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Ecological assessment of a subtropical floodplain wetland of the Ganga basin in the context of changing climate using GIS tools

Bandana Das Ghosh[a], Sanjeet Debnath[a], Uttam Kumar Sarkar[b,*], Basanta Kumar Das[a], Mishal Puthiyottil[a], Canciyal Johnson[a] and Gunjan Karnatak[a]

[a] ICAR-Central Inland Fisheries Research Institute, Barrackpore, West Bengal 700120, India
[b] ICAR-National Bureau of Fish Genetic Resources, Lucknow, Uttar Pradesh 226002, India
*Corresponding author. E-mail: uksarkar1@gmail.com

UKS, 0000-0001-8166-4375

ABSTRACT

Climate change associated with anthropogenic stressors are considered the main threat to the tropical wetlands, resulting in reduced water connection followed by a decline in ecological functions. This article presents a systemic approach to assess the present ecological status of a tropical floodplain wetland concerning the fisheries and associated ecosystem services. The analysis of historic climatic data indicated significant change (increasing average annual air temperature, $R^2 = 0.098$; decreasing total annual rainfall, $R^2 = 0.042$). In addition, a significant reduction in the wetland area was also observed. Altogether, 45 fish species were reported in the studied wetland, of which 2 are listed as endangered and 7 are near threatened. The present study demonstrated the variation of the important fisheries-related environment and nutrient parameters of the wetland through the geographic information system (GIS)-based spatial distribution map for the reader's digest. It has been found that the provisioning ecosystem services are higher in number (n=9) followed by supporting (n=6), regulating (n=4), and cultural (n=2) ecosystem services. Finally, we have discussed some important case-specific sustainable climate-smart adaptation and mitigation approaches to strengthen the resilience and adaptive capacity of fishers.

Key words: climate change, fisheries adaptation, floodplain wetland, GIS mapping

HIGHLIGHTS

- The analysis of climatic data (1985–2020) showed a considerable change in climatic parameters.
- Forty-five species were reported in the wetland, of which 2 are listed as endangered and 7 are near threatened.
- We used GIS tools to demonstrate spatial variation, and mapping of nutrient and water parameters are influenced mostly by climatic parameters.

1. INTRODUCTION

Wetlands occupy approximately 6% of the terrestrial surface and provide a variety of ecological services to the surrounding population (Mao *et al.* 2018). Tropical floodplain wetlands are typically situated next to rivers, lakes, and oceans and formed through hydrological circumstances (Kingsford 2000). These are rich, biologically sensitive ecosystems that support unique aquatic biodiversity and play a vital role in providing livelihoods and nutritional security to a large segment of the population in developing countries (Pathak *et al.* 2004). However, they are disappearing globally as a result of increased human activity and climate change, particularly in Asia and several mid- and high-latitude regions (Zhang *et al.* 2017). Besides the direct and indirect effects of rising temperature, changes in rainfall intensity and frequency, extreme climatic events such as drought, flooding, and the frequency of storms, floodplains have been converted for intensive agricultural exploitation in developing countries (Naiman & Decamps 1997). Freshwater ecosystems and the associated fish diversity and fisheries are changing at the same pace under the changing climate (Woodward *et al.* 2010; Sarkar *et al.* 2019). Global wetlands have lost up to 87% of their original area since 1700 (Hu *et al.* 2017).

Floodplain wetlands play an important role in the economic, social, and cultural activities of rural India. However, wetland fishery resources of the country are under continuous threat of environmental degradation due to natural as well as anthropogenic activities, resulting in ecosystem imbalance, shrinkage in water spread area, a decline in biodiversity and a decrease in fish production at an alarming rate (Sarkar & Borah 2018). Wetlands of India have been subjected to acute conversion, hydrologic modification (dam/barrage building), and chronic loss (alteration of wetlands, degradation of water quality, groundwater depletion, invasion of alien species and extinction of natural biota) causing loss of floodplain wetland biodiversity and degradation causing a drop in fish production (Phukan & Saikia 2014; Das 2015). Lack of consistency in government policy governing economics, environment protection, and development planning, as well as a lack of sound governance in scientific management have contributed to the degradation of these water bodies (Turner *et al.* 2000; Kumar *et al.* 2013).

Inland floodplain wetlands in India cover a 0.55 Mha area, which is one of the major resources for freshwater fish and is indispensable for different economically important and migratory fish species (Sarkar & Borah 2018). Typically, the Gangetic plains of West Bengal have a considerable number of natural wetlands (area: 42,500 ha) in India contributing to the economy and food security of the state. Inland water bodies of West Bengal harbour around 190 varieties of native fishes, which is about 23% of total freshwater fishes found in India (Mahapatra *et al.* 2014). Productive floodplain wetlands play an important role in fisheries, livelihood, and the nutritional security of the rural population of West Bengal (Sarkar *et al.* 2020a, 2020b, 2020c). The alarming reduction in fish yield has had a significant impact on the lives and livelihoods of indigenous fishers as well as other stakeholders that rely on these resources directly or indirectly. Human encroachment for habitation and agricultural use resulted in habitat degradation and the contraction of wetland areas throughout India, accelerating the deterioration of the Gangetic planes in terms of its ecology (Sarkar *et al.* 2020a, 2020b, 2020c). Flood control measures like the formation of dams as well as sluice-gate near the feeding river area can also affect the productivity of wetlands by preventing or limiting auto-stocking. Uncontrolled weed infestations, particularly water hyacinth, are a threat to floodplain wetland fisheries as the spreading plant accelerates eutrophication in wetlands that lead to a variety of problems in navigation, fishing, boating tourism, water quality, and species diversity (Lahon *et al.* 2023). Aside from water hyacinth, Ipomoea infestation is frequent in the studied region, causing wetland ecosystem degradation and shrinkage of the water spread area through eutrophication. The lack of effective equipment and gear particularly built for floodplain wetlands also makes it difficult to maximise the potential of wetland resources.

The health of inland water bodies is directly connected to aquatic biodiversity, and even minor changes have major impacts on it. The effect of unpredictable climatic events such as shifts in rainfall patterns, recurrent floods, droughts, and cyclones is the major constraint for sustaining the healthy ecology of the wetlands, fisheries, and livelihoods of fishers (Sarkar & Borah 2018). Extreme climatic events such as floods and droughts are becoming more frequent, and hurt socioeconomic growth (Faye 2022). The impact of climate change was observed by various authors (Chen *et al.* 2018; Mehvar *et al.* 2019; Saintilan *et al.* 2019; Das Sarkar *et al.* 2020) on various types of wetland ecosystems and in diverse agro-climatic zones using prediction models (Ekwueme 2022) and other tools. However, the application of the geographic information system (GIS) to understand and manage wetland fisheries has not been adequately explored in India. The GIS is an important tool for collecting, storing, reviewing, processing, combining, analysing, and displaying data spatially related to lakes and their basins (De Mers 1997). It was found during the literature review that the scientific reports on assessing the overall health and importance of tropical floodplain wetlands in India are scanty. There is a dearth of comprehensive studies and literature on the spatio-temporal change of floodplain wetland resources in the face of ecological degradation, encroachment, and area shrinkage due to harmful climate change and anthropogenic activities. Especially in Asia, the wetland management plans are in their nascent phase (Sarkar *et al.* 2021). To fill in this gap, there is an urgent need to produce region- or location-specific studies indicating the all-around present conditions of wetlands with respect to their ecology and productivity.

