, riverine and lacustrine, and transitional and lacustrine zones was 42.27%, 44.61%, and 45.26%, respectively (Table 2). The three species *P. ranga, P. chola,* and *S. phulo* contribute to almost 50% of the dissimilarity between the zones, indicating that they are more typical of those zones in the Rihand reservoir (Table 2). Similarly, the average dissimilarity between summer and

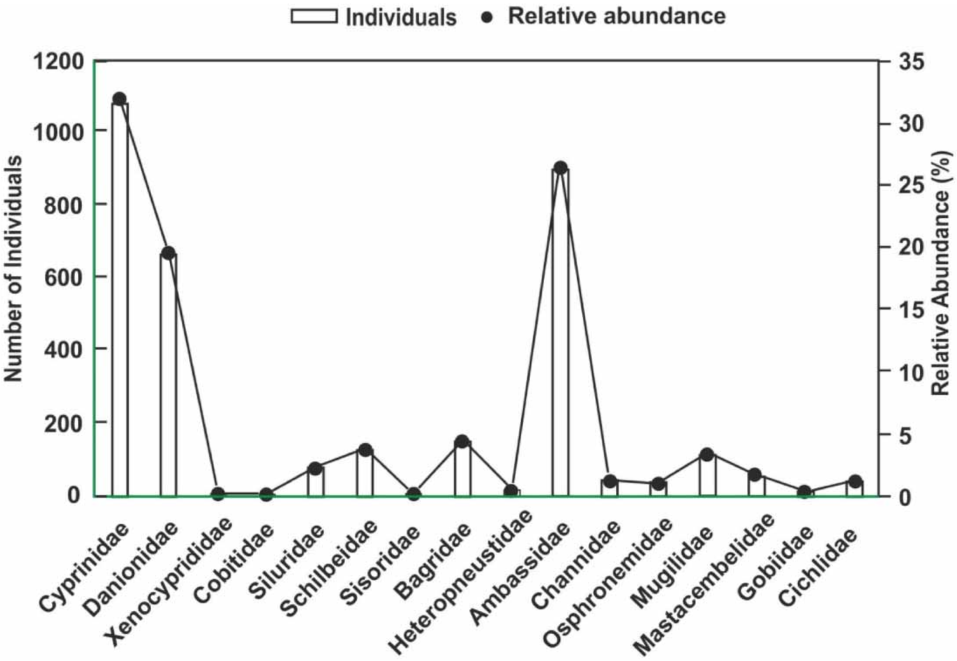

Figure 3 | Abundance and relative frequency (%) of specimens caught by family in the Rihand reservoir.

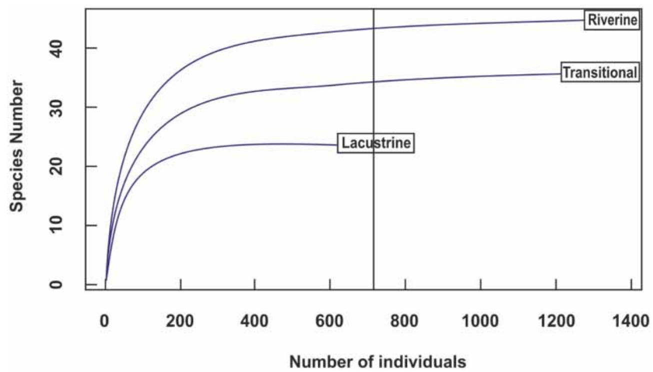

Figure 4 | Individual-based refraction curve for the fish species richness by zones in the Rihand reservoir.

winter, summer and monsoon, and winter and monsoon were 47.74%, 45.96%, and 42.82%, respectively (Table 3). The three species *S. phulo*, *P. ranga,* and *P. ticto* together contribute to more than 50% of the dissimilarity between the groups suggesting them to be more typical of the various seasons (Table 3).

The indicator species analysis revealed significant indicator values for seven species, namely *P. ranga, S. phulo, O. cotio, P. ticto, L. gonius, C. mrigala*, and *P. chola* out of 53 fish species observed in the reservoir. *P. ranga* was the indicator species for the transitional zone. *S. phulo, O. cotio, P. ticto,* and *L. gonius* were the indicator species for the summer season. *C. mrigala* was found to be the type species representing the monsoon season, and *P. chola* was the indicator species for the winter season (Table 4). The indicator fish species for the riverine and the lacustrine zones could not be identified.

As per IUCN (2022), out of the 49 endemic fish species recorded from the reservoir, four were near-threatened (NT) (*C. chitala, O. bimaculatus, A. coila,* and *B. bagarius*), one was vulnerable (*W. attu*), 43 were of least concern (LC), and one was not evaluated (NE). Among the exotic fish species, *Hypophthalmichthys molitrix* is categorized as NT, *C. carpio* as vulnerable (VU), *C. idella* as NE, and *O. niloticus* as LC (Table 1).

