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Hydrological And Water Quality Drivers Of Exotic Fish Assemblages In A Semi-Arid Indian Reservoir: A Multivariate Ecological Assessment

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Abstract
Invasive alien species and damming - the most serious reasons for alterations in aquatic ecosystems - and understanding their interaction is essential for both conceptual and practical applications. Invasive alien species are a key factor in global ecological disruption, being the second most significant cause of species extinction. Simultaneously, establishment of dams has a negative impact on freshwater ecosystems, causing severe repercussions for aquatic species e.g. habitat loss, population decline and competition with native species. Our study of Thippagondanahalli reservoirs highlights the critical link between hydrological factors and exotic fish populations. Our findings indicate that the first two axes (RDA1 and RDA2) account for 82.2% of the total explained variance regarding the variation of seven exotic fish species in relation to fifteen hydrological variables. The research suggests that current hydrology and morphology conditions of the Reservoir and influenced by anthropogenic activities, is associated with the dominance of exotic fish species. Efforts are necessary to restore the natural hydro-morphology affected by damming in order to resolve the challenges posed by invasive exotic species effectively.
Keywords: *Fisheries management, Invasive alien species, Fish conservation, Hydrology*

INTRODUCTION

In India, reservoirs have been built across nearly all hydrographic basins over the past five decades, primarily to supply water to urban areas, support irrigation and generate electricity [1]. Hydropower dams are a renewable energy source by human intervention to ensure a reliable and manageable water supply. While these reservoirs contribute to economic growth at both regional and local levels, they also cause substantial and long-lasting alterations to natural hydrological patterns. However, their construction and operation negatively impact freshwater ecosystems and food security, potentially disrupting plankton dynamics within the reservoir [2,3], which in turn affects fish communities [4]. Changes in water quality have led to significant shifts in fish populations. Initially, fish diversity increases considerably after reservoir construction due to the creation of new habitats and altered ecological conditions. However, as reservoirs age, diversity declines [5]. Additionally, harmful fishing practices, sewage accumulation and introduction of exotic species further degrade habitats, leading to the decline or extinction of fish species [6]. Moreover, these factors affect fish assemblages, as well as the hydrological and geomorphological structure of the reservoirs [7, 8, 9, 10].

Fishing, as the primary secondary use of reservoirs, significantly impacts the reservoir environment. In particular, fishing activities affect flora, fauna, and water quality [11]. Additionally, it can sometimes help to manage the population of large exotic fish, providing refuge from predation for native species in heavily altered environments, such as reservoirs. This dynamic contributes to the concept of reconciliation ecology [12]. To protect biodiversity, it is advisable to explore alternative renewable energy sources or consider the reconfiguration of existing dams to enhance electricity production rather than construction of new hydropower dams [13]. A study by Yan et al. [14] highlights that dam construction can negatively affect upstream fish diversity by either elimination or restriction of fish migration. Moreover, dams can disrupt natural flow patterns, impacting species that rely on seasonal flows for their life cycles and potentially leading to population decline.

Invasive alien species are ranked as the second most significant factor contributing to species extinction and ecological disruption. Both invasive alien species and damming represent major changes in aquatic ecosystems and understanding the processes governing biological invasions in these environments is essential from both conceptual and practical perspectives [15]. A deeper understanding of reservoir limnology facilitates the development and implementation of environmentally responsible management approaches [3]. A thorough understanding of the physical, chemical and biological processes within the reservoir enables researchers and environment policy makers to identify the root causes of ecological degradation.

Previous studies have examined water quality and exotic species assemblages in Indian reservoirs, emphasising the role of altered water quality, spatial variation, spread of exotic species, impact of exotic fish on the native species and the food web. However, there is a lack of comprehensive studies on physio-chemical variables to understand the mechanisms of underlying exotic fish dominance, especially in a semi-arid reservoir such as Thippagondanahalli Reservoir.

Addressing this research gap, our current study seeks an integrated approach by combining water quality parameters, heavy metal concentrations and physical habitat variables to assess their influence on exotic fish assemblage by using multivariate ordination techniques. This study aims to provide an understanding of the ecological drivers facilitating exotic species. Moreover, limnological data can guide sustainable fishing practices, optimise dam operations and inform adaptive management plans that respond to changing climatic and hydrological conditions. It serves as the scientific foundation for integrating ecological sustainability with water demand in the reservoir system. Specifically, the objectives of this study are to evaluate the impact of water quality degradation and heavy metal pollution in exotic fish assemblages in Thippagondanahalli Reservoir; determine the patterns of exotic fish species in relation to environmental gradients and thereby understand the effects with the help of multivariate techniques, such as Redundancy analysis.