On this ground, the present study was conducted by incorporating a systematic investigation of climatic and hydrological influences on floodplain wetland fish diversity as well as fish production trends. To the best of our knowledge, this is the first study to demonstrate the spatial analysis of a threatened tropical floodplain wetland using the Kriging geospatial technique. The first aim of the present study was to comprehensively analyse the historic pattern of climate change in the selected region in relation to its impact on the wetland ecology including the fish diversity and production trends. The paper also highlights the role of the GIS for ecosystem-based fisheries management and research needs for conserving biodiversity and sustainably increasing the productivity. The second aim of the study was to estimate the influence of changing climates on the ecosystem services provided by the wetland by utilising stakeholders' perceptions. The present account also suggests several climate-resilient adaptation measures for the improvement of the ecosystem health of the wetland in relation to the benefit of fishers.

2. MATERIALS AND METHODS

2.1. Study area

Media wetland (22°52′35″N, 88°46′29″E) is located in the eastern part of India, covering an area of about 108 ha in the floodplains of the lower stretch of the Ganga River. Fisheries and other agricultural practices within this closed wetland are governed and monitored by the Konkana Fishermen Welfare Society, which has 148 active fisher members belonging to the scheduled caste category. Culture-based fisheries practice is dominant over the capture-based fisheries in the wetland. Three sampling stations were selected, which were at approximately equal distances across different parts of the wetland area (Figure 1). Sampling for the present study was conducted once a month, throughout a calendar year (2021–2022), covering all the seasonal variations of the sample.

2.2. Data collection and analysis

2.2.1. Primary data

Fish and environmental samples were collected in triplicate from each site, monthly (Sarkar *et al.* 2020a, 2020b, 2020c). Water temperature, pH, salinity, total dissolved solids (TDS), and conductivity were determined with the multi-parameter Testr™ 35 series (OAKTON). The depth of the water column was estimated through the Hondex™ digital depth sounder. Transparency was measured using a 20-cm diameter standard black-and-white Secchi disk (Strickland & Parsons 1972). DO was measured by a digital DO meter (Ultron DO5510). Total alkalinity (TA), hardness, available phosphate (AP), nitrate (N), free carbon dioxide (FCO_2), and chlorophyll-a (Chl-a) were measured using standard methods (APHA 1998). Primary productivity (gross primary productivity: GPP and net primary productivity: NPP) was measured through *in situ* analysis of community respiration following Vollenweider (1969). The Trophic State Index (TSI) was calculated following Lamparelli (2004). After conducting experimental fishing, samples were brought and identified in the laboratory based on specific morphometric and meristic characteristics following Talwar & Jhingran (1991) and Vishwanath *et al.* (2011).

2.2.2. Secondary data

The monthly climatic data (mean air temperature and total annual rainfall) of the concerned districts (North 24 Parganas, West Bengal, India) were collected (1985–2020) from the Indian Metrological Department (IMD), Alipore, Kolkata, India for the study period. On the other hand, the yearly fish production statistics were collected from the existing fishermen cooperative society's record book.

2.2.3. Data analysis

Long period average (LPA) was utilised as a baseline to measure the change in rainfall and temperature in the present study (Lianthuamluaia *et al.* 2023). One-way analysis of variance (ANOVA) followed by Tukey's post hoc test was carried out to investigate potential differences in the environmental parameters across the stations of the wetland. Data on fish diversity were initially collected and then organised according to taxonomic orders. The conservation status has been documented according to the IUCN Red List of Threatened Species (IUCN 2020). The richness and evenness of fish species at each station were also determined following standard indices (Table 1). To investigate the relationship between environmental conditions and fish community structure, Canonical Correspondence Analysis (CCA) at a significance threshold of $p < 0.05$ was done using PAST3.26. We utilised the CCA for each site to estimate the relative value of each site, which links fish abundance and environmental characteristics. The CCA was applied to the total fish data matrix as well as the environmental data matrix, resulting in a direct environmental interpretation of the generated ordination axes. Trend analysis of the available production data was carried out to assess the pattern of fish production in the wetlands. The present fish species richness (number of different species) was compared with the previously (before three decades) found fish species richness by cross-verification with the local fishermen through a standard questionnaire prepared by ICAR-CIFRI (2020), India.

2.3. GIS mapping

In the present study, a Landsat 8 Operational Land Imager (OLI) multispectral image (path 148, row 38, resolution 30 m) with less than 10% cloud coverage was downloaded from the USGS Earth Explorer website to extract the water spread area for the wetland. The GPS coordinates of the points were collected during on-field sampling. The water area of the wetland was digitised, and the percentage of the area was measured. Layer stacking and radiometric correction processes have been used during data processing (Abd El-Kawy *et al.* 2011; Dibs *et al.* 2015). After the image correction, false colour

