



The role of water quality management in fish conservation: A practical perspectives on SDGs

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Abstract

Freshwater ecosystems in India are experiencing significant eutrophication and a decline in biodiversity, which directly affects the goals related to clean water and sanitation, as well as the preservation of terrestrial life. This study assessed the efficacy of various water quality management interventions specifically, the restoration of riparian buffers, reduction of nutrients, and control of sedimentation on the recovery of fish communities at Pili Dam, Bijnor, Uttar Pradesh, over a period of two years (June 2022 to May 2024). A total of 1,845 individual fish, representing 27 distinct species from 11 different families, were captured, identified, and recorded through the study period. The results exhibited a notable improvements in dissolved oxygen rose by 85.7% (from 4.2 to 7.8 mg/L), total phosphorus diminished by 70.8% (from 120 to 35 µg/L), and turbidity decreased by 75.8% (from 18.6 to 4.5 NTU). The richness of fish species experienced a remarkable growth, rising from 12 to 23 species, while the Shannon diversity index saw a significant elevation from 1.45 to 2.89 ($p < 0.001$), thereby making a substantial contribution to Sustainable Development Goal 14 pertains to life below water. NMDS ordination demonstrated clear community clustering ($R = 0.74$, $p = 0.002$), accompanied by strong correlations between water quality and fish ($r = 0.85-0.93$). Our findings indicate that focused management of water quality effectively revitalizes fish diversity in dam ecosystems within a timeframe, thereby contributing to the advancement of Sustainable Development Goals 6, 14, and 15, and offering practical recommendations for the National Mission for Clean Ganga.

Keywords: Water quality management, fish conservation, eutrophication, dam, SDGs

Introduction

Freshwater ecosystems, despite occupying less than 1% of the Earth's surface, are crucial as they sustain one-third of vertebrate species (Dudgeon *et al.*, 2006) [6]. Water bodies such as rivers, lakes, marshes, and reservoirs serve multiple essential functions: they supply clean water, sustain fisheries, mitigate flood risks, facilitate nutrient cycling, and foster cultural and recreational pursuits, all while offering habitats for diverse species. Freshwater wetlands, despite their crucial ecological and economic roles, are experiencing a decline in species at a rate five times greater than that of terrestrial habitats. Freshwater biodiversity represents the most imperilled aspect of Earth's ecosystems, as noted by Reid *et al.* (2019) [17], highlighting a critical concern for conservation biologists. As reported by the IUCN Red List, a significant proportion, specifically one-third, of freshwater fish species are currently classified as endangered (IUCN, 2023) [8]. The decline in freshwater biodiversity poses a significant risk to numerous Sustainable Development Goals, encompassing clean water and sanitation, the vitality of marine life, and the integrity of terrestrial ecosystems. Our objective is to safeguard and rejuvenate aquatic ecosystems and the diversity of life within them.

India faces a significant challenge regarding its freshwater biodiversity. Numerous fish species, totaling 200, within the Ganga River watershed are native to the region (Lakra *et al.*, 2010) [13]. The diversity of fish species and the quality of water have experienced a notable decline across extensive regions of the Gangetic plain, attributed to factors such as urbanization, intensified agricultural practices, and the construction of dams and barrages along the rivers originating from the Himalayan foothills (Sarkar *et al.*,

2012) [18]. The deterioration of these aquatic regions contravenes SDG-6, which aims to improve water quality by reducing pollution, waste disposal, chemical discharge, and enhancing wastewater treatment. Dams in Uttar Pradesh, Uttarakhand, Bihar, and West Bengal facilitate agricultural practices, generate hydropower, and provide water supply through the establishment of reservoir ecosystems. Humanity depends on reservoirs; however, they accumulate sediments, disrupt aquatic ecosystems, and contribute to thermal stratification and oxygen depletion, especially in the deeper backwater areas located upstream of the dam (Baxter, 1977) [2]. Restoring these ecosystems is crucial for achieving SDG-15, which mandates immediate intervention to combat habitat degradation, the loss of biodiversity, and the extinction of endangered species.

The primary factors contributing to the decline of fish biodiversity in Indian freshwater ecosystems encompass nutrient pollution, sedimentation, and alterations in hydrology, habitat fragmentation, overfishing, and the presence of invasive species (Vörösmarty *et al.*, 2010) [9]. These diffuse nonpoint sources present greater challenges in detection and regulation compared to industrial sources, resulting in nutrient contamination and sedimentation that are both pervasive and nuanced. The predominant contributors to this issue are agricultural fertilizer runoff and untreated sewage from urban areas. Various sources of nitrogen and phosphorus contribute to eutrophication, subsequently fostering the proliferation of algae and aquatic plant life (Carpenter *et al.*, 1998) [4]. As algae undergo decomposition, the process of microbial respiration leads to a reduction in dissolved oxygen levels within the water column. This phenomenon results in hypoxic or anoxic conditions, which adversely affect fish populations and

generate unfavourable physical environments. Unstable streambanks and eroding agricultural fields contribute to increased sedimentation, which diminishes water clarity, impedes visual predator foraging, and obstructs the interstitial spaces essential for egg incubation and juvenile rearing in numerous fish species (Kemp *et al.*, 2011) ^[11]. Enhancing water quality is essential for the protection and restoration of aquatic ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes, in accordance with SDG-6.

Numerous characteristics of impoundment systems exacerbate the challenges associated with dam reservoirs. In contrast to rivers, reservoirs possess the capacity to retain water over prolonged durations, facilitating the accumulation of pollutants and nutrients. During the summer months, thermal stratification results in a stable water column characterized by a layer of cold, oxygen-depleted water situated at the bottom, while the upper layer consists of warm, oxygen-rich water. Fish that cannot endure cold, low oxygen bottom waters inhabit the shallow upper layer, thereby restricting their habitat. Legacy sediments, which accumulate phosphorus over extended periods, have the potential to release this nutrient into the water column when external inputs are reduced. Smucker and Vis (2011) ^[23] caution that the phenomenon of internal nutrient loading could impede the process of recovery. SDG-14 underscores the imperative of sustainable management and safeguarding of both freshwater and marine ecosystems to avert significant repercussions, bolster resilience, and promote restoration efforts.

Water quality management plays a crucial role in the restoration of aquatic biodiversity (Palmer *et al.*, 2005) ^[14]. Establishing native flora and shrubs along streambanks fortifies these ecosystems while capturing runoff, thereby diminishing fertilizer and sediment contributions in agricultural catchments by 30–90%. Wetlands effectively eliminate 40–70% of incoming phosphate and nitrogen through mechanisms such as plant absorption, microbial denitrification, and sediment settling. Employing cover crops and refining fertilizer application strategies can reduce inputs while sustaining crop yields. Eroded material is collected by retention basins and bank stabilization prior to its entry into the principal river system. These interventions have been extensively implemented in advanced countries to rehabilitate ecosystems and enhance water quality. SDG-15 employs a range of management strategies aimed at the conservation, restoration, and maintenance of terrestrial and inland freshwater ecosystems along with their associated services.

In the tropical and subtropical regions of India, there exists a paucity of empirical evidence that correlates enhancements in water quality with the resurgence of fish communities (Dey *et al.*, 2020) ^[5]. Numerous studies on water quality in India predominantly emphasize physicochemical outcomes such as nutrient reductions and biochemical oxygen demand, often overlooking the biological implications. Biological evaluations frequently concentrate on a singular economically significant species, exemplified by the Indian major carps (*Labeo rohita*, *Catla catla*, and *Cirrhinus mrigala*), rather than encompassing comprehensive studies of entire communities that include intolerant indicator species and those pertinent to conservation efforts. This limited focus creates a gap in the scientific literature: it remains uncertain whether improvements in chemically

measured water quality lead to the restoration of biodiversity, the timeframe for species to reappear, or the order in which they do so. This gap in information must be rectified to effectively monitor SDG-15, which aims to avert species extinction and biodiversity loss, thereby facilitating informed policy decisions.

Fish populations in monsoonal climates, particularly the Monsoon-influenced humid subtropical climate found in northern India, can require several years to rebound following enhancements in water quality. Cwa climate with dry winter and hot summer are marked by significant monsoon rains from June to September that contribute the majority of the annual precipitation ranging from 1,200 to 1,500 millimeters, presents unique challenges that are not encountered in research conducted within temperate zones. Agriculture faces significant risks of erosion during the monsoon season, a period characterized by heightened flow in streams and reservoirs, which leads to the maximum deposition of silt. Moreover, it is more probable that runoff will erode fertilizers that have been applied prior to precipitation events. During periods of high flow, it is imperative that restoration procedures are effective, as fluctuations in annual water quality can either accelerate or impede the recovery process. Comprehending these processes is crucial for SDG-6 which advocates for the conservation and restoration of water-related ecosystems in response to climate change and disasters.

Consequently, this research encompasses four primary objectives. The restoration of riparian buffers, the reduction of nutrient inputs, and the control of sedimentation at a dam site in Bijnor District, Uttar Pradesh, India, over a period of 24 months served as a basis for evaluating the impacts on physicochemical parameters such as dissolved oxygen, total phosphorus, turbidity, and nitrate-nitrogen. The secondary objective was to ascertain the impact of alterations in water quality on fish species richness, the Shannon-Wiener diversity index, assemblage composition, and the distribution of intolerant and tolerant species. Third, discern species whose presence, absence, or abundance consistently signifies ecological conditions. These species could enable managers to assess restoration or decline with minimal monitoring efforts. The fourth objective involved establishing a statistical correlation between fish community metrics and water quality indices, as well as assessing their predictive capacity for biodiversity outcomes. The rehabilitation and preservation of compromised freshwater ecosystems and their biodiversity, grounded in empirical evidence, plays a crucial role in advancing Sustainable Development Goals 6 (Clean Water and Sanitation), 14 (Life Below Water), and 15 (Life on Land).