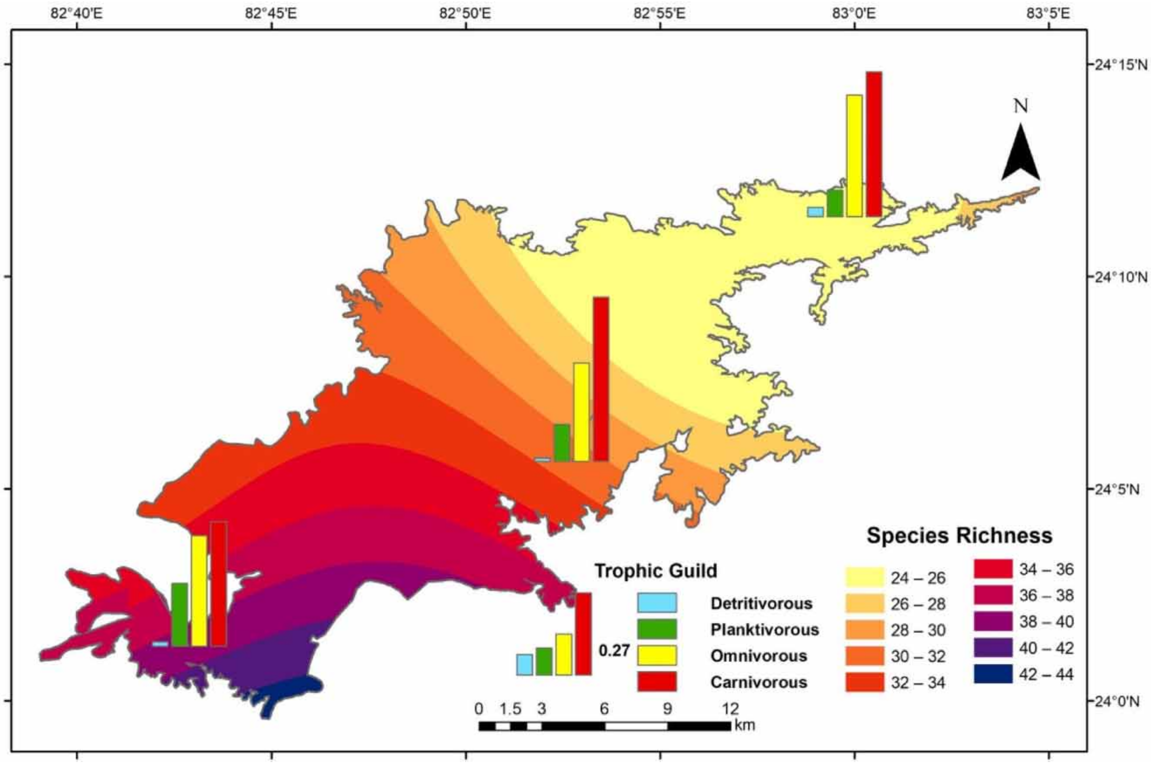

Figure 5 | GIS map depicting spatial variations of fish species richness and trophic guilds in the Rihand reservoir.

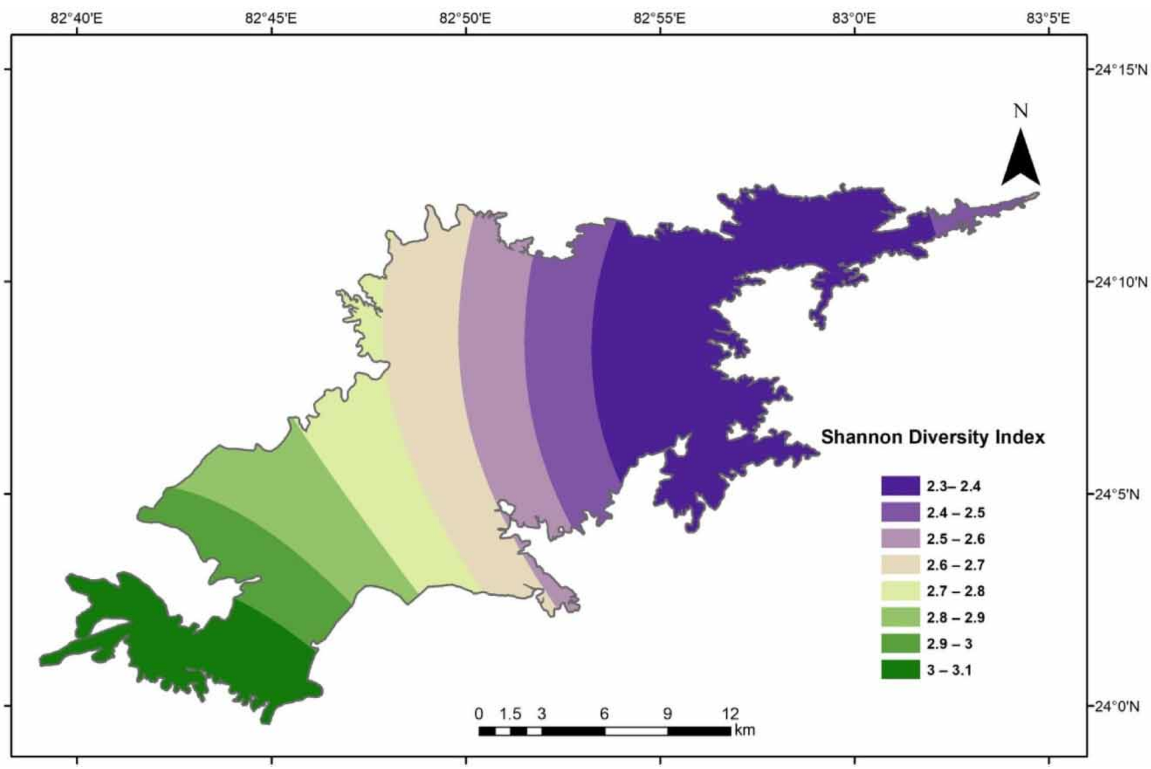

Figure 6 | GIS map showing the spatial variations of the Shannon diversity index of fish in the Rihand reservoir.