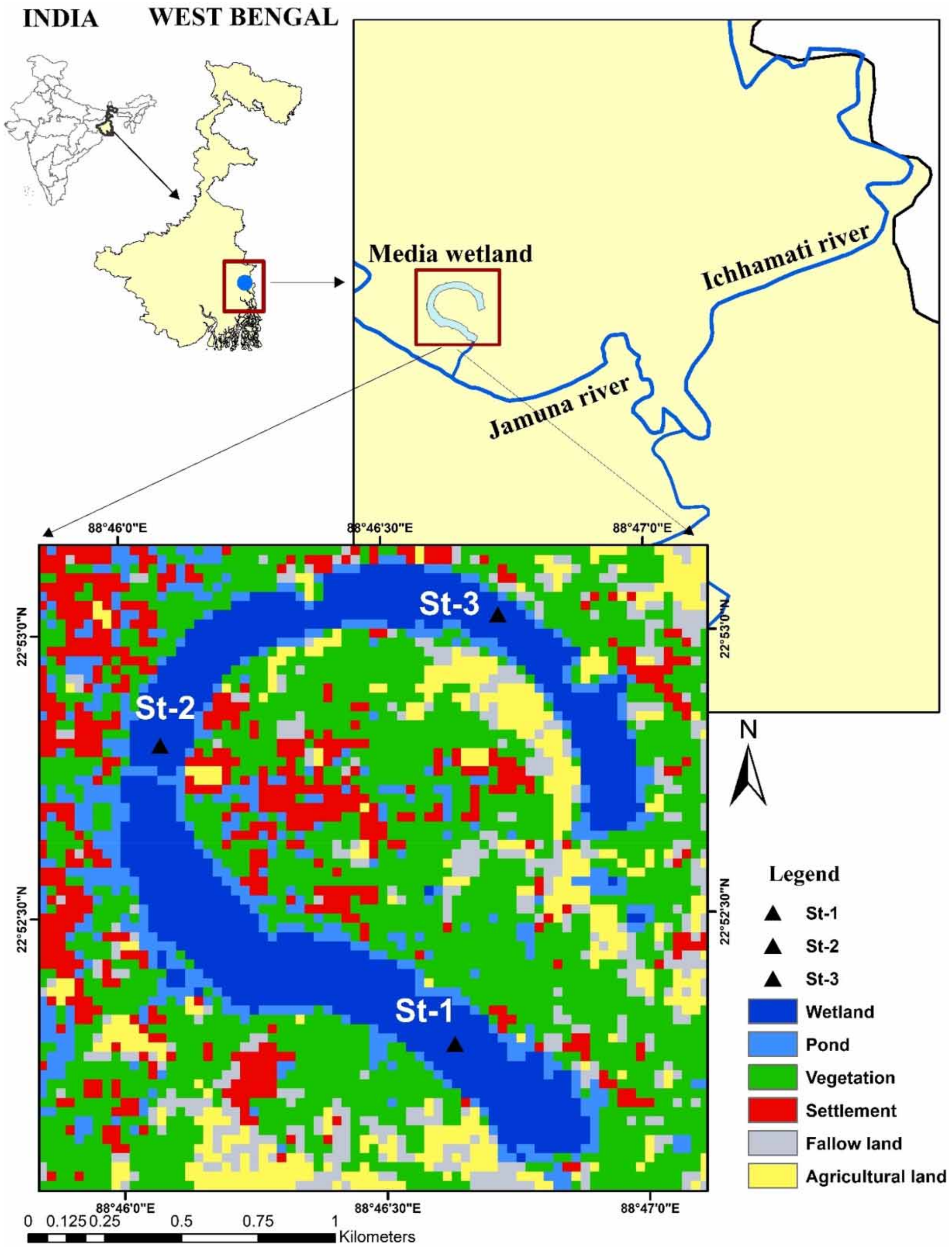

Figure 1 | Location including different sampling stations of the Media wetland, West Bengal, India.

composition (FCC) and the composite band were created for better and clearer visualisation of the image. The spatial interpolation maps were created through the 'Kriging' interpolation method, an advanced geostatistical analysis (Isaak & Srivastava 1989; ESRI 2013). Kriging is a superior approach and differs from others in that it exploits spatial correlation between sampled locations during the process to interpolate values in the spatial field (Chakraborty *et al.* 2022). The interpolation was applied concerning the different environmental datasets by transferring spatial data into the GIS platform using ArcGIS 10.4.

Table 1 | Different species diversity and evenness indices used in the study

Index	Equation	Reference
Shannon–Weiner diversity index (H')	$H' = -\sum P_i \, lnP_i$	Shannon & Weiner (1949)
Simpson diversity index (D_{Sim})	$D_{\text{Sim}} = 1 - \frac{\sum n_i(n_i - 1)}{\sum N(N-1)}$	Whittaker (1965)
Pielou's Evenness index (J')	$J' = \frac{H'}{lnS}$	Pielou (1975)

2.4. Assessment of ecosystem services

Data regarding the present and previous status of different ecosystem services were collected from detailed interactions with the fish farmers of the wetland through the questionnaire. We interviewed 50 people (age 55 ± 5 years), who have been experienced in wetland fisheries for a long time, and gathered information about the present and previous status of the wetland ecosystem services, classified as provisioning, regulating, cultural, and supporting (MEA 2005). The Rapid Assessment of Wetland Ecological Services (RAWES) technique has been used for developing the ecosystem service index (ESI) following Fennessy *et al.* (2007) and Kotze *et al.* (2012) with modification. Scoring was given as per the response of the stakeholders on the status of the concerned ecosystem service on a scale, namely significant positive (+2), positive (+1), neutral (0), negative (−2), and significantly negative (−1). Groups of ecosystem services (all 21 identified services) were added together and divided by the number of services in that category (provisioning $n_{\text{total}} = 9$, regulating $n_{\text{total}} = 4$, cultural $n_{\text{total}} = 2$, and supporting $n_{\text{total}} = 6$). The ecological services scores were numerically transformed to express and compared with the ESI of four ecosystem services categories through a single formula:

$$\text{ESI} = \frac{\sum (n_{+2} + n_{+1}) + (n_{-2} + n_{-1})}{\sum n_{\text{total}}}$$

The overall framework of the model used for the ecological assessment of the vulnerability of the Media wetland is shown in Figure 2.

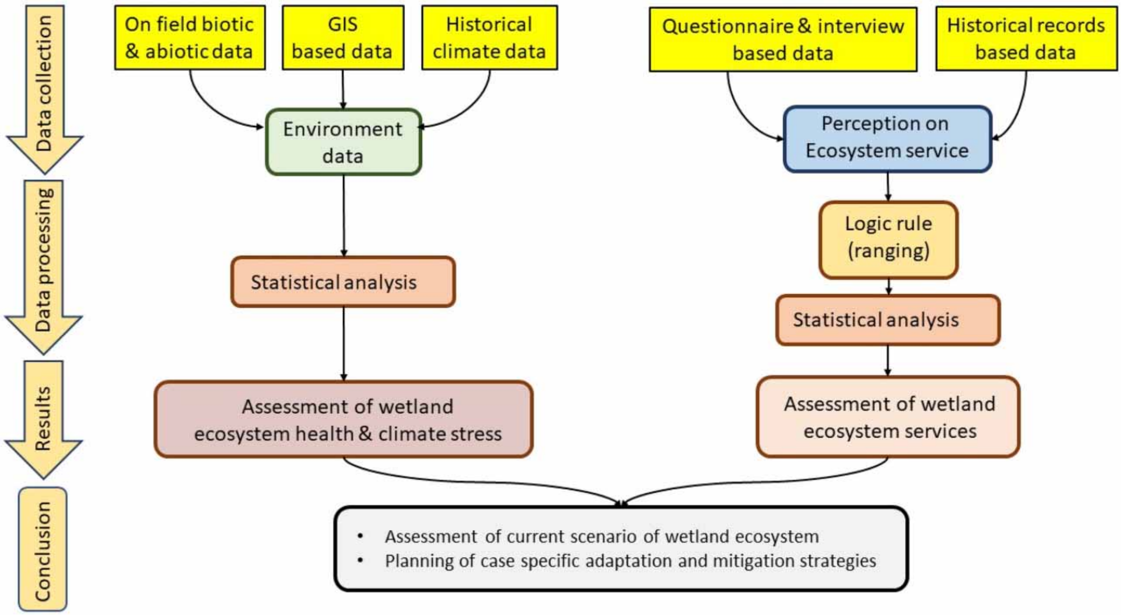

Figure 2 | Framework of the model used for the ecological assessment of the vulnerability of the Media wetland.