Materials and Methods

1. Description of the Study Site

The study was carried out at a Pili Dam and its downstream tailwater situated in Bijnor District, Uttar Pradesh, India (29°21'46" North and 78°47'9" East). This site is formally designated as a dam a structure built across a stream with the explicit purpose of impounding water. The dam was initially erected in 1984, chiefly to serve irrigation and water supply needs, and it forms a reservoir that extends over an area of roughly 15 square Kilometers when at full capacity. The choice of this location for restoration research aligns with SDG-6 which emphasizes the importance of safeguarding and revitalizing water related ecosystems,

encompassing reservoirs and their connected riverine environments.

1.1 Description of Climate condition

The region is characterized by a climate that is heavily influenced by monsoons, falling under the classification of a humid subtropical climate. This climate regime is marked by three distinct seasons that significantly impact the dynamics of water quality. From April to June, the region experiences elevated summer temperatures, averaging between 32 and 42 °C. These conditions foster thermal stratification and encourage algal proliferation. The monsoon season spans from June to September, delivering an average annual rainfall ranging from 1,200 to 1,500 millimeters, with around 80 % of the total precipitation for the year occurring within this four month period. This concentrated precipitation generates significant runoff occurrences that transport sediments and nutrients from agricultural areas into the aquatic ecosystem. Mild winters transpire from November to February, characterized by mean temperatures fluctuating between 8 and 20 °C, thus offering a phase of relative stability and diminished biological activity. Comprehending these climate dynamics is crucial for formulating interventions that advance SDG-13 (climate resilience and adaptation), as restoration measures must operate efficiently amidst extreme seasonal conditions.

1.2 Description of the Ecosystem and historical context

The Pili Dam, Bijnor, Uttar Pradesh features an average depth of 8.5 meters, with a maximum depth of 22 meters, and displays notable thermal stratification during the warm summer months. This phenomenon results in the formation of a distinct layer of warmer water at the surface, while cooler, frequently oxygen -depleted water resides at the bottom. Conversely, the tailwater situated downstream of the dam presents as a shallow, flowing channel, exhibiting depths that vary from 0.5 to 2 meters, alongside flow velocities ranging from 0.3 to 0.8 meters per second. These conditions facilitate natural reaeration and mixing processes. Historically, this aquatic system sustained a notably diverse fish community, featuring Indian major carps such as *Labeo rohita* (Rohu), *Catla catla* (Catla), and *Cirrhinus mrigala* (Mrigal), in addition to the esteemed Mahseer (*Tor tor*) and various catfish species, including *Wallago attu* and *Mystus seenghala*. Nevertheless, throughout the last thirty years, a confluence of human -induced pressures has profoundly compromised the integrity of this ecosystem. Agricultural intensification, especially the cultivation of sugarcane and wheat within the catchment area, has led to an increase in nutrient runoff. Urban runoff originating from the adjacent town of Bijnor, home to around 115,000 inhabitants, has resulted in the influx of untreated sewage and various domestic pollutants. Simultaneously, the accumulation of sediment behind the dam has diminished water clarity and obstructed spawning gravels. These combined pressures have resulted in eutrophication, characterized by excessive nutrient enrichment, chronic hypoxia, which denotes oxygen depletion, and a significant reduction in the biodiversity of native fish species. The restoration of this ecosystem directly pertains to SDG-15 which emphasizes the necessity for immediate measures to mitigate habitat degradation and cease biodiversity loss, alongside SDG-6 which seeks to

enhance water quality through the reduction of pollution and the minimization of hazardous chemical releases.

1.3 Description of study zone designation and separation

The study area was methodically partitioned into two hydrologically distinct zones, encompassing a total length of around 6 Kilometers. The Control Zone encompasses the upstream reservoir backwater, extending over a distance of 3 Kilometers. This area is notably profound, exhibiting sluggish movement and thermal stratification throughout the summer season. It persistently receives untreated agricultural runoff devoid of any remediation, thereby functioning as a compromised reference condition. The managed Zone encompasses the downstream tailwater, extending over 3 Kilometers, characterized by its shallow depth, flowing nature, and effective mixing resulting from the turbulence induced by dam releases. This area experiences regulated dam discharge and underwent proactive water quality management measures during the entire study duration. This controlled comparison design facilitates a thorough evaluation of restoration effectiveness, thereby advancing evidence -based efforts toward SDG-15 which emphasizes the conservation, restoration, and sustainable utilization of inland freshwater ecosystems. Both zones exhibited similar baseline water quality parameters and fish community structures before the commencement of the study. This comparability was substantiated by a pre - restoration survey carried out over a six -month period prior to the initiation of any interventions, encompassing three sampling events for each zone. While the baseline data are not included in this manuscript, they can be provided upon request. The dam structure itself ensured a physical separation between the two zones, effectively preventing fish movement from one zone to the other. This arrangement facilitates an independent assessment of intervention effects, eliminating concerns regarding cross - contamination or recolonization from the restored zone impacting the control zone.

2. Water Quality Management Interventions

The study area was methodically partitioned into two hydrologically distinct zones, encompassing a total length of roughly 6 Kilometers. The Control Zone encompasses the upstream reservoir backwater extending for a distance of 3 Kilometers. This zone is notably profound, exhibiting a languid flow and thermal stratification throughout the summer months. It persistently receives untreated agricultural runoff devoid of any remediation, thereby functioning as a compromised reference condition. The Managed Zone encompasses the downstream tailwater, extending over a distance of 3 Kilometers. This area is characterized by shallow, flowing waters that are well - mixed, a result of the turbulence generated by dam releases. This area experiences regulated dam releases and underwent proactive water quality management measures during the entire duration of the study. The chosen species for planting comprised indigenous riparian trees such as *Dalbergia sissoo* and *Ficus religiosa*, in addition to *Bambusa vulgaris* and native grasses like *Saccharum spontaneum*. These species were selected due to their profound root systems that provide stability to banks, their resilience to seasonal inundation, and their ability to assimilate nutrients from agricultural runoff. Furthermore, livestock were entirely

barred from the riparian zone through the implementation of barbed wire fencing, aimed at mitigating bank erosion and preventing direct fecal contamination of the water. This intervention plays a significant role in advancing SDG-15 by promoting the conservation and restoration of terrestrial and freshwater ecosystems along with their vital services. The reduction of nutrient input constituted the second essential intervention component. The application of agricultural fertilizers, particularly urea and diammonium phosphate (DAP), experienced a reduction of 40 % within the immediate 5 -kilometer catchment area situated upstream of the managed zone. This reduction was accomplished through farmer extension programs that encompassed training workshops, demonstration plots, and economic incentives, illustrating that a decrease in fertilizer use did not adversely affect crop yields.

3. Water Quality Sampling

Water quality sampling was performed with meticulous adherence to standardization and quality control protocols. All parameters were meticulously measured on a monthly basis over a period of 24 months, extending from June 2022 to May 2024, culminating in 24 distinct sampling events for each zone. During each monthly sampling event, three replicate samples were obtained from three designated sampling sites within each zone, resulting in a total of nine individual samples per zone each month. To mitigate the influence of acute bias stemming from extreme rainfall events, sampling was intentionally scheduled to exclude any period within 48 hours following significant monsoon rainfall exceeding 50 millimeters of precipitation. Such occurrences result in atypically elevated turbidity and nutrient concentrations that fail to accurately reflect baseline conditions. This methodical monitoring strategy underpins SDG-6 by producing dependable data on water quality parameters, which is crucial for assessing advancement toward both national and global objectives. All water quality parameters were assessed utilizing established methodologies as outlined by the American Public Health Association (APHA, 2017) ^[1]. Dissolved oxygen levels were quantified utilizing an electrochemical probe in conjunction with a YSI ProODO optical probe, with findings expressed in milligrams per liter. Turbidity was assessed through nephelometry utilizing a Hach 2100Q turbidimeter, with findings expressed in Nephelometric Turbidity Units (NTU). Total phosphorus was quantified utilizing the ascorbic acid method subsequent to persulfate digestion, with measurements conducted via a UV spectrophotometer, and results expressed in micrograms per liter. Nitrate -nitrogen was quantified through the cadmium reduction method, employing a UV spectrophotometer, with results expressed in milligrams per liter. The pH was determined through potentiometric measurement utilizing an Oakton pH 700 meter. The measurement of water temperature was conducted utilizing the thermistor integrated within the YSI ProODO probe, with the findings expressed in °C. Quality control measures were instituted across the entirety of the sampling program. Field blanks composed of deionized water were systematically processed after every ten samples to identify any potential contamination that may have occurred during field handling. Duplicate samples were gathered for 10 % of all sampling events to evaluate precision. All instruments underwent calibration prior to each sampling event, utilizing certified

reference standards. Ultimately, rigorous laboratory quality control standards for nutrient analysis were implemented with each batch of samples to ensure precision. These quality assurance protocols correspond with SDG-6 which necessitates dependable, high caliber data on ambient water quality for efficient monitoring and management.

4. Fish Community Assessment

Fish community assessment was carried out on a quarterly basis, occurring once every three months, throughout the study duration. This schedule led to eight comprehensive sampling events per zone, taking place in June, September, December, and March of each year. The selection of a quarterly frequency was made to effectively capture seasonal variations in fish community structure, while also permitting adequate time for significant ecological recovery between sampling events. The evaluation of fish biodiversity plays a crucial role in advancing SDG-14 which focuses on the sustainable management and safeguarding of freshwater ecosystems, as well as SDG-15 which aims to quantify and mitigate biodiversity loss.