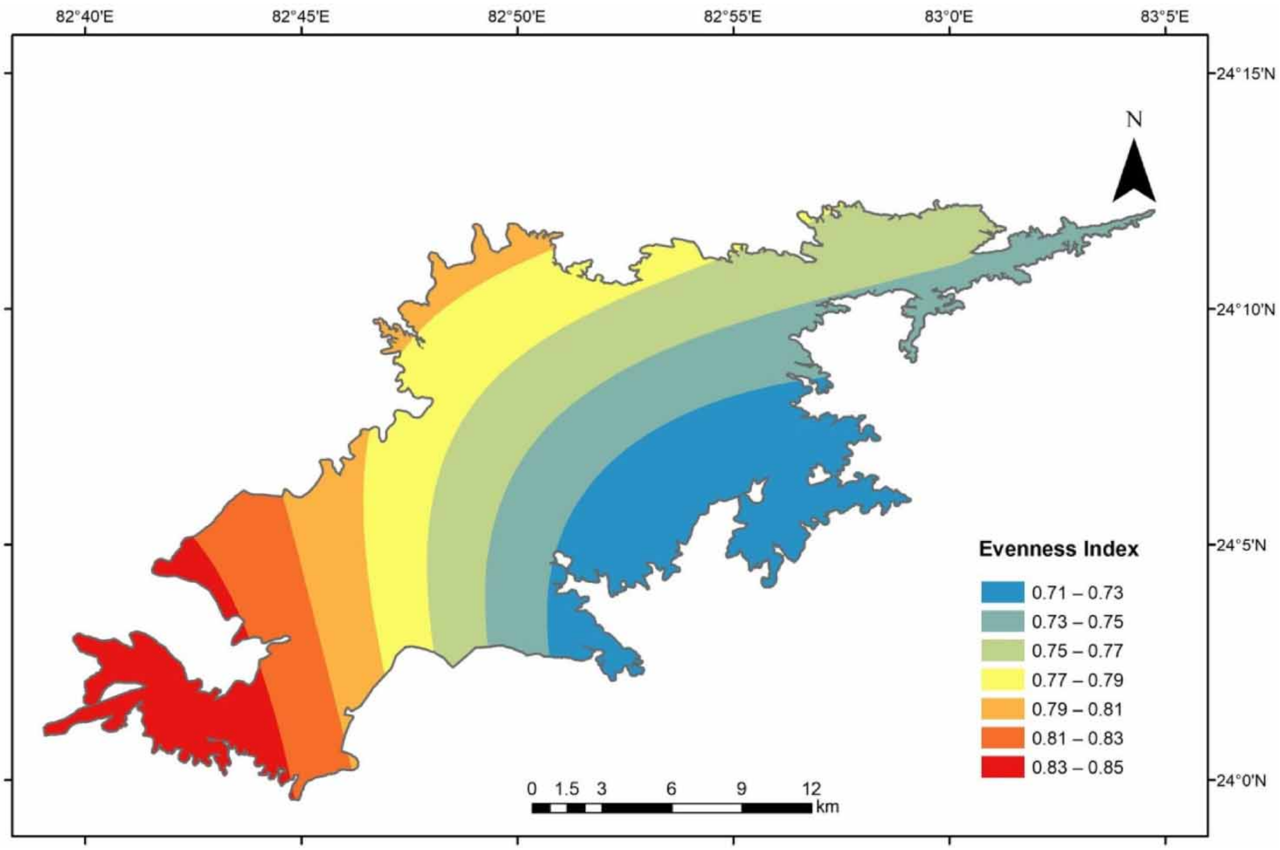

Figure 7 | GIS map showing the spatial variations of the evenness index of fish in the Rihand reservoir.

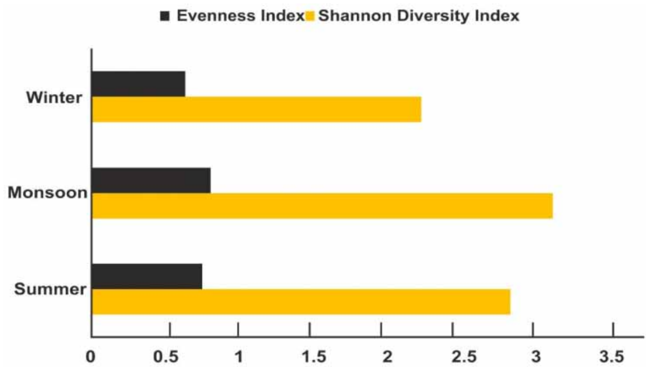

Figure 8 | Temporal variations in Shannon diversity index and evenness index of fishes in Rihand reservoir.

The statistical properties, such as skewness, coefficient of variation (CV), confidence intervals (CI), minimum, maximum, and median of the studied water quality parameters in the reservoir are given in Table 5. The maximum surface water temperature was noted in the summer season throughout the reservoir and the highest transparency was recorded in the winter seasons in all three zones. They differed significantly between the summer and monsoon seasons ($p < 0.05$) but were insignificant between the zones ($p < 0.05$) (Table 5). Most of the water quality parameters, viz. specific conductivity, alkalinity, total hardness, and pH, differed significantly between seasons ($p < 0.05$) except dissolved oxygen ($p > 0.05$). The water nutrients like nitrate, phosphate, and silicate showed significant variations between the seasons ($p < 0.05$) (Table 5). All the studied water quality traits showed no significant variation along the spatial gradient of the reservoir (Table 5).

Table 2 | Percentage contribution of the most abundant species to the average dissimilarity between zones and contribution of the most abundant species to dissimilarity

Species	Average dissimilarity			Contribution to dissimilarity		
	R × T	R × L	T × L	R × T	R × L	T × L
Parambassis ranga	9.997	6.468	17.29	23.65	14.5	38.21
Puntiu chola	5.629	7.458	4.951	13.32	16.72	10.94
Salmophasia phulo	4.982	5.906	7.585	11.79	13.24	16.76
Puntius sophore	3.52	4.183	0	8.328	9.378	0
Minimugil cascasia	3.483	4.23	0.3336	8.239	9.484	0.737
Pethia ticto	1.991	1.823	2.278	4.711	4.088	5.033
Osteobrama cotio	1.789	1.636	2.455	4.233	3.668	5.424
Pethia conchoniuus	1.67	3.08	2.004	3.951	6.905	4.428
Cirrhinus reba	1.487	0.876	1.477	3.517	1.964	3.262
Chanda nama	1.472	1.57	1.453	3.483	3.52	3.211
Spereta seenghala	1.419	1.864	1.844	3.358	4.18	4.075
Mastacembelus armatus	1.31	1.679	0.6283	3.099	3.763	1.388
Labeo gonius	0.9896	0.5995	1.197	2.341	1.344	2.645
Wallago attu	0.9537	1.192	0.4244	2.256	2.673	0.9377
Cirrhinus mrigala	0.8321	1.008	0.9381	1.969	2.259	2.073
Silonia silondia	0.7429	1.034	0.4007	1.758	2.319	0.8853
Average dissimilarity	**42.2673**	**44.6065**	**45.2591**			

Table 3 | Percentage contribution of the most abundant species to the average dissimilarity between seasons and contribution of the most abundant species to dissimilarity

Species	Average dissimilarity			Contribution to dissimilarity		
	S × W	S × M	M × W	S × W	S × M	M × W
Salmophasia phulo	10.04	6.208	5.932	21.04	13.51	13.86
Parambassis ranga	9.669	10.09	8.885	20.25	21.95	20.75
Pethia ticto	4.146	3.539	0.5343	8.684	7.701	1.248
Puntius sophore	3.633	3.602	0.5639	7.611	7.837	1.317
Minimugil cascasia	3.327	3.504	1.25	6.969	7.625	2.92
Puntiu chola	3.248	5.457	11.82	6.803	11.88	27.6
Pethia conchoniuus	2.936	3.049	1.229	6.149	6.635	2.871
Osteobrama cotio	1.955	2.572	2.014	4.095	5.596	4.705
Cirrhinus reba	1.488	1.613	0.8031	3.116	3.511	1.876
spereta seenghala	1.433	0.973	2.541	3.001	2.117	5.934
Mastacembelus armatus	1.303	0.5023	1.698	2.73	1.093	3.965
Chanda nama	1.27	0.9977	1.732	2.66	2.171	4.046
Labeo gonius	1.162	1.314	0.5539	2.434	2.86	1.294
Wallago attu	0.8925	1.172	0.7653	1.87	2.551	1.788
Cirrhinus mrigala	0.6209	0.775	1.711	1.301	1.686	3.997
Silonia silondia	0.6135	0.5888	0.7858	1.285	1.281	1.835
Average dissimilarity	**47.7369**	**45.9568**	**42.8183**			