3. RESULTS

3.1. Water quality

One-way ANOVA followed by a post hoc test showed statistically significant differences ($p < 0.05$) for electrical conductivity, total phosphate, nitrate, and Chl-a throughout the year. Analysis of Pearson's correlation coefficient (Figure 3) showed a significant ($p < 0.05$) positive correlation of pH with TDS. Similarly, transparency was positively ($p < 0.05$) correlated with depth and TP. DO and TA were positively ($p < 0.05$) correlated with hardness. TP was positively ($p < 0.05$) correlated with nitrate. Chl-a was positively ($p < 0.05$) correlated with algal bloom. On the other hand, a significant ($p < 0.05$) negative correlation was found between pH and TP; TDS and DO; nitrate and Chl-a.

3.2. Climate data analysis

Trend analysis of the climate data during the period 1985–2020 was presented in Figure 4. The annual average air temperature indicated an increasing trend ($R^2 = 0.098$) with a rapid increase of 0.50 °C over the last 5 years for the long period

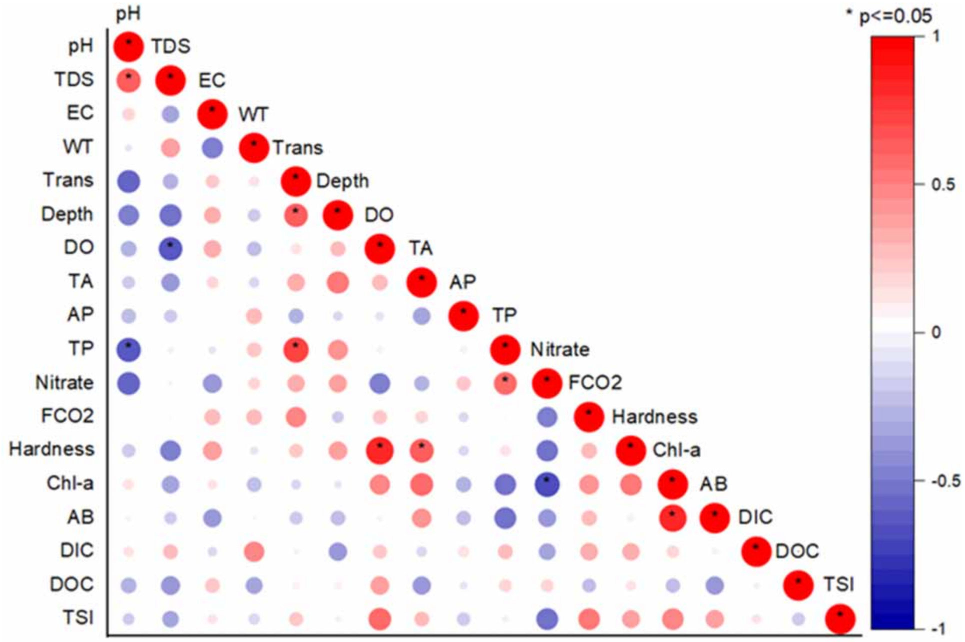

Figure 3 | Correlation plot of different ecological parameters of water from the Media wetland.

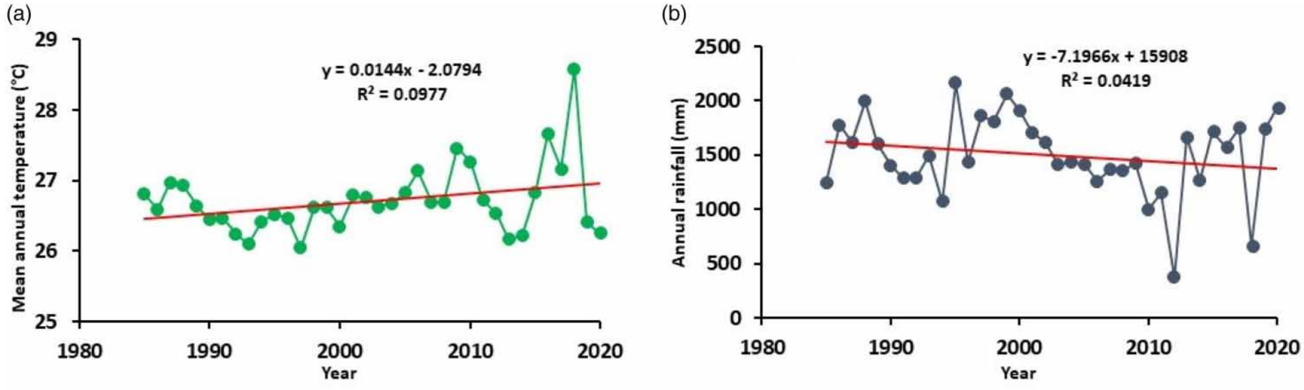

Figure 4 | (a) Temperature trend and (b) annual rainfall trend in North 24 Parganas district, West Bengal, India.

average (LPA) from 1985 to 2020. On the other hand, total annual rainfall during the same period indicated a decreasing trend ($R^2 = 0.042$) with an increase of 34.85 mm in the last 5 years considering the LPA.

3.3. Fish species diversity and production

Among 45 fish species, Cyprinidae was found to be abundant, followed by Channidae, Bagridae, Mastacembelidae, Notopteridae, Siluridae, Osphronembelidae, Teardontidae, Anabantidae, Ambassidae, Synbranchidae, Belonidae, Clariidae, Sisoridae, Schilbeidae, Ailiidae, Danionidae, and Anguilidae (Figure 5(a)). During the period of study, the values of Shannon–Weiner diversity index (H'), Simpson diversity index (D_{Sim}), and Pielou's Evenness index (J') were found to be 1.44, 0.049, and 0.871, respectively. Assessment of the conservation status of fish species in the Media wetland shows that out of 45 species, 33 were under least concern (LC), 7 species under near threatened (NT), 2 species under endangered (EN), 1 species under not evaluated (NE), 1 species under critically endangered (CR), and 1 species under data deficiency (DD) (Figure 5(b)). The current study found that carnivorous fishes are more abundant (48.88%) followed by omnivorous fishes (37.77%) and herbivorous fishes (13.33%). According to the stakeholders' responses, the number of fish species encountered is 45 at present, which was previously (before 30 years) recorded as 50–60 from the Media wetland (Supplementary material, Appendix 1). In the present study, fish production trend analysis showed an increasing trend from the year 2011 to 2021 which was collected from the fishermen cooperative society (Figure 5(c)). The fish production increased from 15,455.23 kg in 2011 to 28,114.21 kg in 2021.

3.4. Influence of environmental factors on fish production

The relation of eight important environmental variables with individual fish species was shown in CCA (Figure 6). Of the available 45 fish species, only 14, those comprising the dominant 70% of the entire fish communities, were selected for analysis. Axis 1 and Axis 2 of the triplot explained 83.33 and 16.67% variability, respectively. The result shows that there are three distinct species groups: group 1 (*Labeo rohita* and *Cirrihinush mrigala*) greatly associated with dissolved organic carbon; group 2 (*Mystus tengara* and *Xenentodon cancila*) closely associated with FCO_2 and conductivity; and group 3 (*Amblypharyngodon mola, Clarias magur, Salmostoma bacaila,* and *Anabas testudineus*) closely associated with aquatic algae, pH, and dissolved inorganic carbon. Other environmental parameters, namely rainfall, temperature, and depth, also influenced the abundance of the fish.