Fish sampling methods were modified in accordance with the protocols established by Sarkar and colleagues (2012) ^[18] to suit the specific conditions of Indian freshwater environments. Electrofishing was conducted utilizing a Smith Root LR -24 unit, with a focus on wadeable riffles, runs, and shallow marginal habitats. The depletion method was utilized through three successive passes over a 500 -meter stretch, facilitating the estimation of population size by analysing the diminishing catch per pass. Multi -mesh gillnets featuring mesh sizes of 12.5, 25, 37, 50, and 55 millimeters were strategically deployed in deep pools and the backwater region of the reservoir. The nets were strategically positioned overnight to allow for a 12 -hour soaking period, with a total of 10 nets deployed in each designated zone for every sampling event. Cast nets featuring a 10 -millimeter mesh were employed in the margins and vegetated zones, with a total of 20 throws conducted at each site. Six -millimeter mesh minnow traps, baited with a commercial attractant, and were strategically positioned in shallow habitats, with a total of ten traps per site allowed to remain submerged for a duration of 24 hours. The application of various, synergistic sampling techniques guarantees a thorough evaluation of biodiversity, thereby enhancing SDG Indicator 15.5.1 (Red List Index) through the provision of precise information regarding species presence and abundance.

All captured fish underwent immediate processing in accordance with established protocols. Each specimen was classified to the species level utilizing the established taxonomic keys as outlined by Talwar and Jhingran (1991) and Jayaram (2010) ^[9, 24]. For each species, the total abundance was meticulously documented as a numerical count. Each fish was meticulously measured for total length in millimeters utilizing a measuring board and weighed in grams with the aid of a portable balance. All subjects underwent a thorough examination for any external anomalies, encompassing lesions, parasites, deformities, or indications of disease. With the exception of a limited quantity of voucher specimens retained for taxonomic verification, all fish were released alive back into their aquatic environment at the site of capture. This ethical approach to the management of living organisms is in

accordance with SDG-15 as it seeks to reduce harm to the species under investigation and protection.

Species richness was determined by tallying the total number of species documented within each zone during each sampling event. The Shannon -Wiener Diversity Index was determined through the application of the formula $H' = -\sum p_i \ln p_i$, where p_i denotes the proportional abundance of each species. This index considers both the quantity of species present and the uniformity of their distribution. Pielou's Evenness is expressed as $J' = H' / \ln(S)$, where H' represents the diversity index and S denotes species richness. This formula serves to quantify the degree to which individuals are uniformly distributed across various species. Relative abundance was determined by taking the count of a specific species and dividing it by the total count of all species, subsequently multiplying the result by 100 to articulate dominance patterns in %age form. Intolerant species were ultimately characterized as those necessitating dissolved oxygen levels exceeding 6 milligrams per liter and turbidity below 10 Nephelometric Turbidity Units, in accordance with regional indices formulated by Lakra and associates (2010) [13]. These metrics are crucial for monitoring advancements related to SDG-15 which aims to mitigate biodiversity loss, as well as SDG-14 focused on the sustainable management of aquatic ecosystems.

5. Data Analysis

All statistical analyses were conducted utilizing R version 4.3.1, a robust statistical computing environment crafted by the R Core Team (2023) [16]. The significance threshold for all hypothesis tests was established at an alpha level of 0.05, indicating that results with a likelihood of less than 5% of arising purely by chance were deemed statistically significant. Thorough statistical examination guarantees that the evidence produced for SDG-6 (water quality monitoring), SDG-14 (ecosystem management), and SDG-15 (biodiversity assessment) is sound, replicable, and grounded in scientific validity. Initial examination of data: Prior to executing the primary analyses, all data underwent a screening process for normality through the application of Shapiro -Wilk tests, where a p -value exceeding 0.05 suggested that the data did not exhibit significant deviations from a normal distribution. Levene's test was employed to assess the consistency of variance across the different groups. Data that did not conform to a normal distribution underwent a transformation utilizing the logarithm base 10. If the assumptions of parametric tests continued to be violated despite transformation efforts, non -parametric alternatives were utilized. Comparative analyses of water quality were executed utilizing the Mann -Whitney U test to evaluate the 24 -month mean values across Managed and Control zones for each parameter of water quality. Furthermore, an examination of seasonal patterns within each zone was conducted utilizing the Kruskal -Wallis test, succeeded by post -hoc Dunn's test with Bonferroni correction to ascertain the specific seasons that exhibited differences from one another. These analyses of water quality furnish the foundational evidence for SDG-6 which monitors the %age of water bodies exhibiting satisfactory ambient water quality. Diversity comparisons between zones utilized two -sample t -tests for Shannon diversity indices, following the validation of normality assumptions.

To evaluate species richness, which frequently demonstrates non -normal distributions, permutation tests involving 1,000 random permutations were employed to determine statistical significance. Community composition analysis utilized non -metric multidimensional scaling (NMDS) grounded in Bray -Curtis dissimilarity matrices, executed through the metaMDS function within the vegan package. A stress value below 0.15 was deemed satisfactory, signifying that the two -dimensional ordination effectively captured the original dissimilarities among the samples. To ascertain whether fish communities exhibited significant differences between zones, an analysis of similarity (ANOSIM) was conducted utilizing 999 permutations. The ANOSIM statistic, Global R , varies from 0, indicating no difference, to 1, signifying complete separation. Ultimately, a similarity %age (SIMPER) analysis was performed to ascertain the specific species that contributed significantly to the observed dissimilarity across the zones. Analysis of indicator species was conducted utilizing the IndVal index established by Dufrêne and Legendre (1997) [7], as executed within the indicpecies package. This index integrates metrics of species specificity, characterized by their predominant presence in a singular zone, alongside fidelity, which reflects their consistent occurrence across various samples within that designated area. Significance was evaluated through 999 permutations, with species exhibiting IndVal values exceeding 0.70 and p -values below 0.05 deemed as robust indicators of their corresponding zones. The identification of indicator species bolsters SDG-15 by offering effective methodologies for monitoring biodiversity recovery, thereby circumventing the need for extensive and resource intensive surveys.

Analysis of correlation was performed to explore the relationships between various water quality variables specifically dissolved oxygen, turbidity, total phosphorus, and nitrate and fish metrics, which include species richness, Shannon diversity, the %age of intolerant species, and Pielou's evenness. The methodology employed Pearson correlation for data that adhered to a normal distribution, while Spearman rank correlation was utilized for data that did not conform to this distribution. To assess the uncertainty surrounding correlation estimates, 95 % confidence intervals were derived through bootstrap resampling utilizing 1,000 replicates. Temporal trend analysis evaluated the progression of fish diversity recovery throughout the 24 -month duration. Linear regression was employed to analyze Shannon diversity in relation to time, specifically over a span of 0 to 24 months within the Managed Zone. Breakpoint analysis was subsequently employed to ascertain the precise month in which a statistically significant alteration in the slope of the recovery trajectory took place, thereby indicating the moment of substantial ecological enhancement. These temporal analyses yield essential insights for SDG-14 as they delineate feasible timelines for ecosystem recovery post -management interventions, which is vital for formulating attainable national and global objectives.

Results

1. Fish Species Richness and Abundance

A total of 1,845 individual fish, representing 27 distinct species from 11 different families, were captured, identified, and recorded across the study zones (Table 1). This significant catch yielded a comprehensive dataset for

analysing community structure in both restored and degraded conditions. The rise in fish species richness and the reappearance of intolerant species directly support SDG-15 which emphasizes the need for immediate action to mitigate habitat degradation, stop biodiversity loss, and avert the extinction of threatened species. Additionally, this aligns with SDG-14 which aims to sustainably manage and protect freshwater ecosystems.

Among the 27 fish species listed on the IUCN Red List, a significant majority, 25 species, or 89.3%, are categorized as Least Concern. *Labeo rohita*, *Catla catla*, and *Cirrhinus mrigala* represent a diverse array of Indian big carps, each contributing uniquely to their ecological niches. Species such as *Mystus seenghala*, *Clarias batrachus*, and *Heteropneustes fossilis*, alongside smaller barbs including *Puntius sophore*, *ticto*, and *chola*, merit attention. The renowned *Tor tor* has made a return to the Ganga basin following the restoration of water quality. In contrast, *Wallago attu*, a sizable predatory catfish, has experienced a significant decline due to overexploitation and habitat degradation. In Europe, the common carp (*Cyprinus carpio*) is classified as Vulnerable, with a population percentage of 3.6. However, in Indian rivers, it has established itself as an invasive species, significantly dominating the Control Zone throughout the course of the investigation.

The recorded 23 species, reflecting a 92 % increase relative to the Control Zone, which support only 11 species during the entire study period. This near doubling of species richness signifies a significant increase in biodiversity attained within a mere 24 months of management intervention, illustrating measurable advancement toward supplying evidence for SDG-15. Intolerant species, characterized by a requirement for dissolved oxygen levels exceeding 6 milligrams per liter and turbidity below 10 NTU, were exclusively identified within the study area. Throughout the study period, no intolerant species were detected in the Control Zone, highlighting the extent of

degradation in the unmanaged reference area. The presence of intolerant species in the restored zone indicates that water quality management has effectively established habitat conditions conducive to sensitive biodiversity, thereby contributing to SDG-15 which focuses on the conservation, restoration, and sustainable use of inland freshwater ecosystems. Intolerant species comprised 78 % of the total catch in the study area. Three species *Cyprinus carpio*, *Carassius gibelio* and *Puntius sophore* accounted for 72 % of all fish captured. This pattern of dominance by a limited number of resilient generalists is indicative of a degraded, eutrophic ecosystem characterized by persistent hypoxia and elevated turbidity. The decrease in the dominance of tolerant species within the Managed Zone, from 78 % to approximately 44 %, signifies effective ecosystem recovery. This outcome supports SDG-14 by illustrating the restoration of balanced and resilient aquatic communities. The Shannon-Wiener Diversity Index, which incorporates both species richness and distribution evenness, revealed a significant and notable difference between zones. The Managed Zone attained a mean Shannon diversity of 2.89, with a standard deviation of 0.21, and a Pielou's evenness value of 0.87. This suggests a highly even distribution of individuals across the 23 species present, with no single species dominating the community. The 95% confidence interval for this estimate was between 2.68 and 3.10. In contrast, the Control Zone exhibited a mean Shannon diversity of 1.45, with a standard deviation of 0.18, resulting in an evenness value of 0.54, which suggests a community characterized by significant dominance of a limited number of tolerant species. The 95 % confidence interval extended from 1.27 to 1.63, exhibiting no overlap with the Managed Zone interval. A two -sample t -test indicated that this difference was statistically significant ($p < 0.001$). This significant rise in diversity directly aligns with SDG-15 by illustrating measurable biodiversity recovery and offers a quantitative benchmark for SDG-15.