Table 4 | The indicator species analysis depicting significant values for the fish assemblages for the seasons and zones in the Rihand reservoir

Species	Indicator value (Ind. Value)	*p*-value	Zone/season
Parambassis ranga	53.12	0.0129	Transition
Salmophasia phulo	49.65	0.0294	Summer
Osteobrama cotio	60.18	0.0248	Summer
Pethia ticto	91.11	0.0138	Summer
Labeo gonius	59.38	0.0248	Summer
Cirrhinus mrigala	51.79	0.0499	Monsoon
Puntiu chola	59.94	0.0247	Winter

CCA of the fish abundance of 15 commercially important fish with limno-chemical parameters showed that the first and second axes described 41.6% and 29.1% of the total variance. A permutation test ($n = 999$) described a significant relationship between fish abundance and environmental variables ($p < 0.05$). The biplot showed that dissolved oxygen, water temperature, and chlorophyll-a had a more positive effect on the species *C. reba* (CMR), *Labeo rohita* (LRO), and *O. niloticus* (ONI) and negatively influenced *M. armatus* (MAR), *W. attu* (WAT), and *C. mrigala* (CMR) than the other environmental variables. Species *C. chitala* (CCH), *S. silondia* (SSI), *L. calbasu* (LCA), and *S. seenghala* (SSE) were more influenced by transparency and negatively affected by specific conductivity. The species *C. garua* (CGA), *S. aor* (SAO), and *G. catla* (GCA) were positively influenced by specific conductivity and negatively impacted by transparency. The CCA diagram shows that specific conductivity and transparency had a more substantial effect on the abundance of the fish species than the other studied parameters, viz. dissolved oxygen, chlorophyll-a, and water temperature, in the reservoir (Figure 9).

DISCUSSION

The current investigation is the first report from the Rihand reservoir showing the patterns of fish assemblages at temporal and spatial gradients and also documents long-term effects on the fish fauna after the dam construction in 1962. The fish species richness in the reservoir (53) was less than that recorded from its parent river Sone (89) (Joshi *et al.* 2014). This could be due to extensive variations in water flow, availability of food resources, temperature, and changes in nutrient regimes (Williams *et al.* 1998; Lianthuamluaia *et al.* 2019; Sandhya *et al.* 2019; Alam *et al.* 2021a). The fish species recorded in the present reservoir are as per the mean species richness in large reservoirs (60) of India reported by Jhingran (1991).

In this study, we observed that fish assemblage changed along the spatial gradient from the riverine zone toward the dam part (lacustrine zone) of the reservoir. The species richness and diversity increased from the lacustrine zone towards the upper part of the reservoir where the influence of the river was the highest. This might be due to the existence of heterogeneous habitats in the riverine zone of a mature reservoir that resembles the environmental conditions of its historical flowing-river condition (Lianthuamluaia *et al.* (2019); Pennock *et al.* 2021). This is in agreement with the studies in the Panchet reservoir except for the fish abundance, which was highest in the transitional zone (Sandhya *et al.* 2019). Lianthuamluaia *et al.* (2019) observed the highest species richness and abundance in the riverine zone, while the Shannon diversity and evenness indices were the highest in the transitional zone. Alam *et al.* (2021a) also documented the highest abundance and species richness in the transitional zone of the Jargo reservoir, India, and the highest diversity and evenness indices in the transitional zone. Many investigations have revealed that most of the fish species prefer areas and depth layers within the reservoirs that are the most productive and the warmest (Draštík *et al.* 2008; Prchalová *et al.* 2009). The spatial distribution of fish fauna within the reservoir is influenced by the depth and the fish species richness and their abundance decreases with increasing depth (Prchalová *et al.* 2008, 2009). The thermal and oxygen stratifications in the reservoir influence the vertical distribution of the fish fauna (Prchalová *et al.* 2009). Prchalová *et al.* (2009) found in their studies that most of the fish avoided depths below the thermocline (temperature < 16 °C, and oxygen concentration < 5 mg l^{-1}). The lacustrine zone of the reservoir is usually the least productive and the deepest zone of the reservoir. Hence, the species richness and abundance were noted to be the lowest in the lacustrine zone, the lower part of the reservoir among the three zones of the studied reservoir. Similar findings have been reported in Chandil (Lianthuamluaia *et al.* 2019), Panchet (Sandhya

Table 5 | The statistical properties such as mean ± SD, minimum, maximum, median, skewness, coefficient of variation (CV) and confidence intervals (CI) of the studied physico-chemical parameters in the Rihand reservoir