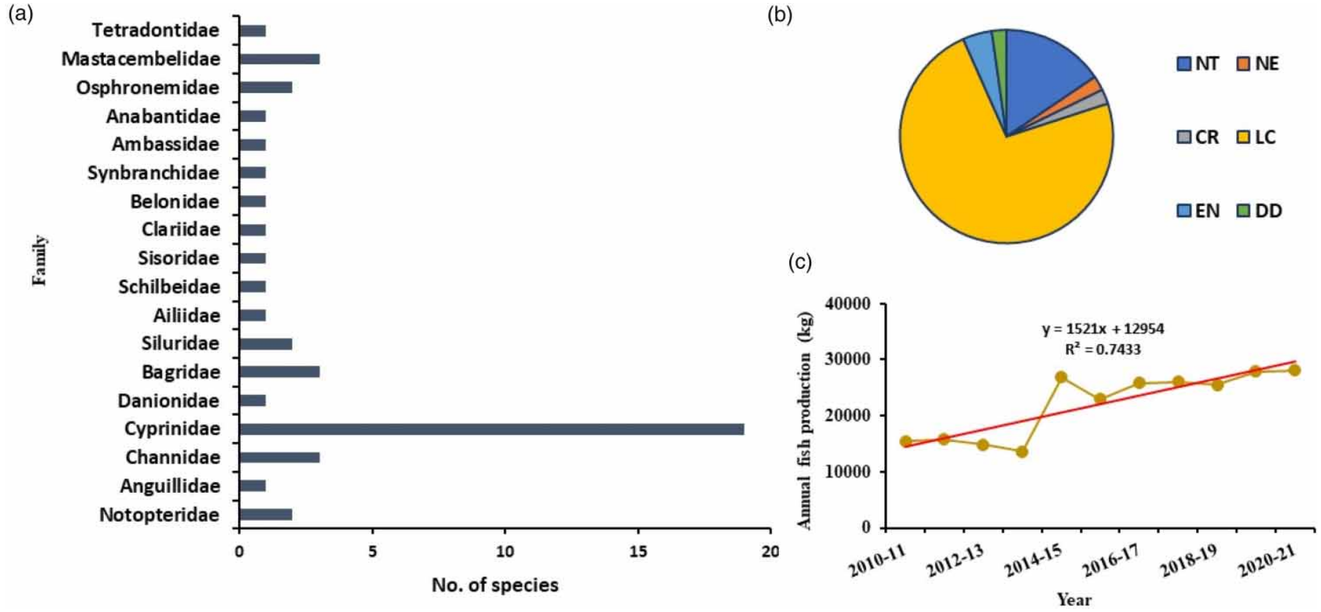

Figure 5 | (a) Family-wise fish distribution; (b) conservation status of fish of the Media wetland; and (c) fish production trend.

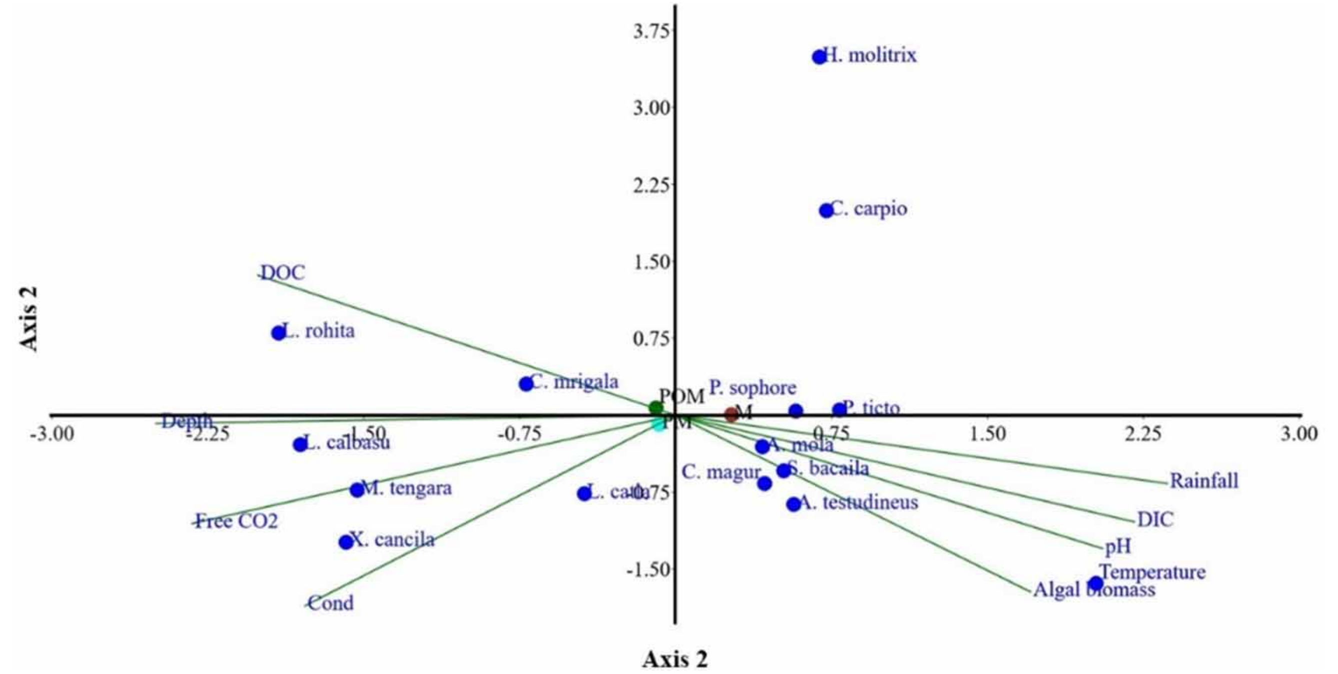

Figure 6 | Triplot of CCA relating the important environmental variables with fish species of the Media wetland.

3.5. GIS mapping

The thematic maps (Figure 7) were constructed to represent the spatial variation of the water depth, pH, transparency, DO, total phosphate, nitrate, macrophyte abundance, and Chl-a. The water quality parameter is directly linked with the fish production and climatic parameters. The average water depth varied between 5.4 and 6 m during the sampling period. Water transparency was in the range of 1.5–1.8 m. The average water pH of the wetland was 7.6. The distribution pattern of DO in the wetland was 6.4–8.5 mg/l in all the areas of the wetland. The average water total phosphate was 0.46 mg/l. The macrophyte abundance was higher in the range of 30–40% and Chl-a was high (44–46 mg/l) in the same area where macrophyte abundance is higher. In addition, the wetland shrinkage pattern of the Media wetland during 2002–2022 has been mapped and presented in Figure 8. It has been found that more than 20% of the water area is reduced compared to the base year 2002.