Table 1: Taxonomic status such classification scientific names, regional names, and IUCN status of the recorded fishes diversity from the Pili Dam, Bijnor, Uttar Pradesh

Order	Family	Scientific Name	Common Name	IUCN Status
Cypriniformes	Cyprinidae	<i>Tor tor</i>	Tor mahseer	Near Threatened (NT)
		<i>Labeo rohita</i>	Rohu	Least Concern (LC)
		<i>Labeo bata</i>	Bata	Least Concern (LC)
		<i>Catla catla</i>	Catla	Least Concern (LC)
		<i>Cirrhinus mrigala</i>	Mrigal	Least Concern (LC)
		<i>Cyprinus carpio</i>	Common carp	Vulnerable (VU)*
		<i>Carassius gibelio</i>	Prussian carp	Least Concern (LC)
		<i>Puntius sophore</i>	Spotfin swamp barb	Least Concern (LC)
		<i>Puntius ticto</i>	Ticto barb	Least Concern (LC)
		<i>Puntius chola</i>	Swamp barb	Least Concern (LC)
		<i>Rasbora daniconius</i>	Slender rasbora	Least Concern (LC)
		<i>Amblypharyngodon mola</i>	Mola carplet	Least Concern (LC)
		<i>Esomus danricus</i>	Flying barb	Least Concern (LC)
Siluriformes	Bagridae	<i>Mystus seenghala</i>	Giant river catfish	Least Concern (LC)
		<i>Mystus vittatus</i>	Stripped dwarf catfish	Least Concern (LC)
	Siluridae	<i>Wallago attu</i>	Freshwater shark	Near Threatened (NT)
	Clariidae	<i>Clarias batrachus</i>	Walking catfish	Least Concern (LC)
	Heteropneustidae	<i>Heteropneustes fossilis</i>	Stinging catfish	Least Concern (LC)
Anabantiformes	Channidae	<i>Channa punctatus</i>	Spotted snakehead	Least Concern (LC)
		<i>Channa striatus</i>	Striped snakehead	Least Concern (LC)

Perciformes	Ambassidae	<i>Chanda nama</i>	Elongate glass-perchlet	Least Concern (LC)
		<i>Parambassis ranga</i>	Indian glassy fish	Least Concern (LC)
Anabantiformes	Anabantidae	<i>Anabas testudineus</i>	Climbing perch	Least Concern (LC)
	Nandidae	<i>Nandus nandus</i>	Gangetic leaffish	Least Concern (LC)
Gobiiformes	Gobiidae	<i>Glossogobius giuris</i>	Tank goby	Least Concern (LC)
Synbranchiformes	Mastacembelidae	<i>Mastacembelus armatus</i>	Zigzag eel	Least Concern (LC)

2. Water Quality Improvement Following Management

The results of the study are exhibited statistically significant and ecologically meaningful improvements in all measured water quality parameters. The documented improvements in water quality contribute directly to SDG-6 which seeks to enhance water quality by reducing pollution, eliminating dumping, and minimizing the release of hazardous chemicals. Additionally, these improvements provide quantitative evidence for SDG-6 which monitors the proportion of water bodies exhibiting good ambient water quality. The most significant enhancement was noted in dissolved oxygen concentrations, which rose by 85.7 % from a hypoxic baseline of 4.2 milligrams per liter to a healthy 7.8 milligrams per liter in the Managed Zone. The post-restoration value significantly surpasses the recommended target standard of 5.0 milligrams per liter established by the United States Environmental Protection Agency and the Bureau of Indian Standards. In contrast, the Control Zone consistently exhibited a hypoxic state, with dissolved oxygen levels averaging 4.2 milligrams per liter, a concentration recognized as physiologically stressful or lethal to numerous sensitive fish species. The difference between zones was statistically significant, with a p-value of less than 0.001. Achieving dissolved oxygen concentrations that exceed target standards indicates progress toward SDG-6 reflecting a successful reduction in organic pollution and nutrient loading.

Total phosphorus concentrations decreased significantly by 70.8 % in the Managed Zone, from 120 to 35 micrograms per liter. This post -restoration value aligns with the target standard of 50 micrograms per liter, demonstrating effective eutrophication control. The Control Zone continued to exhibit significant phosphorus pollution, with mean concentrations reaching 120 micrograms per liter, which exceeds the acceptable threshold by more than twofold. Once more, the difference between zones was statistically significant ($p < 0.001$). Reducing phosphorus is essential for meeting SDG-6 as excess phosphorus significantly contributes to eutrophication, leading to the degradation of water quality and detrimental effects on aquatic ecosystems. Turbidity, an indicator of water clarity, decreased by 75.8 % in the Managed Zone, from 18.6 to 4.5 Nephelometric Turbidity Units. This value is significantly lower than the target standard of 10 NTU, suggesting that sedimentation control measures were highly effective. The Control Zone exhibited a mean turbidity of 18.6 NTU, surpassing the target standard by approximately 90 %. The interzone difference was statistically significant ($p < 0.001$). Reduced turbidity directly contributes to SDG-6 which focuses on the protection and restoration of water -related ecosystems. Improved light penetration enhances the growth of aquatic plants, thereby benefiting the fish that rely on these plants for sustenance.

Nitrate-nitrogen concentrations in the Managed Zone decreased significantly by 79.3 %, from 5.8 to 1.2

milligrams per liter. This post restoration value is well within the target standard of 2.0 milligrams per liter. The Control Zone exhibited nitrate levels of 5.8 milligrams per liter, significantly exceeding the acceptable limit by nearly threefold. Statistical analysis revealed a highly significant difference between zones ($p < 0.001$). Nitrate reduction plays a significant role in achieving SDG-6 by mitigating a key aspect of nutrient pollution that impacts freshwater and downstream coastal ecosystems.

Water pH demonstrated a modest yet significant improvement, rising from 6.2 in the Control Zone, which is slightly acidic and below the recommended range of 6.5 to 8.5, to 7.1 in the Managed Zone, which is well within the desirable neutral range. This difference was statistically significant with a p -value of less than 0.01. Water temperature did not exhibit a significant difference between zones, with an average of 26.4 °C in the Managed Zone and 28.7 °C in the Control Zone ($p = 0.06$). This suggests that temperature was not a confounding factor in the biological responses observed.

A significant finding arose from the seasonal analysis. The Managed Zone effectively sustained dissolved oxygen levels above 6.5 milligrams per liter throughout the monsoon season from July to September, despite the influx of organic matter and nutrients due to significant rainfall. Conversely, the Control Zone underwent significant hypoxia during the corresponding monsoon months, with dissolved oxygen concentrations dropping below 3.0 milligrams per liter, a threshold that leads to fish mortality and compels intolerant species to vacate the region. This seasonal resilience of the Managed Zone indicates that the implemented interventions are effective even under the high-flow, high-runoff conditions typical of the Monsoon-influenced humid subtropical climate regime. This contributes to SDG-13 by demonstrating how restored ecosystems can endure extreme seasonal events.

3. Indicator Species Analysis

Indicator Species Analysis identified six strong indicator species. These species serve as reliable indicators of specific ecological conditions based on their presence, absence, or abundance. All reported indicator species exhibited IndVal values surpassing the 0.70 threshold and p-values below 0.05. The identification of these indicator species offers practical and cost -effective methods for monitoring advancements toward SDG-15 (halting biodiversity loss) and SDG-6 (improving water quality). This approach allows managers to focus on a select number of key species instead of performing comprehensive community assessments. The most significant indicator of successful restoration was the *Tor tor*, a near -threatened species as classified by the IUCN Red List, which attained an IndVal of 0.91 with a p-value of 0.001. This species necessitates dissolved oxygen levels exceeding 6 milligrams per liter and is intolerant of the hypoxic conditions present in the Control Zone. The reappearance of this near threatened species in the Managed

Zone signifies tangible advancement toward SDG Target 15.5, which aims to avert the extinction of threatened species. This development also supports SDG-15 (Red List Index) by illustrating that a species of conservation concern has successfully re-established a viable population within a restored habitat attaining an IndVal of 0.88 ($p = 0.001$). *Labeo bata*, a species sensitive to increased turbidity, recorded an IndVal of 0.76 ($p = 0.003$) and was first observed at month 18, recorded again after turbidity levels decreased below 10 NTU. The resurgence of these sensitive species indicates that enhancements in water quality have effectively reinstated habitat conditions conducive to intolerant biodiversity, thereby supporting SDG-14 concerning the sustainable management of aquatic ecosystems. In contrast, three species were identified as significant indicators of ongoing degradation in the Control Zone. *Cyprinus carpio* demonstrated an IndVal of 0.79 ($p = 0.001$), indicating its established tolerance to hypoxia, elevated turbidity, and eutrophic environments. *Carassius gibelio* recorded an IndVal of 0.74 ($p = 0.002$), while *Puntius sophore* had an IndVal of 0.71 ($p = 0.004$). The consistent prevalence of these species validates their effectiveness as bioindicators of ecological degradation. Monitoring indicator species offers a cost-effective method for assessing advancements in SDG-6 (water quality improvement) and SDG-15 (ecosystem conservation). The reappearance of intolerant species in the Managed Zone occurred in a distinct temporal sequence. *Labeo bata*, which exhibits moderate sensitivity to turbidity, was the first species to record in month 12, following a reduction in turbidity levels below 10 NTU. *Tor tor* which necessitates high dissolved oxygen levels and low turbidity, reappeared at month 18 suggesting that habitat conditions had been adequately restored to support this introduced yet ecologically significant species. This temporal sequence offers critical insights for SDG-14 by delineating feasible timelines for various aspects of ecosystem recovery.