		Seasons			Zones		
		Summer	**Monsoon**	**Winter**	**Riverine**	**Transitional**	**Lacustrine**
Temperature (°C)	Mean ± SD	$32.72^a \pm 1.45$	$31.2^a \pm 0.91$	$20.8^b \pm 1.29$	$28.35^c \pm 6.37$	$28.65^c \pm 6.22$	$27.72^c \pm 5.15$
	Median	32.05	31.10	21.15	32.05	31.10	30.10
	Minimum	31.80	30.00	18.6	18.60	20.00	21.10
	Maximum	35.90	32.9	22	32.90	35.90	31.9
	Skewness	1.660	0.438	−0.809	−0.782	−0.454	−0.630
	CV (%)	0.048	0.0346	0.062	0.225	0.217	0.186
	CI	31.051–34.381	30.066–32.334	19.441–22.159	21.666–35.034	22.121–35.179	22.312–33.122
Transparency (cm)	Mean ± SD	$91.33^a \pm 39.1$	$45.17^a \pm 27$	$268.5^b \pm 43.53$	$134.5^c \pm 113.32$	$126.33^c \pm 106.45$	$144.17^c \pm 116.2$
	Median	86.5	33.5	269.0	114.0	94.0	93.5
	Minimum	48.0	21.0	190.0	21.0	23.0	40.0
	Maximum	162.0	81.0	309.0	266.0	309.0	309.0
	Skewness	0.618	0.547	−0.932	0.224	0.848	0.621
	CV (%)	0.470	0.615	0.162	0.843	0.843	0.806
	CI	46.280–136.387	16.005–74.328	222.82–314.18	15.576–253.424	14.616–238.051	22.220–266.113
pH	Mean ± SD	$8.22^a \pm 0.07$	$7.44^b \pm 0.32$	$8.12^a \pm 0.18$	$7.94^c \pm 0.44$	$8.02^c \pm 0.25$	$7.82^c \pm 0.56$
	Median	8.20	7.42	8.20	7.94	8.07	8.10
	Minimum	8.10	7.04	7.80	7.14	7.67	7.04
	Maximum	8.30	7.94	8.30	8.30	8.30	8.30
	Skewness	−0.228	0.153	−0.902	−1.113	−0.254	−0.631
	CV (%)	0.009	0.0504	0.022	0.056	0.0316	0.072
	CI	8.138–8.296	7.050–7.837	7.924–8.309	7.476–8.407	7.753–8.284	7.224–8.409
Alkalinity (mg/l)	Mean ± SD	$78.00^b \pm 4.97$	$57.50^{ab} \pm 5.63$	$59.5^a \pm 6.57$	$63.17^c \pm 10.43$	$66.67^c \pm 10.67$	$65.17^c \pm 13.80$
	Median	78.0	58.0	60.5	65.0	62.0	62.0
	Minimum	69.0	46.0	48.0	46.0	58.0	48.0
	Maximum	84.0	64.0	68.0	76.0	83.0	84.0
	Skewness	−0.539	−0.888	−0.690	−0.534	0.708	0.280
	CV (%)	0.0698	0.112	0.110	0.165	0.160	0.212
	CI	72.290–83.710	50.739–64.260	52.610–66.389	52.212–74.121	55.468–77.865	50.679–79.654
Chloride (mg/l)	Mean ± SD	$18.46^b \pm 2.96$	$15.62^{ab} \pm 2.01$	$14.20^a \pm 1.27$	$15.62^c \pm 2.38$	$17.04^c \pm 4.01$	$15.62^c \pm 2.01$
	Median	17.75	15.62	14.20	15.62	16.33	15.62
	Minimum	15.62	12.78	12.78	12.78	12.78	12.78
	Maximum	24.14	18.46	15.62	19.88	24.14	18.46
	Skewness	8.868636×10^{-1}	1.249436×10^{-15}	0.000000	8.416976×10^{-1}	8.714213×10^{-1}	1.249436×10^{-15}
	CV (%)	0.175	0.129	0.089	0.152	0.235	0.128
	CI	15.062–21.858	13.513–17.727	12.867–15.533	13.126–18.114	12.825–21.255	13.513–17.727
Dissolved oxygen (mg/l)	Mean ± SD	$9.27^a \pm 2.37$	$8.27^a \pm 0.84$	$8.56^a \pm 1.58$	$8.08^b \pm 0.99$	$9.92^b \pm 2.51$	$8.09^b \pm 0.82$
	Median	8.12	8.28	8.32	8.12	9.20	8.08
	Minimum	7.52	7.04	6.88	7.04	7.52	6.88
	Maximum	14.40	9.68	10.88	9.68	14.40	9.44
	Skewness	1.566	0.309	0.369	0.433	0.974	0.252
	CV (%)	0.28	0.104	0.185	0.122	0.253	0.102
	CI	6.543–11.989	7.360–9.173	6.900–10.221	7.042–9.118	7.291–12.549	7.230–8.957
Specific conductivity (μS/cm)	Mean ± SD	$287.05^b \pm 32.29$	$110^a \pm 15.72$	$89.83^a \pm 11.19$	$158.37^c \pm 94.6$	$171.9^c \pm 112.67$	$156.62^c \pm 89.87$
	Median	274.90	114.00	88.00	109.50	116.5	119.00
	Minimum	264.20	79.00	75.00	79.0	86.00	75.00
	Maximum	358.20	123.00	109.00	280.6	358.20	271.20
	Skewness	1.673	−1.441	0.577	0.660	0.877	0.585
	CV (%)	0.123	0.145	0.125	0.597	0.655	0.574
	CI	249.927–324.173	93.314–126.686	78.083–101.584	59.091–257.643	53.657–290.143	62.305–250.928
TDS (mg/l)	Mean ± SD	$143.58^b \pm 16.47$	$54.5^a \pm 7.80$	$42.67^a \pm 5.72$	$78.43^c \pm 47.89$	$84.95^c \pm 57.43$	$77.36^c \pm 45.73$
	Median	137.60	56.50	41.50	54.00	57.50	59.00

(*Continued.*)

Table 5 | Continued

		Seasons			Zones		
		Summer	Monsoon	Winter	Riverine	Transitional	Lacustrine
	Minimum	131.90	39.00	36.00	39.00	41.00	36.00
	Maximum	179.8	61.00	53.00	140.00	179.80	135.50
	Skewness	1.672	−1.488	0.922	0.660	0.869	0.571
	CV (%)	0.125	0.145	0.134	0.611	0.676	0.591
	CI	124.687–162.479	46.217–62.78323	36.669–48.665	28.173–128.693	24.685–145.215	29.375–125.359
Total hardness (mg/l)	Mean ± SD	61.67[a] ± 14.62	40.33[a] ± 15.18	53.33[a] ± 18.23	52.00[b] ± 23.49	53.00[b] ± 14.07	50.33[b] ± 18.52
	Median	62.00	39.00	48.00	53.00	58.00	41.00
	Minimum	40.00	16.00	36.00	16.00	36.00	36.00
	Maximum	88.00	60.00	84.00	88.00	66.00	84.00
	Skewness	0.388	−0.335	0.760	−0.008	−0.391	1.149
	CV (%)	0.260	0.377	0.342	0.452	0.265	0.368
	CI	44.854–78.480	24.381–56.286	34.204–72.46	27.344–76.656	38.233–67.767	30.896–69.771
Phosphate (μg/l)	Mean ± SD	0.045[a] ± 0.022	0.023[b] ± 0.017	0.025[b] ± 0.01	0.027[c] ± 0.011	0.029[c] ± 0.011	0.0373[c] ± 0.031
	Median	0.039	0.020	0.025	0.023	0.031	0.027
	Minimum	0.020	0.001	0.022	0.020	0.011	0.001
	Maximum	0.079	0.048	0.029	0.048	0.042	0.079
	Skewness	0.416	0.325	0.174	1.575	−0.430	0.408
	CV (%)	0.545	0.747	0.113	0.404	0.393	0.824
	CI	0.0193–0.0710	0.00486–0.0401	0.0220–0.0280	0.0154–0.038	0.0168–0.0405	0.005–0.070
Silicate (mg/l)	Mean ± SD	4.65[a] ± 0.58	1.76[b] ± 0.50	7.34[a] ± 2.24	4.60[c] ± 2.24	4.10[c] ± 2.61	5.04[c] ± 3.46
	Median	4.62	1.51	8.06	4.16	3.97	4.64
	Minimum	3.84	1.30	3.20	2.28	1.41	1.30
	Maximum	5.55	2.52	9.43	7.94	8.18	9.43
	Skewness	0.157	0.701	−1.144	0.436	0.419	0.196
	CV (%)	0.136	0.291	0.305	0.488	0.635	0.688
	CI	3.989–5.311	1.219–2.291	4.985–9.684	2.243–6.961	1.367–6.835	1.402–8.671
Dissolved organic matter (mg/l)	Mean ± SD	0.415[a] ± 0.27	1.097[b] ± 0.093	1.815[c] ± 0.22	1.115[c] ± 0.71	1.20[c] ± 0.62	1.01[c] ± 0.65
	Median	0.34	1.090	1.77	1.205	1.09	0.995
	Minimum	0.15	0.98	1.58	0.15	0.30	0.23
	Maximum	0.98	1.28	2.10	2.03	2.1	1.88
	Skewness	1.294	0.664	0.236	−0.164	0.0630	0.097
	CV (%)	0.714	0.099	0.121	0.637	0.513	0.640
	CI	0.104–0.726	0.983–1.211	1.584–2.046	0.369–1.861	0.555–1.848	0.332–1.688
Chlorophyll-a (μg/l)	Mean ± SD	1.246[a] ± 0.40	0.267[a] ± 0.38	7.48[b] ± 3.24	2.154[c] ± 2.115	3.952[c] ± 5.27	2.884[c] ± 3.35
	Median	1.068	0.107	7.480	1.068	1.068	1.602
	Minimum	1.07	0.107	4.272	0.107	0.107	0.107
	Maximum	2.136	1.067	11.748	5.34	11.748	9.612
	Skewness	1.789	1.789	0.141	0.681	0.737	1.166
	CV (%)	0.350	1.450	0.433	0.982	1.334	1.264
	CI	0.788–1.704	−0.145 to 0.679	4.076–10.876	−0.066 to 4.373	−1.582 to 9.485	−0.943 to 6.710