3.6. Assessment of ecosystem services

A total of 21 ecosystem services were identified in the Media wetland and were summed up and divided by the number of services in the category (provisioning = 9, regulating = 4, cultural = 2, supporting = 6) as shown in Figure 9. The maximum ESI value score is 0.952 for the Media wetland. It has been found that the average values for cultural ecosystem services are much higher (38.07%) followed by provisioning (28.17%), supporting (21.06%), and regulating (12.69%) ecosystem services.

4. DISCUSSION

Wetland ecology and biota are primarily impacted by wetland habitat factors. Water's physicochemical qualities are influenced by hydrological, geological, climatic, and anthropological variables (Bartram & Balance 1996). The temperature of the surface water in the examined wetland upsurges from pre-monsoon to monsoon season. DO in water decreases when water temperature rises (Bouslah *et al.* 2017). Water pH is a crucial factor in determining the health of any wetland, and it plays a significant part in aquatic species' life cycles by controlling metabolic activities (Palit *et al.* 2018). During the investigation, the alkaline pH of the water fluctuated significantly ($p < 0.05$). TDS levels were found to be high during the monsoon season, which could be attributed to the runoff of residential waste, garbage, and wastewater (Verma *et al.* 2012; Choudhary *et al.* 2014). During the monsoon season, the concentration of DO was lower, which could be attributed to increased rainfall throughout the research period. A similar range of DO concentrations was found in Kailash Khal, a Sundarban tropical

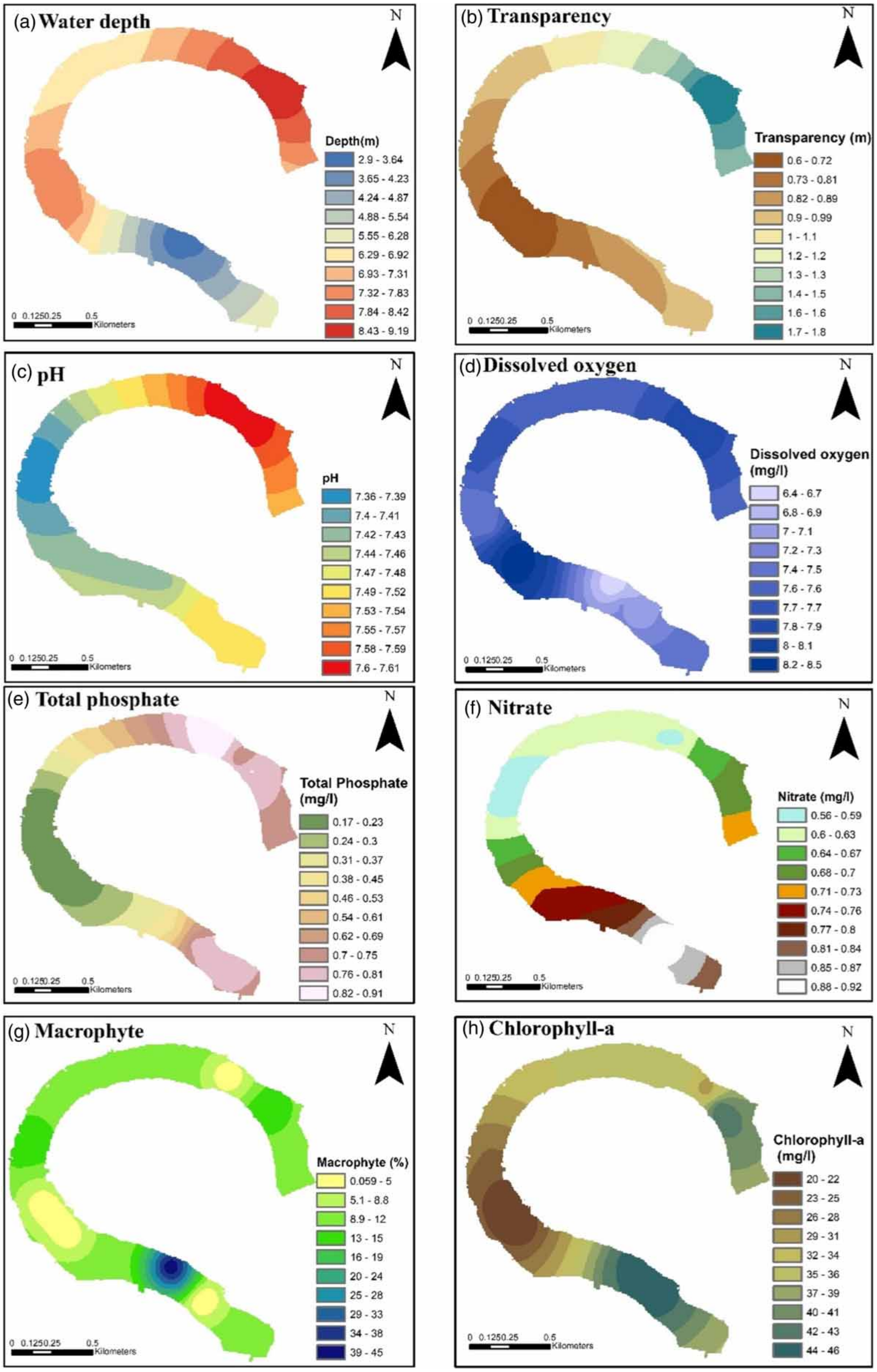

Figure 7 | GIS map showing spatial variations of (a) water depth, (b) transparency, (c) pH, (d) DO, (e) total phosphate, (f) nitrate, (g) macrophytes, and (h) Chl-a in the Media wetland.

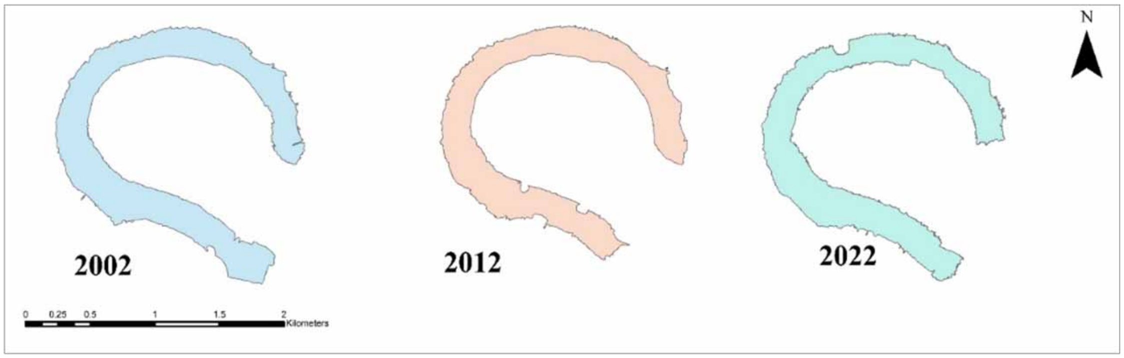

Figure 8 | GIS image revealing the water area shrinkage (from left – first: 2002; second: 2012; third: 2022) in the Media wetland.