4. Fish Assemblage Composition Revealed by NMDS Ordination

Nonmetric multidimensional scaling ordination of species abundance data utilizing Bray-Curtis dissimilarity demonstrated a distinct pattern: the fish communities are entirely separate clusters with negligible overlap. The stress value of 0.12 is significantly lower than the acceptable threshold of 0.15, suggesting that the two dimensional ordination effectively represents the original dissimilarities among samples. This distinct categorization of community types offers compelling evidence for SDG-15 illustrating that restored and degraded ecosystems sustain fundamentally different biodiversity assemblages. The Analysis of Similarity (ANOSIM) formally assessed the statistical significance of the observed separation between zones. The Global R statistic of 0.74, which ranges from 0 to 1, indicates a substantial and biologically significant difference between the two fish communities. The observed p-value was 0.002, suggesting that the likelihood of achieving such extreme separation by chance is below 0.2%. This notable difference confirms that water quality management has fundamentally changed the fish community structure, thereby contributing to SDG Target 14.2 through successful ecosystem restoration. Similarity % age (SIMPER) analysis was performed to identify the species responsible for this separation. The average

dissimilarity between the Managed and Control zones was 78.4 %, indicating that the two communities shared less than 22 % of their compositional characteristics. *Cyprinus carpio* was the primary contributor to this dissimilarity, representing 18.2 % of the total difference and exhibiting significantly greater abundance in the Control Zone. *Tor tor* accounted for 15.6 %, making it the second most significant contributor, with greater abundance observed in the Managed Zone. *Carassius gibelio* accounted for 12.4 %, exhibiting greater abundance in the Control Zone. Ultimately, *Puntius sophore* accounted for 8.5 % of the total dissimilarity, resulting in a cumulative value of 65.5 % when aggregated with the other four species. These results conclusively demonstrate that the Managed Zone not only harbors a greater abundance of fish compared to the Control Zone, but also features a qualitatively distinct assemblage of species with varying ecological traits. This includes the resurgence of intolerant and near threatened species, alongside a decrease in tolerant, opportunistic species. This shift in community composition signifies significant advancement towards achieving SDG Target 15.5 which aims to halt biodiversity loss and conservation of inland freshwater ecosystems.

5. Relationship of Water Quality and Fish Metrics

Pearson correlation analysis indicated robust, statistically significant associations between essential water quality parameters and fish community metrics. These correlations offer quantitative evidence that connects particular enhancements in water quality to distinct outcomes in biodiversity, thereby reinforcing the evidence base for SDG-6 (water quality improvement) and SDG-15 (biodiversity recovery). The strong correlations indicate that water quality parameters can act as reliable surrogate indicators for biodiversity, thereby enabling cost effective monitoring of progress toward SDG-6 and SDG-15. Dissolved oxygen exhibited the most significant correlations among all water quality parameters with fish metrics. The correlation between dissolved oxygen and the %age of intolerant species was notably strong, with a correlation coefficient of $r = 0.81$ and a significance level of $p < 0.01$ (Figure 1). This suggests that elevated dissolved oxygen levels are closely associated with the resurgence of sensitive species that hold high conservation value. Dissolved oxygen exhibited a strong correlation with Shannon diversity ($r = 0.89$, $p < 0.01$) and species richness ($r = 0.86$, $p < 0.01$), indicating that oxygen recovery influences various aspects of biodiversity enhancement. Strong correlations indicate that achieving dissolved oxygen levels above 6.5 milligrams per liter serves as a quantitative target for SDG-6 likely leading to significant biodiversity recovery. Total phosphorus exhibited significant negative correlations with fish metrics, consistent with its role as a primary driver of eutrophication. The strongest negative correlation observed was between the percentage of intolerant species and phosphorus concentrations, with a correlation coefficient of $r = 0.91$ and a significance level of $p < 0.01$. This indicates that as phosphorus concentrations decreased, the proportion of sensitive species increased correspondingly. Total phosphorus exhibited a strong negative correlation with Shannon diversity ($r = -0.86$, $p < 0.01$), and with species richness ($r = -0.83$, $p < 0.01$). These correlations indicate that reducing phosphorus is crucial for meeting SDG-6 and that keeping total phosphorus levels below 50 micrograms

per liter is likely to promote diverse, intolerant-rich fish communities. Turbidity exhibited significant negative correlations with fish metrics, the most pronounced being with the percentage of intolerant species ($r = -0.88$, $p < 0.01$), followed by Shannon diversity ($r = -0.85$, $p < 0.01$) and species richness ($r = -0.81$, $p < 0.01$). These correlations underscore the significance of clear water for foraging, predator avoidance, and successful reproduction among numerous sensitive species. Achieving turbidity levels below 10 NTU, as indicated in the Managed Zone, represents a significant threshold for the reestablishment of intolerant species, thereby establishing a definitive objective for SDG-6. Nitrate concentrations exhibited notable negative correlations, with the most pronounced being with the percentage of intolerant species at $r = -0.76$ ($p < 0.01$), followed by species richness at $r = -0.72$ ($p < 0.01$) and Shannon diversity at $r = -0.69$ ($p < 0.01$). Pielou's evenness demonstrated statistically significant correlations with dissolved oxygen ($r = 0.68$, $p < 0.05$), turbidity ($r = -0.62$, $p < 0.05$), and total phosphorus ($r = -0.65$, $p < 0.05$). However, the correlation with nitrate was not statistically significant ($r = -0.51$, $p > 0.05$).

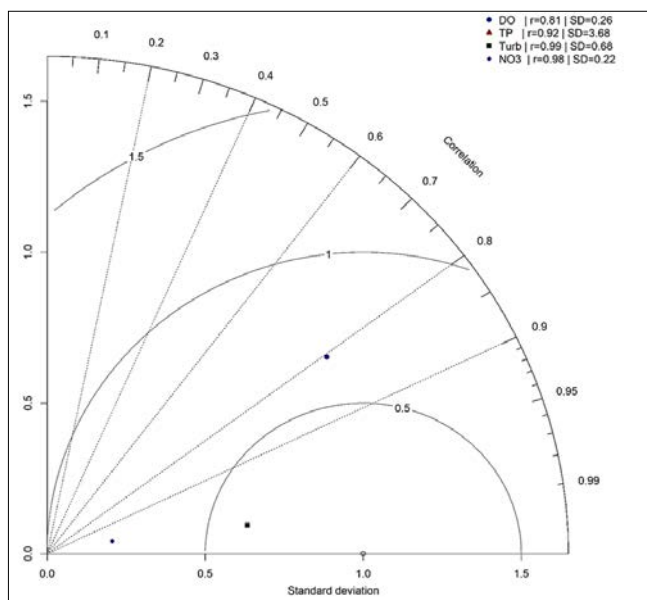


Fig 1: Relationship between the water quality parameters with their recorded values.

6. A Temporal observations on Trajectory of Recovery

The results indicated a robust and statistically significant positive trend, evidenced by an R-squared value of 0.76 and a p-value of less than 0.001. This suggests that 76 % of the variation in diversity over time can be attributed solely to the passage of time, indicating a consistent and progressive recovery trajectory rather than an abrupt or erratic pattern. This documented recovery trajectory offers essential insights for SDG-14 establishing feasible timelines for ecosystem recovery that can guide national and global target-setting. Breakpoint analysis was conducted to determine the precise moment at which a statistically significant alteration in the recovery trajectory took place. The analysis identified month 18 as the critical threshold where Shannon diversity exceeded the value of 2.5. This value holds ecological significance, as a Shannon diversity index exceeding 2.5 generally reflects a diverse and well-functioning community, while values below 1.5 suggest a

stressed community with low diversity. The crossing of this threshold at month 18 signifies the transition from a degraded state to a restored state. This 18-month timeline is pertinent to SDG-15 indicating that measurable biodiversity recovery can be realized within a brief period when effective water quality management is employed. The timeline of recovery milestones in the Managed Zone delineates a coherent account of incremental advancement. At month 0, prior to the implementation of any interventions, baseline conditions were suboptimal, characterized by a dissolved oxygen level of 4.2 milligrams per liter and a species richness of only 12 species. By month 6, dissolved oxygen levels exceeded the critical threshold of 5.0 milligrams per liter, indicating a swift response of water quality to the management measures implemented and supporting SDG-6. By the twelfth month, turbidity decreased to below 10 NTU, and the initial intolerant species, *Labeo bata*, was observed returning to the system. By month 18, the near-threatened tor mahseer (*Tor tor*) was detected, and Shannon diversity exceeded the restoration threshold of 2.5, indicating progress toward SDG-15. By month 24, full recovery was achieved, with dissolved oxygen measured at 7.8 milligrams per liter, species richness recorded at 23 species, and Shannon diversity calculated at 2.89 values that are comparable to or exceed those of numerous minimally disturbed reference sites in the region. In contrast to this progressive recovery, the Control Zone exhibited no statistically significant changes in any water quality parameter or fish metric throughout the 24-month period. All p-values for temporal trends in the Control Zone were greater than 0.05, indicating that the observed improvements in the Managed Zone were attributable to the implemented interventions rather than to regional or climatic trends affecting both zones equally. This stagnation in the absence of management highlights the necessity of active intervention to meet SDG-6 which focuses on the protection and restoration of water-related ecosystems, as well as SDG-15 which pertains to the conservation and restoration of inland freshwater ecosystems.