Note: Means with the same superscript (a/b/c) do not differ from each other (Tukey's HSD test; CV, coefficient of variance; CI, confidence interval.

et al. 2019), and Jargo (Alam *et al.* 2021a) reservoirs in India as well as in other countries globally (Oliveira *et al.* 2004; Terra *et al.* 2010; Pennock *et al.* 2021). This might be due to alterations in the historical and local processes like homogenization of the habitats and great variations in the water level and finally, the water quality parameters in the reservoir that favored a lesser number of native fish species in the lacustrine zone of the reservoirs (Terra *et al.* 2010; Sandhya *et al.* 2019; Pennock *et al.* 2021). This is following studies by Sandhya *et al.* (2019) and Alam *et al.* (2021a) in reservoirs in India. The abundance of the commercially important major carps (*L. rohita, C. mrigala*, and *L. calbasu*), and catfish (*S. silondia*, *M. seenghala, M. aor, B. bagarius*, *C. garua*, *O. bimaculatus*, and *E. vacha*) declined in abundance from riverine zone towards the lacustrine zones, which indicated that reservoirs act as ecological barriers. The information on the patterns of fish faunal diversity and abundance on the longitudinal scale in the reservoir is vital for fishery managers. The highest fish fauna diversity in the reservoir

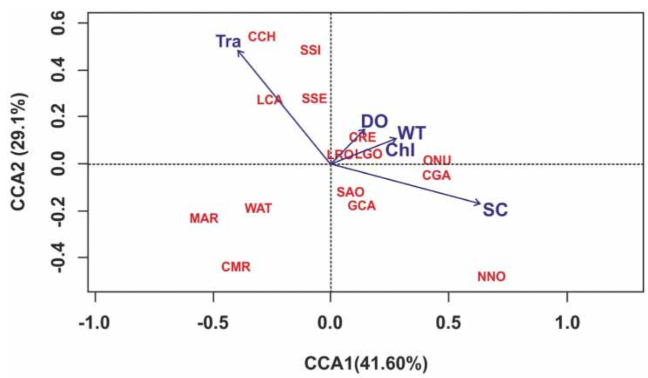

Figure 9 | CCA biplot of the fish abundance of the top 15 commercially important fishes of the Rihand reservoir with abiotic variables.

was observed in the monsoon season. The catchment area of the reservoir is dominated by cultivated and forest lands. It gets adequate nutrient inputs from the runoff during the monsoon months. Most of the rheophilic fish species in streams connected to reservoirs use reservoirs during the monsoon season, which is their spawning season (Alam *et al.* 2021a; Koushlesh *et al.* 2022). The rainy season is also the main breeding season for a majority of the fish species in the tropical reservoirs in India (Lianthuamluaia *et al.* 2019; Sandhya *et al.* 2019). Also, several seasonal streams feed the reservoir resulting in higher flow during monsoon. Hence, the maximum fish diversity was observed during the monsoon season. The higher species richness and diversity have also been reported in other Indian reservoirs during monsoon (Lianthuamluaia *et al.* 2019; Sandhya *et al.* 2019; Alam *et al.* 2021a). The overall average dissimilarity between different zones and seasons was high due to the presence of three species, viz. *P. ranga*, *P. chola*, and *S. phulo*. The contribution of *P. ranga* in dissimilarity was up to 23.65% and 38.21%, respectively, for riverine and transitional zones and for transitional and lacustrine zones. Similarly, dissimilarity between different seasons was due to the presence of *S. phulo* (21.04%) during summer and winter, *P. ranga* (21.95%) during summer and winter, and *P. chola* (27.6 %) during monsoon and winter seasons. Fish fauna are a main indicator of the effects of obstruction to ecological connectivity and environmental modification (Kocovsky *et al.* 2009; Pelicice *et al.* 2015). All seven species, viz. *P. ranga, S. phulo, O. cotio, P. ticto, L. gonius, C. mrigala,* and *P. chola,* were identified as indicator species that may be important for benchmarking the environmental alterations in the Rihand reservoir. Terra *et al.* (2010) identified 11 out of 35 fish species as indicator fish species for the different zones of the Funil reservoir in the Paraíba do Sul River basin, Brazil.