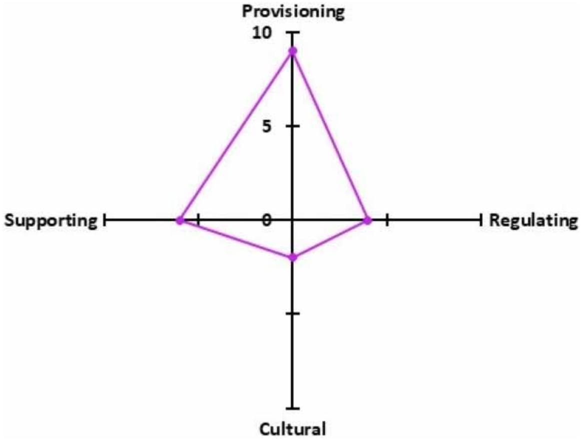

Figure 9 | Categories of ecosystem services provided by the Media wetland.

wetland (Gogoi *et al.* 2019). Transparency is a significant limiting factor for the productivity of the wetland and usually depends on suspended clay, silt, particle organic matter, dispersed aquatic organisms, and pigments created by the decomposition of existing organic matter (Michael 1969). The current study observed the least transparency during the summer, which is related to the effects of wind, suspended organic debris, phytoplankton enrichment, and increasing temperature. Michael (1969) and Kumar (1985) both documented seasonal variations in lake water transparency. The recent investigation discovered that seasonal changes in the water column were significant and largely depended on rainfall. According to Sugunan *et al.* (2000), the majority of wetlands in West Bengal are subject to water stress, and reduced rainfall is the primary reason for water balance challenges in closed wetlands. According to Lamparelli's (2004) TSI, a Media wetland can be classified as a mesotrophic wetland (range: 44–54). However, according to Das Sarkar *et al.* (2020), most of the wetlands in the studied region were found to be early eutrophic according to Carlson's TSI and were advanced to eutrophic according to Lamparelli's TSI. Kumari *et al.* (2021) discovered that sewage-fed wetlands had a higher TSI than floodplain wetlands.

The present study area has been experiencing an increased average annual temperature and a decrease in total annual rainfall. Sarkar *et al.* (2019, 2022) also recorded an increase in air temperature and a decrease in rainfall trend along the middle and lower stretch of the Ganga River basin. A similar study was carried out in the West Bengal districts of Maldah and Murshidabad by Naskar *et al.* (2022), and their findings are in parallel with the present study. Several other investigations in the Ganga Basin have been conducted (Das *et al.* 2013; Rathore *et al.* 2013), and it was established that variations in climatic characteristics such as rainfall pattern and temperature have a significant impact on the water quality parameters or micro-habitats found in associated wetlands. Seasonal fluctuations in wetland vegetation and fauna indicate that the wetland resources are climate-dependent for their viability (Rathore *et al.* 2013; Sarkar & Borah 2018). According to Sarkar *et al.* (2018), floodplain wetlands are biologically sensitive habitats that are thought to be the most impacted ecosystem by climate change. A shift in climatic conditions can actively alter the breeding season of the wetland fish community. The temperature varies substantially depending on the climatic conditions of the geographic location, and it also varies greatly during the day. In comparison to the current study, Bhowmik (1988) reported that minimum and maximum temperatures in West Bengal wetlands ranged from 17.5 to 32.0 °C.

In the present study, 45 species were described from the Media wetland indicating a declining trend in species diversity during the last few decades. Aziz *et al.* 2021 noticed the active participation of fishermen, and identified 63 species of fish and shellfish, belonging to 12 taxonomic orders in HakalukiHaor in 2018. Edwards *et al.* (2012) studied the fish fauna in Canyon Reservoir, and species diversity was also reduced. This kind of observation is common in other studies (Naskar *et al.* 2022; Sarkar *et al.* 2022). Mondal & Kaviraj (2009) recorded 49 fish species in the Gopalnagar and Dumur wetland of North 24 Parganas, West Bengal. Chakraborty (2002) observed 35 species from the Matura wetland and Ghosh & Biswas (2017) recorded 33 species from the wetland of Nadia district West Bengal, which is lower than the present finding. The fish species diversity decreases in the present study might be due to several reasons like habitat degradation, loss of river connectivity, climate change, pollution, anthropogenic activity like jute retting, agriculture run off, and sewage water disposal in the wetland (Sarkar & Borah 2018). In this study, the family Cyprinidae was found to be the major contributor to the overall wetland fish diversity. A similar pattern of observation was found by Sarkar *et al.* (2020a, 2020b, 2020c) and Mistry (2016). The conservation status shows few species in the NT and EN categories which need attention for their conservation. The species richness has declined in the last decades, Shannon–Weiner diversity index in the present study was significantly lower than that found by Sarkar *et al.* (2020a, 2020b, 2020c) in three similar floodplain wetlands (2.89–3.09), whereas the Simpson's index (0.049) was found to be less than previous studies that range from 0.93 to 0.94 (Sarkar *et al.* 2020a, 2020b, 2020c). Suriya *et al.* (2022) observed in Sago Palm Wetlands, Thailand, 62 species belonging to 24 families, and Cyprinidae was found to be the major family. The species diversity index was in the range of 0.66–2.67, the evenness index was in the range of 0.64–0.95, and the species richness index ranged from 0.36 to 6.86, indicating an intermediate–low uniformity, with a medium species number in the area. The value of evenness in the present study was quite good and reflects the homogeneous distribution of fishes throughout the wetland. Similar findings were reported from Coochbehar, West Bengal by Das (2018).

GIS and remote sensing will be useful for mapping the resources, and these maps will act as decision support systems for their long-term usage and management. Hu *et al.* (2020) used remote sensing imaging and land use models to quantify long-term wetland degradation in Hangzhou Bay from 1984 to 2016 and projected the spatial locations of wetland degradation until 2046 under various scenarios. Sarkar *et al.* (2021) used GIS technologies to conduct a spatio-temporal change analysis of floodplain wetlands in West Bengal and reported a reduction of the potential wetland coverage by 37.20–57.68%. A similar observation was found in the present study. The GIS-based study was also carried out in large reservoirs like Pong, Himachal Pradesh, India (Chakraborty *et al.* 2022). Regional changes in climatic variability have not only impacted the hydrodynamics of the wetland ecosystem of Indo-Gangetic plains but also impacted the biological diversity of wetlands (Sarkar *et al.* 2019). The wetlands of West Bengal, especially the lower Gangetic plains (North 24 Parganas), have witnessed chronic macrophyte infestation with increased eutrophication (Karnatak *et al.* 2022). Our findings are also in line with the same.