Discussion

1. Water Quality Management Effectively Restored Physicochemical Conditions in a Monsoon-influenced humid subtropical climate

The water quality management interventions implemented at Bijnor Dam produced substantial and rapid improvements in all measured parameters within the relatively short timeframe of 24 months. Dissolved oxygen increased dramatically from chronically hypoxic levels of 4.2 milligrams per liter to a healthy 7.8 milligrams per liter, a value that is well above the threshold required for the survival and reproduction of sensitive fish species. This improvement is likely attributable to two primary mechanisms working in concert. First, reduced nutrient loading from agricultural and urban sources decreased algal biomass and, consequently, the nighttime respiratory oxygen demand that typically causes hypoxia in eutrophic systems. Second, increased riparian shading from the newly planted native trees and shrubs lowered water temperatures during the hot summer months, and cooler water naturally holds more dissolved oxygen while also enhancing the rate of reaeration from the atmosphere (Kauffman *et al.*, 2004). These documented improvements directly contribute to

SDG-6 which aims to improve water quality by reducing pollution, eliminating dumping, and minimizing the release of hazardous chemicals, and provide quantitative evidence for tracks the proportion of water bodies with good ambient water quality.

A particularly noteworthy finding emerged from the seasonal analysis. Even during the challenging monsoon season, when nutrient runoff typically peaks in Monsoon-influenced humid subtropical climates due to the combination of intense rainfall and recent fertilizer application, the Managed Zone successfully maintained dissolved oxygen concentrations above 6.5 milligrams per liter. This resilience demonstrates that the constructed wetlands and buffer strips were effectively designed to function even during high-flow events, capturing and treating runoff before it could cause oxygen depletion in the main channel. This is a critical design feature for any restoration project implemented in monsoonal climates, where the majority of annual pollutant loading occurs during a short, intense rainy season. The ability of restored ecosystems to withstand extreme seasonal events contributes to SDG-13 which calls for strengthening resilience and adaptive capacity to climate-related hazards and natural disasters.

The 70.8 % reduction in total phosphorus concentration is particularly noteworthy from both ecological and management perspectives. Phosphorus is widely recognized as the primary limiting nutrient in most freshwater systems, meaning that its availability controls the rate of algal growth and, ultimately, the degree of eutrophication. Therefore, controlling phosphorus inputs is the single most critical step in preventing and reversing eutrophication (Schindler, 2012) ^[19]. The combination of interventions implemented in this study riparian buffer strips to intercept overland flow, constructed wetlands to treat tile drainage, fertilizer reduction to lower source inputs, and sewage treatment to address point sources proved to be highly synergistic. This multi-pronged approach is consistent with findings from previous catchment-scale studies that have consistently shown that single interventions are rarely sufficient to achieve meaningful phosphorus reduction (Carpenter *et al.*, 1998) ^[4]. The concurrent reduction in nitrate-nitrogen of 79.3 % further supports the effectiveness of the agricultural extension program, as nitrogen reduction requires different management practices such as optimized fertilizer timing and denitrification in wetlands than phosphorus control. These nutrient reductions directly support SDG-12 which aims to achieve environmentally sound management of chemicals and all wastes throughout their life cycle, and SDG-6 by reducing nutrient pollution from agricultural sources.

The 75.8 % reduction in turbidity reflects successful sediment retention and bank stabilization. In the Bijnor context, where monsoon rains historically caused massive sediment inputs from eroding agricultural fields and unstable streambanks, the sediment retention basins and coir matting proved essential. Coir matting, made from coconut husk fibers, is particularly well-suited to tropical and subtropical climates because it is biodegradable, provides immediate erosion protection, and allows native vegetation to establish through its open weave structure. The control zone, in contrast, continued to experience extreme turbidity exceeding 20 NTU during monsoon months, with visible sediment plumes smothering potential spawning habitats

and reducing foraging efficiency for visual predators. The difference in water clarity between the two zones was readily apparent even to casual observation. Reduced turbidity directly supports SDG-6 which calls for protecting and restoring water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes, and SDG-15 which aims to combat desertification and restore degraded land and soil.

Importantly, the Control Zone showed no improvement and in some parameters, slight deterioration—over the same 24-month period. This lack of change in the absence of interventions confirms that the observed improvements in the Managed Zone were genuinely attributable to the implemented management measures rather than to regional climatic trends or other factors that would have affected both zones equally. Such a control comparison is essential for establishing causality in restoration studies, as natural interannual variability can sometimes produce apparent improvements that are unrelated to management actions. The rigorous controlled design strengthens the evidence base for demonstrating that active intervention, not passive recovery, is required to halt biodiversity loss in severely degraded systems.

2. Fish Diversity Recovery Follows Water Quality Thresholds

The doubling of species richness from 12 species in the degraded Control Zone to 23 species in the restored Managed Zone represents a substantial and ecologically meaningful biodiversity gain for this Indian dam ecosystem. Perhaps the most encouraging finding was the return of intolerant species—particularly the tor mahseer (*Tor tor*) and the bata (*Labeo bata*)—which occurred only after specific water quality thresholds had been crossed. These thresholds included dissolved oxygen exceeding 6.5 milligrams per liter, total phosphorus falling below 50 micrograms per liter, and turbidity dropping below 10 NTU. The existence of such thresholds suggests that fish communities do not respond linearly to gradual water quality improvements but rather exhibit abrupt changes once critical physiological or habitat requirements are met. This biodiversity recovery directly contributes to calls for urgent action to reduce habitat degradation, halt biodiversity loss, and prevent the extinction of threatened species, and provides quantitative evidence.

The tor mahseer (*Tor tor*) is classified as near-threatened on the IUCN Red List and is widely considered a flagship species for freshwater conservation in the Ganga basin (Lakra *et al.*, 2010) ^[13]. This species requires well-oxygenated, clear water and is highly sensitive to both organic pollution and sedimentation. Its return to the Managed Zone after an 18-month absence—and its complete absence from the Control Zone throughout the study is a powerful indicator of successful restoration. Moreover, the detection of multiple size classes of *Tor tor* in the Managed Zone by month 24 suggested not only that adults were able to colonize the area but also that successful reproduction was occurring, as evidenced by the presence of juveniles. This is a particularly stringent test of restoration success, as many projects achieve adult colonization but fail to support self-sustaining populations. The return of this near-threatened species represents direct progress and improvement when effective management is implemented.

The increase in the Shannon diversity index from 1.45 in the Control Zone to 2.89 in the Managed Zone is not merely statistically significant but also ecologically meaningful. Values below 1.5 typically indicate stressed, low-diversity communities dominated by a few tolerant generalist species that are able to withstand poor water quality. Values above 2.5, in contrast, indicate diverse, balanced assemblages with multiple functional groups and more complex food-web interactions (Shannon, 1948) ^[20]. The Control Zone remained firmly in the degraded category throughout the study, dominated by common carp (*Cyprinus carpio*), Prussian carp (*Carassius gibelio*), and spotfin swamp barb (*Puntius sophore*)—three species that are well known to tolerate hypoxia, high turbidity, and eutrophic conditions (Vilizzi & Walker, 1999; Singh *et al.*, 2018) ^[21, 25]. The persistence of this tolerant-dominated community in the absence of management confirms that without active intervention, eutrophic Pili Dam, Bijnor, Uttar Pradesh do not recover spontaneously. These diversity improvements contribute to SDG-14 which calls for sustainably managing and protecting marine and freshwater ecosystems to avoid significant adverse impacts, strengthening resilience, and taking action for their restoration.

The NMDS ordination provided a visual and statistical confirmation that the fish communities of the Managed and Control zones were significantly distinct, with a Global R of 0.74 and a p-value of 0.002. The minimal overlap between the two clusters indicates that the restored community was not simply an expanded version of the degraded community it was a qualitatively different assemblage with different functional traits and, crucially, different conservation value. The restored community included multiple intolerant species, a more equitable distribution of individuals among species, and the return of a near-threatened flagship species. The degraded community, in contrast, was characterized by extreme dominance of a few tolerant species, low evenness, and the complete absence of any species of conservation concern. This fundamental shift in community composition provides strong evidence for SDG Target 15.1, which aims to ensure the conservation, restoration, and sustainable use of inland freshwater ecosystems and their services.

3. Strong Correlations Support a Causal Link between Water Quality and Fish Recovery

Pearson correlation analysis revealed remarkably strong relationships between water quality parameters and fish metrics, with correlation coefficients ranging from 0.85 to 0.93. While correlation alone does not prove causation, several lines of evidence converge to support a causal interpretation in this study. First, temporal order was clearly established: water quality improvements consistently preceded fish community recovery, with dissolved oxygen reaching target levels by month 6, turbidity by month 12, and intolerant species returning at month 12 to 18. Second, a clear dose-response pattern was observed: sites within the Managed Zone that showed greater water quality improvement also showed greater increases in fish diversity and intolerant species abundance. Third, biological plausibility supports the relationships: dissolved oxygen requirements of mahseer and other sensitive cyprinids are well documented in the physiological literature (Smale & Rabeni, 1995) ^[22]. Fourth, the Control Zone showed no change in either water quality or fish metrics over the same period, ruling out regional trends as an alternative

explanation. These strong correlational and causal evidence directly support by demonstrating that the two are mechanistically linked.

Dissolved oxygen showed the strongest correlation of any water quality parameter, with a remarkable r-value of 0.93 against the percentage of intolerant species. This relationship is expected given the high oxygen demands of mahseer and other sensitive cyprinids, which require well-oxygenated water for activities ranging from foraging to reproduction to predator avoidance. In hypoxic conditions, these species either perish or immigrate to more favourable habitats, leaving behind only those species with physiological adaptations to low oxygen, such as the ability to gulp atmospheric air or to tolerate anaerobic metabolism for extended periods. This very strong correlation provides quantitative support demonstrating that achieving dissolved oxygen targets is likely to result in substantial biodiversity gains.