The consequence of damming a river was observed by a higher number of species exclusively observed in the upper reaches of the reservoir (riverine zone) than those exclusively found near the dam. In the riverine zone, 14 species were documented that were not recorded from the transitional and lacustrine zones of the reservoir. On the other hand, only two species that were exclusive to the lacustrine site were observed. A ten-year study (1971–1981) in the reservoir following dam construction of the commercial fishery by the ICAR-Central Inland Fisheries Research Institute showed the dominance of *G. catla* (84.2%–92.1%) in the catch (Jhingran 1991). The historic fish catch-record analysis (1998–2018) exhibited a drastic reduction in the catch of rheophilic species such as *B. bagarius* and *E. vacha* (Figure 10) to almost nil, while some species like *G. catla*, *L. calbasu*, *S. siolondia*, *S. seenghala,* and *O. niloticus* have increased. The specific factors favoring some species to flourish need to be identified for the successful management of the fisheries in the reservoir in the future. Hora (1949), in his pre-impoundment study, reported 44 species of fish near the dam site, while only 24 species of fish were recorded in this study. The species recorded during the pre-impoundment survey, viz. *Glyptothorax cavia, G. horai, G. annandalei, G. telchitta, Erethistoides montana, Garra gotyla, Amblyceps mangois, Chagunius chagunio, Pseudolaguvia ribeiroi, Barilius bendelensis*, *Schistura denisonii,* and *Crossocheilus latius* were not documented (Hora 1949). In tropical regions, the monsoon season is the spawning period for most of the species wherein the rainfall is maximum. The higher rainfall during the monsoon season increases the water flow, food resources, and habitat availability, and improvement in the ecological conditions might have favored higher fish species richness and abundance in the riverine zone of the reservoir. The small-sized *P. ranga, S. phulo, P. chola, O. cotio, M. cascasia, P. sophore,* and *P. ticto* were among the most abundant species in the reservoir. Their ability to breed throughout the year along with their ability to complete their life-cycles in lentic waters possibly favored them in their proliferation and higher abundance in the reservoir. The construction of the dam

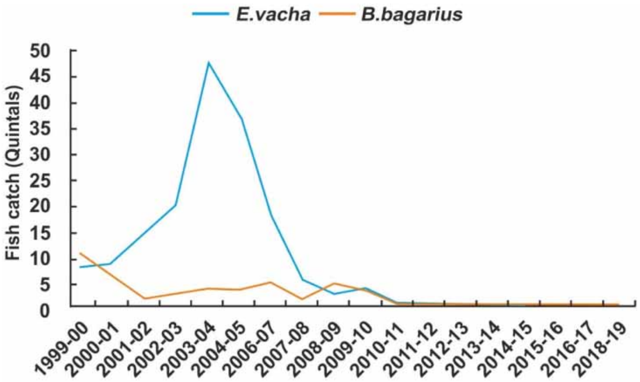

Figure 10 | Trends in the catch of *E. vacha* and *B. bagarius* in the Rihand reservoir.

restricted the distribution of rheophilic species like *E. vacha, E. murius, G. annandalei, B. bagarius, A. coila, L. guntea,* and *T. khudree* to the riverine zone of the reservoir, which is a long-term impact of damming a perennial river and may further negatively reduce their population size. Hence, the dam construction has affected the fish fauna by altering the composition and abundance, with a reduction, disappearance, or a distinct increase in the population of some species, resulting in the interruption of the fish communities in the reservoir. Similar findings have been reported in some Indian reservoirs and also around the globe (Gehrke *et al.* 2002; Anderson *et al.* 2006; Terra *et al.* 2010; Lianthuamluaia *et al.* 2019; Sandhya *et al.* 2019; Alam *et al.* 2021a).

Some exotic fish species introduced in India for commercial aquaculture, recreational activity, and biological control have found their way into Indian waters through accidental entry as escapees from the aquaculture systems or contaminants with stocking material and many of them are now common in reservoirs of India (Jhingran 1991; Sarkar *et al.* 2018; Alam *et al.* 2021b, 2022; Johnson *et al.* (2022).). They breed around the year and compete for space and food with the native fish fauna (Alam *et al.* 2015a, 2015b). *O. niloticus*, an exotic fish observed for the first time in 2014, has established successfully in the Rihand reservoir with an average contribution of 6.5 tonnes per year (Alam *et al.* 2021b) and poses a threat to the diversity of the native fish fauna and fishery resource management of the reservoir (Sarkar *et al.* 2018; Lianthuamluaia *et al.* 2019; Sandhya *et al.* 2019; Alam *et al.* 2021a, 2021b; Johnson *et al.* 2022). Regular monitoring of this exotic species is important to understand its adverse impact on biodiversity and invasiveness in the reservoir.

The impoundment of a lotic system into a lentic system usually results in changes in the trophic guild and the availability of food resources for the fish communities in the reservoir, favoring opportunistic over specialist groups of fishes and leading to homogenization of the biotic communities (Sandhya *et al.* 2019; Alam *et al.* 2021a). The dominance of invertivorous, planktivorous, omnivorous, and piscivorous fishes has been documented in some large reservoirs (Sandhya *et al.* 2019; Alam *et al.* 2021a; Sajina *et al.* 2021; Koushlesh *et al.* 2022). In this study, a greater abundance of carnivorous fish was observed in this reservoir. This could be ascribed to the high abundance of small-sized prey fish like *P. ranga, S. phulo, P. chola, O. cotio, M. cascasia, P. sophore,* and *P. ticto*. Similar reports have been documented from other reservoirs in India (Sandhya *et al.* 2019; Alam *et al.* 2021a). The distribution and assemblage pattern in the reservoir is influenced mainly by predation (Agostinho *et al.* 2010; Sandhya *et al.* 2019). This reservoir is an abode of four near-threatened fish species and these three were documented only from the riverine (tail) region of the reservoir, viz. *O. bimaculatus, A. coila,* and *B. bagarius,* and one, *C. chitala* both from the intermediate and riverine zones of the reservoir and also in small numbers that suggest conservation action measures in the river–reservoir interface. Earlier reports also advocated the riverine and transitional zones of the reservoir for management and conservation efforts of fish resources in the reservoir (Sandhya *et al.* 2019; Pennock *et al.* 2021).