It has been found that regional climate variability may influence the reproductive behaviour of fish (Lianthuamluaia *et al.* 2023). In the current study, the CCA revealed that environmental parameters such as rainfall, temperature, algal biomass, dissolved inorganic carbon, depth, conductivity, FCO_2, and dissolved organic carbon influenced fish diversity. Similar findings were recorded by Aziz *et al.* (2021), who demonstrated how the climatic and anthropogenic variables are responsible for the loss of fish diversity in Hakaluki Haor, an ecologically significant wetland of northeast Bangladesh. Environmental influence was also obtained on fish assemblage patterns in Chandil reservoir, Jharkhand (Lianthuamluaia *et al.* 2019).

In the present study, the ESI score by the RAWES method depicts a moderate level of ecosystem services provided by the wetland and a similar observation was documented by Mandal *et al.* (2021) at Indrakpur, Ramavchandrapur, Kasthahali, and Purbasthali wetlands, which belongs to the same region as the current study. Kumari *et al.* (2023) documented nearly the same ecological services from the Bhomra wetland, Nadia, India.

5. RECOMMENDATION OF CLIMATE SMART ADAPTATION STRATEGIES

Although specific information on assessing the impact of climate change on floodplain wetlands is limited, it is clear that climate change will cause irreversible changes in the ecology of the natural hydrological network (Sarker 2022), as evidenced by a study on potential changes in floodplain inundation and connectivity between river and floodplain wetlands under projected future climates conducted in the river catchment area of Western Australia (Karim *et al.* 2016). According to Chen *et al.* (2015), inland natural wetlands, particularly those in dry and semiarid regions, would be influenced by changes in precipitation, runoff, temperature, and evapotranspiration owing to changes in precipitation, runoff, temperature, and evapotranspiration. As anticipated by the International Panel on Climate Change (IPCC 2023), increased flood intensity may result in erosion of floodplain wetland embankments, changes in sediment intake and nutrient load, and an accelerated hydro-cycle impacting notably closed wetlands. According to a predictive study using dynamic modelling, climate change manifested by increased temperature may have a profound impact on the lower Gangetic floodplain wetlands, as rising temperatures may cause erratic rainfall patterns, which may have ramifications on river hydrology (Whitehead *et al.* 2015). Any changes in climatic circumstances, particularly the rainfall pattern and temperature, have a significant impact on the water spread, turbidity, and aquatic vegetation in wetlands. Many scientists have found seasonal fluctuations in wetland flora and fauna, indicating that wetland resources are climate-dependent for their sustainability (Sarkar & Borah 2018; Kumari *et al.* 2023). Natural fish population abundance and species variety are expected to be particularly vulnerable to climatic perturbations, since lower water levels and a lack of rainfall may restrict the number of individuals able to spawn successfully. Heavy rainfall is a fundamental physiological trigger that causes fish to migrate and spawn. On the other hand, increased temperature during breeding and early larval development stages may potentially result in a sex-biased fish population, which may influence natural population increase in the future (Baroiller & Cotta 2001; Angienda *et al.* 2010). However, minor temperature increases throughout the winter in tropical wetlands were found to benefit cultivable fish through accelerated gonadal development and reproduction (Borah & Bujarbaruah 2016).

Given the uncertainties of climate change and anthropogenic stress, region-specific climate resilient adaptation and mitigation measures must be developed and popularised to address climate change-related challenges in the life and livelihood of the population that is directly or indirectly dependent on these ecosystems. Climate change and related stresses are aggravating the situation, putting fishers' livelihoods at risk (Naskar *et al.* 2018). The unpredicted timing of rainfall destabilises the water table of the wetland causing early or delayed breeding season for the associated aquatic fauna. To counter this problem, various strategies like pre-summer enclosure, pen culture, deep pool refuge, and submerged branch pile refuge can be beneficial (Sarkar *et al.* 2018). The application of balanced artificial feed in the pens is advised to manage eutrophication. The majority of urban and peri-urban wetlands get sewage, which increases biological production while degrading the environment (Sarkar *et al.* 2020a, 2020b, 2020c). In this context, the selection of appropriate fish species and the implementation of scientific management methods are critical for the long-term management of these ecosystems. In addition, the current study has uncovered and recorded several indigenous wetland fisheries management strategies that have been used for centuries, even before the phrase 'climate change' existed. A summary of the strategies for adapting to impending threats of climate change for the studied wetland/region is presented in Table 2. Appropriate adaptation and mitigation strategies would bring community empowerment in the face of climate change vulnerability. Protection of biological diversity and integrity of the wetland are important activities to improve the resiliency of wetland ecosystems so that they continue to provide important services under changed climatic conditions.

Table 2 | Different mitigation and adaptation strategies against climate change for the Media wetland

Mitigation strategies	Adaptation strategies
• Management of weedy, predatory, and exotic fishes.	• Shoreline planting
• Management of aquatic weed	• Enclosure/pen culture
• Management of linkage channels	• Deep pool-based fish culture
• De-siltation of wetlands	• Refuge/weed-based fish culture system
• Formation of deep pools	• Submerged branch pile-based fisheries
• Seasonal water recharge	• Increase diversity in culture-based fisheries
• Improvisation of fishing tools	• Ranching responsibly
• Manage overexploitation of climate resilient fish species	• Integration of climate-smart fishing gears
• Early warning system	• Integration with other components
• Sensitisation among stakeholders	• Community approach
	• Judicious exploitation

6. CONCLUSION

This is the first assessment of Media, a tropical floodplain wetland of India, in the context of the fisheries and climate-induced risks using improved approaches. The study established that regional climate variability may have a direct or indirect influence on the water quality, fish diversity, as well as the fish production of the wetland. The application of multiple approaches may be advantageous for building composite vulnerability analysis covering information on biotic and abiotic factors along with historic climate and biological data. The objectives of our study were satisfied and an improved systematic model framework was created for these categories of investigations. The GIS-based thematic maps of the wetland fisheries related to important environmental parameters could be applied for better management policy for the stakeholders. We recommend responsible fishing maintaining the natural breeding grounds of the indigenous fishes. On the other hand, an appropriate adaptation approach should be the restoration of the wetland habitat connectivity, creating deep pools, resolving siltation issues, and linking the water body to the main river channel to recover the natural breeding habitat and augment the natural fish population. The protection and maintenance of floodplain wetlands will help to address the worldwide concerns of livelihood security, water scarcity, and greenhouse gas emissions, as well as ensure a sustainable future. For future generations, a greener planet is preferable. Ideal management of the productivity of floodplain wetlands will significantly contribute to the achievement of the United Nations Sustainable Development Goals for the period 2016–2030, to eradicate poverty and hunger, and wellbeing for all ages of the global population.

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AUTHORS CONTRIBUTION

B.D.G. was involved in sampling, data generation, and manuscript preparation; S.D. was involved in sampling, data analysis, manuscript preparation, and revision; U.K.S. guided and monitored the research activities, B.K.D. did project administration, acquired funds, and supervised the study; M.P., C.J., and G.K. supervised the study.

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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