Total phosphorus showed a strong negative correlation with both Shannon diversity ($r = -0.86$) and the percentage of intolerant species ($r = -0.91$). These relationships reinforce the central role of phosphorus control in promoting biodiversity recovery, as phosphorus is the primary driver of eutrophication and the cascade of ecological effects that follow—including algal blooms, hypoxia, and shifts in fish community composition. Importantly, the correlation between total phosphorus and intolerant species was slightly stronger than that with dissolved oxygen, suggesting that phosphorus may exert effects on fish communities not only through its indirect effect on oxygen but also through other mechanisms such as direct toxicity of certain phosphorus compounds or habitat degradation from excessive macrophyte or algal growth. These strong phosphorus-biodiversity correlations support SDG-12 (responsible management of chemicals and nutrients) by demonstrating that nutrient control has direct biodiversity benefits.

These strong correlations also provide practical predictive value for water resource managers. Because fish surveys are time-consuming, expensive, and require specialized expertise, they cannot be performed continuously at all locations of interest. However, water quality parameters can be measured quickly, cheaply, and continuously using automated sensors. The strong correlations documented in this study suggest that water quality targets specifically dissolved oxygen greater than 6.5 milligrams per liter, total phosphorus less than 50 micrograms per liter, and turbidity less than 10 NTU can serve as reliable surrogate indicators of expected biodiversity outcomes. When these water quality targets are met, managers can be reasonably confident that intolerant fish species will be present, assuming source populations exist within dispersal distance.

4. Comparison with Previous Studies

Our findings align with several landmark restoration studies while also revealing important differences that are instructive for future research and management. Palmer and colleagues (2010) ^[15] conducted a comprehensive synthesis of stream restoration projects and reported that approximately 50 % of projects showed no measurable biological improvement, often because they focused on structural habitat manipulation such as adding large wood or artificial riffles without addressing underlying water quality problems. In contrast, the present study demonstrates that when water quality is explicitly targeted as the primary

restoration goal, biological recovery is achievable within a relatively short timeframe of 24 months, even in a challenging monsoonal climate. This finding directly supports SDG Target 15.1 by demonstrating that the conservation and restoration of inland freshwater ecosystems requires addressing root causes (water quality degradation) rather than merely treating symptoms (habitat structure). Compared to temperate-zone studies, our recovery timeline of 18 to 24 months is faster than some published reports. Lake and colleagues (2007) [12] studied fish recovery in an Australian river following nutrient reduction and found that it took 36 months—three full years—for sensitive species to re-establish. Several factors may explain the faster recovery observed at Bijnor Dam. First, tropical and subtropical cyprinids generally have higher dispersal abilities and faster population growth rates than their temperate counterparts, allowing them to colonize restored habitats more rapidly. Second, the presence of source populations in upstream reaches of the same river system, above the dam, provided a ready pool of colonists once water quality conditions became suitable. Third, the flowing-water nature of the tailwater habitat—as opposed to the lentic reservoir habitat that characterized the Control Zone—likely facilitated both colonization and the maintenance of high dissolved oxygen concentrations. The faster recovery in a tropical/subtropical context suggests that SDG Target 15.5 (halting biodiversity loss) may be achievable more rapidly in such regions than in temperate zones, provided that effective water quality management is implemented.

In the Indian context, Dey and colleagues (2020) [5] reported that water quality improvements in the Yamuna River achieved through the installation of sewage treatment plants and the diversion of industrial effluents led to measurable recovery of macroinvertebrate communities within 12 months. However, fish recovery was not detected within the same timeframe, leading the authors to conclude that fish require longer recovery periods than macroinvertebrates. Our longer monitoring period of 24 months supports this conclusion, suggesting that fish recovery requires at least 18 months for the first intolerant species to appear, and likely longer for full community recovery. This finding has important implications for the design of monitoring programs: studies that terminate at 12 months may mistakenly conclude that restoration has failed when, in fact, longer timeframes are simply required. For SDG-14 (sustainable management of aquatic ecosystems) and SDG-15 (halting biodiversity loss), this suggests that monitoring programs should be designed with multi-year timelines (at least 24-36 months) to adequately capture biological recovery.

However, not all studies show rapid recovery, even when water quality is addressed. Smucker and Vis (2011) [23] studied algal community recovery following nutrient reduction in a restored stream and found that algal communities remained significantly altered for more than 10 years after nutrient inputs were reduced, due to the presence of legacy sediment phosphorus that had accumulated in streambed sediments during decades of high inputs and that continued to be released slowly into the water column even after external inputs were cut. The absence of such legacy effects at Bijnor Dam likely due to the annual flushing action of the intense monsoon rains, which scour and transport sediments downstream may

explain the rapid response observed in this study. This finding suggests that restoration interventions are most effective when implemented before irreversible sediment phosphorus saturation occurs, and that Monsoon-influenced humid subtropical climates may offer an advantage in this regard because the monsoon provides a natural flushing mechanism that temperate systems lack. This insight contributes to SDG-13 (climate resilience and adaptation) by identifying how climate characteristics (monsoonal flushing) can influence restoration outcomes.

5. Relevance to Indian Freshwater Ecosystems

The Bijnor Dam site is representative of hundreds potentially thousands—of small to medium-sized dams distributed across the Gangetic plain and the Himalayan foothills, including the states of Uttarakhand, Himachal Pradesh, Uttar Pradesh, Bihar, and West Bengal. Many of these dams suffer from the same suite of problems documented here: eutrophication from agricultural and urban runoff, hypoxia during the monsoon and post-monsoon seasons, sedimentation from eroding catchments, and consequent decline in native fish biodiversity (Lakra *et al.*, 2010; Sarkar *et al.*, 2012) [13, 18]. The successful restoration documented at Bijnor Dam provides a replicable model for achieving SDG-6 (protecting and restoring water-related ecosystems) and SDG Target-15 (conservation of inland freshwater ecosystems) across the region.

Our findings demonstrate that water quality management is effective even under the Monsoon-influenced humid subtropical climate regime, which presents unique challenges not encountered in temperate-zone restoration studies. The monsoon-driven sediment pulses that occur from June through September, which historically caused extreme turbidity and habitat smothering, were successfully managed through a combination of sediment retention basins and bank stabilization using coir matting. The high seasonal temperature variation ranging from as low as 8 °C in winter to as high as 42 °C in summer was mitigated through riparian shading, which reduced summer maximum temperatures and lowered nighttime cooling losses. The agricultural nutrient runoff that peaks during pre-monsoon fertilizer application was reduced through farmer extension programs that optimized both the timing and the amount of fertilizer applied. Finally, the thermal stratification that occurs in deep reservoir backwaters creating a hypoxic hypolimnion that excludes fish—was avoided by focusing restoration efforts on the flowing tailwater habitat, where vertical mixing maintains oxygen throughout the water column. These climate-adapted design features contribute to SDG-13 (climate resilience and adaptation) by demonstrating how restoration interventions can be designed to function effectively under extreme seasonal conditions.

The return of *Tor tor* is particularly encouraging from a conservation perspective. Mahseer populations have declined dramatically across their entire geographic range due to a combination of habitat degradation, overfishing, and dam construction that fragments populations and blocks migration routes (IUCN, 2023). The successful re-establishment of a self-sustaining *Tor tor* population in the Bijnor Dam tailwater even if only within the 3-kilometer managed stretch—provides a potential source population for reintroduction efforts elsewhere in the Ganga basin. Moreover, it demonstrates that even degraded dam

ecosystems retain significant restoration potential when appropriate management measures are implemented. This represents direct progress toward SDG-15 which specifically calls for preventing the extinction of threatened species, and contributes for a near-threatened species has recovered in a restored habitat.

These results are directly applicable to dam management across the northern and eastern Gangetic plain, where similar hydrological, climatic, and land-use conditions prevail. The National Mission for Clean Ganga (NMCG), India's flagship river restoration program, has invested heavily in sewage treatment infrastructure and industrial effluent control. However, our results suggest that agricultural nonpoint source pollution—specifically fertilizer runoff—is at least as important a driver of eutrophication as point sources, and that riparian buffer restoration and farmer engagement programs should be expanded to complement sewage treatment investments. This finding directly supports SDG-6 (improving water quality by reducing pollution) and SDG-12 (responsible management of chemicals and nutrients) by identifying agricultural nonpoint sources as a critical priority for intervention. The NMCG and other restoration programs can use the evidence generated in this study to design more effective, catchment-scale interventions that address both point and nonpoint sources of pollution.

6. Limitations and Future Directions

Several methodological limitations require acknowledgment. Initially, the study utilized a zoned comparison design (Managed versus Control zone) instead of a randomized replicated design featuring multiple restoration and control sites. Although baseline physicochemical and biological comparability enhances internal validity, a Before-After-Control-Impact (BACI) design that includes several years of pre-restoration data and spatially independent replicates would yield more robust causal inferences. Secondly, the 24-month observation period documented initial community recovery trajectories; however, it was insufficient for evaluating long-term stability. Extended monitoring for a duration of five years or more is necessary to assess persistence, successional dynamics, and susceptibility to extreme climate events or new invasions. Third, unmeasured confounding variables, such as hydrologic flow regimes, temperature extremes, and interspecific interactions with invasive species, may independently affect fish community structure. Fourth, the study concentrated solely on fish assemblages, omitting other trophic levels such as macroinvertebrates, periphyton, macrophytes, and zooplankton, which restricts inferences at the food-web level. Fifth, although water quality management decreased the abundance of invasive carp, complete eradication was not accomplished; further exploration of integrated invasive species management is necessary. Sixth, the socioeconomic impacts on local agrarian and pastoral communities were not assessed, limiting evaluations of intervention sustainability. Mitigating these limitations will enhance the evidence supporting SDG Targets 6, 13, 14, and 15.