The fish assemblage pattern and productivity in the reservoir are determined by limno-chemical parameters. Even though the environmental parameters in the reservoir were favorable for fish production, the analysis of the physico-chemical traits suggested the oligotrophic nature of its productivity. In the current study, all the studied water quality parameters were insignificant ($p > 0.05$) spatially indicating constant chemical conditions all over the reservoir. The CCA analysis showed that transparency and specific conductivity greatly influenced the patterns of fish assemblages in the Rihand reservoir. The water temperature, dissolved oxygen, and chlorophyll-a are other important water quality parameters that influence the fish distribution of fish fauna. The substantial impact of environmental parameters on fish assemblage has been described in the Indian reservoirs (Lianthuamluaia *et al.* 2019; Koushlesh *et al.* 2022) and other reservoirs worldwide (Araújo & Santos 2001; Rosso & Quirós 2010; Terra *et al.* 2010; Petesse & Petrere 2012; Pelicice *et al.* 2015). The specific conductivity in the water bodies is determined by the geology of the catchment area from where the water flows into them and can also indicate anthropogenic activities. In the aquatic ecosystem, specific conductivity was found to influence fish assemblages and abundance (Rosso & Quirós 2010; Terra *et al.* 2010). The water transparency determines the fish production in the reservoir as it influences the primary productivity affecting growth of plankton, which is the main food resource for many commercially important fish like *G. catla, L. rohita, L. calbasu*, *L. gonius, C. mrigala,* and *C. reba* in the reservoir. Moreover, low transparency, due to eutrophication in summer and winter and increased turbidity during monsoon can cause the health of the aquatic ecosystem to deteriorate (Kumar *et al.* 2020). Limno-chemical traits are associated indirectly or directly with various biological processes like food and feeding, survival, growth, and reproduction of fish (Karnatak *et al.* 2018; Lianthuamluaia *et al.* 2019). Therefore, for the better management of fish assemblages and diversity in the reservoir, regular monitoring of the environmental parameters would be a judicious strategy.

CONCLUSION

The present study generated baseline data on the status of fish fauna, diversity and assemblage patterns, and the physico-chemical conditions in a large sub-tropical reservoir in northern India. Our findings clearly show that the patterns of fish fauna structuring are different in the riverine, transitional, and lacustrine zones of the Rihand reservoir, which is in agreement with the zonation concept. The results demonstrated considerable negative impacts on the fish fauna of damming a perennial river in the long term as *Glyptothorax cavia, G. horai, G annandalei, G. telchitta, Erethistoides montana, Garra gotyla, Amblyceps mangois, Chagunius chagunio, Pseudolaguvia ribeiroi, Barilius bendelensis, Schistura denisonii,* and *Crossocheilus latiu*, which were documented before the impoundment, could not be recorded during our extensive fish survey. Also, the rheophilic fish species like *C. chitala, O. bimaculatus, A. coila*, and *B. bagarius*, which belong to the threatened category, were observed in the riverine and transitional zones and demand their conservation. A survey is required in the reservoir for the identification of their breeding and nursery grounds in the upper reaches of the reservoir which was beyond the scope of this study. The dam across the Rihand River has modified its ecosystem and acts as an obstacle to the longitudinal downstream movement in the reservoir and the migration of fish fauna upstream of the dam. The migratory species such as *Tor khudree* and *Bagarius bagarius* which were historically present in the catch are now confined in the upper reaches of the reservoir in small numbers. These migratory fish could be restored through the installation of fish passes as a mitigation tool. Also, as mitigation measures for restoring the ecology and fisheries below the dam, a further study on the environmental flow assessment is needed. Limitations to restoring to pristine condition might remain for selected fish species or life-history stages. The ways out for downstream movement within the reservoirs is a complex issue and requires additional research. The accomplishment of fisheries improvement in large reservoirs of India depends on auto-recruitment through the *in situ* breeding of the major carps that feed low in the food chain. This would help in optimizing the productivity of the reservoir. Earlier studies (Natarajan & Pathak 1987; Alam *et al.* 2021b) have shown the occurrence of the breeding population of *L. calbasu, L. rohita*, and *C. mrigala* in the Rihand Reservoir. Their breeding and nursery ground needs to be identified and protected in the riverine zone, which was not investigated in this study. In addition to this, the monsoon ban on fish exploitation and other fishery control measures like regulation of mesh size, fish size, catch limit, etc., during the rainy season (spawning period) needs to be successfully executed to promote the natural recruitment of the Gangetic carps (*G. catla, L. rohita*, and *C. mrigala*). The primary goal behind the construction of the dam in India like other countries of the word has seldom been the enhancement of fish production. To fully realize the fishery potential of the Indian reservoirs, coordinated efforts are needed between the fish managers and other stakeholders. This has the potential to considerably enhance fish production, rural economies, livelihood, and nutritional security. The limitation is that various water demands from the reservoir require a more sensible approach towards the operation of dams. The result also indicated a significant influence of the environmental parameters on the fish abundance and diversity in the reservoir, which could be useful for the development of conservation and management plans for the reservoir. The accomplishment of imminent management and conservation measures necessitates the identification of particular factors that let species be successful after dam construction. *Silondia silondia*, a riverine species, has adapted and successfully flourished in the changed environment. A further study is required to identify factors responsible for its burgeoning in the altered environmental condition. Based on our present research, we recommend an ecosystem-based approach in each zone for the efficient management of the reservoir fisheries. We advocate the inclusion of the riverine and transitional zones into the fisheries management and conservation strategies and also the stocking of the commercially important major carp through the adoption of the cage systems in the deeper zones (transitional and lacustrine) and pen culture in the peripheral and shallower areas of the littoral regions close to the bank of the reservoir as substitutes for land-based aquaculture systems for enhancing fish production. To recover the extirpated species or declining population of some threatened fish species (*O. bimaculatus, T. khudree*, and *B. bagarius*), we suggest their re-stocking in the reservoir through planned ranching so that their genetic integrity is maintained. Strict monitoring of the exotic *O. niloticus* needs to be undertaken to maintain the optimum health of the ecosystem, and understand its invasiveness and impact on the endemic fish population in the reservoir. More efforts are needed towards sensitization and community participation in reservoir fisheries and its management and implementation of policy guidelines.

AUTHOR CONTRIBUTIONS

Absar Alam rendered support in explorations, field data collection, data analysis, and manuscript preparation. Jeetendra Kumar rendered support in field data collection, data analysis, and manuscript preparation. Uttam Kumar Sarkar conceptualized the whole article, implemented the work, guided in manuscript preparation and provided support in manuscript corrections. Dharm Nath Jha rendered support in data analysis and manuscript preparation and correction. Sanjeev Kumar Sahu rendered support in data analysis and manuscript preparation. Shyamal Chandra Sukla Das rendered support in technical input and manuscript corrections. Saket Kumar Srivastava rendered support in field data collection on water quality. Vijay Kumar rendered support in field data collection on water quality. Basanta Kumar Das supported the work and gave overall guidance.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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