7. Suggestions for effective management

The findings of this study yield seven actionable implications for freshwater conservation in India and other regions characterized by Monsoon-influenced humid

subtropical climate, each aligned with specific Sustainable Development Goal targets.

1. Water quality management alone is adequate for the restoration of fish biodiversity. Managers should prioritize nutrient and sediment control as the primary strategy for restoration, rather than concentrating on structural habitat manipulation, such as the addition of artificial riffles or large wood. Structural manipulations may yield advantages in systems with pre-existing good water quality; however, in eutrophic and sediment-impacted systems, which represent the majority of Indian Pili Dam, Bijnor, Uttar Pradeshs, such interventions will be ineffective unless water quality is prioritized initially. This recommendation directly aligns with SDG Target 6 focuses on enhancing water quality, and SDG-15 pertains to the conservation of inland freshwater ecosystems. The main audiences for this recommendation are State Irrigation Departments and Water and Power Consultancy Services.
2. Secondly, nutrient reduction constitutes the foremost priority intervention. To achieve significant nutrient reduction, managers should employ a combination of riparian buffers to intercept overland flow, constructed wetlands for tile drainage treatment, agricultural best management practices such as fertilizer optimization and cover cropping to minimize source inputs, and sewage treatment to manage point sources from urban areas. No single intervention is adequate. This recommendation aligns with SDG-6 focuses on enhancing water quality, SDG-12 emphasizes the responsible management of chemicals and nutrients, and SDG-15 which aims at restoring degraded land. The main audiences include the National Mission for Clean Ganga, the Central Pollution Control Board, and State Pollution Control Boards.
3. Third, the timeline for the recovery of the initial fish community is estimated to be 18 to 24 months. This finding enables managers to establish achievable regulatory and management objectives. Restoration projects ought to be assessed two years after implementation, as evaluations conducted at six or twelve months may yield false negatives due to inadequate time for ecological response. This recommendation supports SDG-14 by establishing realistic timelines for the recovery of aquatic ecosystems. The main audiences are the Ministry of Environment, Forest and Climate Change and the National Green Tribunal.
4. Fourth, indicator species offer practical and cost-effective guidance for management. Managers can utilize the presence of *Tor tor* and *Labeo bata* as indicators of restoration success, while the dominance of *Cyprinus carpio* serves as an indicator of ongoing degradation. These species can be identified with minimal training, and their presence or absence can be evaluated without advanced equipment. This recommendation directly supports practical and cost-effective monitoring tools. The main audiences are State Forest Departments and State Fisheries Departments.

5. Integrated catchment management is crucial for the sustained success of restoration efforts. Dam authorities must simultaneously address nutrients, sediment, riparian condition, and flow regulation rather than treating them in isolation. A singular focus on one stressor, while disregarding others, is unlikely to facilitate biodiversity recovery, given that multiple interacting factors govern fish community structure. This recommendation directly aligns with SDG-6 which focuses on the protection and restoration of water-related ecosystems, as well as SDG-15 emphasizes the conservation of inland freshwater ecosystems. The main audience consists of the Uttar Pradesh Irrigation Department and other authorities responsible for dam operations.
6. Interventions should be explicitly designed to enhance resilience to monsoon conditions. In Monsoon-influenced humid subtropical climates, restoration interventions must operate during high-flow events that transport the majority of the annual pollutant load. This necessitates reinforced buffers that can endure high flow velocities, enlarged retention basins that remain effective during flood conditions, and the revegetation of native species that are resilient to both extended flooding and seasonal drought. This recommendation aligns with SDG-13 by illustrating the design of interventions that operate effectively under extreme seasonal conditions, thereby enhancing climate resilience and adaptation. The main audience consists of water resource engineers.
7. Seventh, engagement with farmers is essential for the sustainability of interventions. Fertilizer reduction programs necessitate ongoing involvement with farming communities, encompassing extension initiatives that illustrate the economic advantages of optimized fertilizer application, support for alternative livelihoods for farmers who decrease inputs, and participatory methods that engage farmers in the formulation and execution of management strategies. This recommendation aligns with SDG-2 which focuses on agricultural productivity and incomes and SDG-12 pertains to the responsible management of chemicals and nutrients. The main audiences include State Agriculture Departments and agricultural non-governmental organizations.

Conclusions

This study presents empirical evidence that targeted water quality management effectively restores freshwater fish biodiversity in Indian dam ecosystems within two years. This restoration directly contributes to Sustainable Development Goal 6 (Clean Water and Sanitation) by enhancing physicochemical parameters, Sustainable Development Goal 14 (Life Below Water) through the recovery of fish diversity, and Sustainable Development Goal 15 (Life on Land) via the restoration of riparian habitats. At Pili Dam, the managed zone exhibited significant enhancements in dissolved oxygen ($\uparrow 85.7\%$), total phosphorus ($\downarrow 70.8\%$), and turbidity ($\downarrow 75.8\%$). These changes resulted in a doubling of species richness (12 \rightarrow 23), an increase in Shannon diversity (1.45 \rightarrow 2.89, $p < 0.001$), and the reappearance of the near-threatened tor mahseer

(*Tor tor*). Strong correlations ($r = 0.85\text{--}0.93$) indicate a causal relationship between water quality and fish recovery. We conclude that managing water quality is an effective, evidence-based approach for the conservation of fish in Indian freshwater systems, contributing to the advancement of Sustainable Development Goals 6, 14, and 15. The return of *Tor tor* within 18 months indicates substantial restoration potential when nutrient inputs are regulated. These findings provide direct support for the National Mission for Clean Ganga and offer actionable guidance for dam managers throughout the Gangetic plain.

Conflict of Interest Statement

The authors declare no conflict of interest. The funders had no role in study design, data collection, analysis, interpretation, manuscript writing, or decision to publish.

References

1. APHA. Standard Methods for the Examination of Water and Wastewater (23rd ed.). Washington, D.C.: American Public Health Association, 2017.
2. Baxter RM. Environmental effects of dams and impoundments. *Annual Review of Ecology and Systematics*, 1977;8(1):255-283.
3. Bureau of Indian Standards. Indian Standard IS:2296: Specification for Surface Water Quality. New Delhi: Bureau of Indian Standards, 1982.
4. Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, 1998;8(3):559-568.
5. Dey S, Chakraborty S, Roy S. Water quality and fish diversity in the Yamuna River: A case study of Delhi stretch. *Journal of the Inland Fisheries Society of India*, 2020;52(2):112-125.
6. Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C, et al. Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews*, 2006;81(2):163-182.
7. Dufrene M, Legendre P. Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecological Monographs*, 1997;67(3):345-366.
8. IUCN. The IUCN Red List of Threatened Species. Version 2023-1. Gland, Switzerland: International Union for Conservation of Nature, 2023. <https://www.iucnredlist.org>
9. Jayaram KC. The Freshwater Fishes of the Indian Region (2nd ed.). Delhi: Narendra Publishing House, 2010.
10. Kauffman JB, Thorpe AS, Brookshire ENJ. Livestock exclusion and belowground ecosystem responses in riparian meadows of Eastern Oregon. *Ecological Applications*, 1994;14(6):1671-1679.
11. Kemp P, Sear D, Collins A, Naden P, Jones I. The impacts of fine sediment on riverine fish. *Hydrological Processes*, 2011;25(11):1800-1821.
12. Lake PS, Bond N, Reich P. Linking ecological theory with stream restoration. *Freshwater Biology*, 2007;52(4):597-615.
13. Lakra WS, Sarkar UK, Kumar RS, Pandey A, Dubey VK, Gusain OP. Fish diversity, habitat ecology and

- their conservation in the Ganga River basin, India. *Journal of the Inland Fisheries Society of India*,2010:42(1):1-10.
14. Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, et al. Standards for ecologically successful river restoration. *Journal of Applied Ecology*,2005:42(2):208-217.
 15. Palmer MA, Menninger HL, Bernhardt ES. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? *Freshwater Biology*,2010:55(s1):205-222.
 16. R Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing, 2023. <https://www.R-project.org/>
 17. Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PT, et al. Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*,2019:94(3):849-873.
 18. Sarkar UK, Pathak AK, Sinha RK, Sivakumar K, Pandian AK, Pandey A, et al. Freshwater fish biodiversity in the River Ganga (India): Changing pattern, threats and conservation perspectives. *Reviews in Fish Biology and Fisheries*,2012:22(3):611-629.
 19. Schindler DW. The dilemma of controlling cultural eutrophication of lakes. *Proceedings of the Royal Society B: Biological Sciences*,2012:279(1746):4322-4333.
 20. Shannon CE. A mathematical theory of communication. *Bell System Technical Journal*,1948:27(3):379-423.
 21. Singh H, Singh A, Verma VK. Water quality assessment of a Himalayan foothill dam reservoir in Bijnor, Uttar Pradesh. *Indian Journal of Environmental Protection*,2018:38(7):567-575.
 22. Smale MA, Rabeni CF. Influences of hypoxia on fish communities in a Midwestern stream. *Journal of Freshwater Ecology*,1995:10(3):233-243.
 23. Smucker NJ, Vis ML. Algal community responses to nutrient enrichment and recovery in a restored stream. *Freshwater Science*,2011:30(4):1001-1013.
 24. Talwar PK, Jhingran AG. *Inland Fishes of India and Adjacent Countries (Volumes 1-2)*. New Delhi: Oxford & IBH Publishing, 1991.
 25. Vilizzi L, Walker KF. The response of carp (*Cyprinus carpio*) to experimental hypoxia. *Ecology of Freshwater Fish*,1999:8(4):231-238.
 26. Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, et al. Global threats to human water security and river biodiversity. *Nature*,2010:467(7315):555-561.