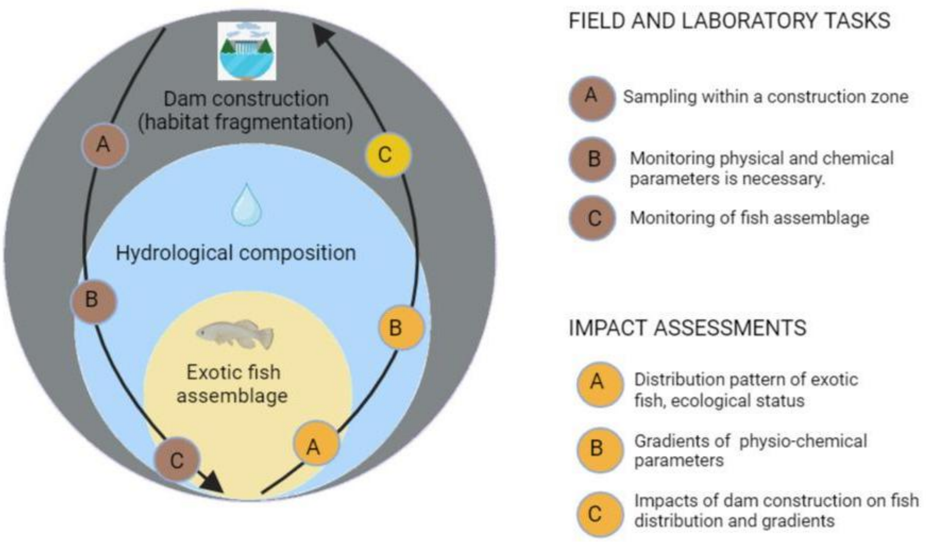

Figure 1. The illustration demonstrates a comprehensive impact assessment of river damming.

2. MATERIAL AND METHODS

2. 1 Study area

Thippagondanahalli Reservoir is a 1935 construct, to supply water to Bengaluru, Karnataka, India. It is located between 12°58'24" to 12°96'49" N and 77°20'33" to 77°35'63" E. The watershed feeding the TG Halli Reservoir comprises two primary river channels: the Arkavathy river (a tributary of the Cauvery) and the Kumudavathy River [17]. This watershed covers approximately 1,447 Km^2 and receives an annual precipitation of around 830 mm, primarily during the monsoons, from June to November. The region's climate is classified as tropical and semi-arid, with an annual rainfall of approximately 700 mm. Since the 1970s, there has been a significant decrease in the inflow of water into the TG Halli Reservoir [18,19].

Investigating this decline in streamflow is crucial for understanding the relationship between hydrological changes and human-induced alterations in land and water management practices in the area.

2. 2 Study model

Survey and sampling have been conducted at the Thippagondanahalli Reservoir from 2022 to 2023 to document the presence of exotic aquatic species in these ecosystems. Figure 1. illustrates the aquatic environment surrounding the Reservoir. The outermost circle, represented in "grey", indicates that dam construction indirectly impacts aquatic fauna, particularly through habitat fragmentation. Moving inward, the "blue circle" highlights the importance of establishing suitable environmental conditions for invasive species, focusing on resulting changes in water composition. Finally, the "innermost circle", depicted in "light yellow", concentrates on the direct impact of construction-related activities and environmental conditions on aquatic fauna. The impact assessment process begins with the collection and interpretation of data on aquatic fauna. This involves conducting physical and chemical analyses using multivariate statistical methods to examine correlations between fish populations and hydrological parameters. The effectiveness of the impact assessment depends on identifying gradients in specific parameters across construction and filling phase zones. These gradients are then integrated with previous findings on aquatic fauna, ultimately addressing the concerns outlined in the "outer grey circle".

2.3 Fish sampling

Species identification has been carried out using standard taxonomic keys and identification manuals [20, 21, 22]. Our approach is both temporal and spatial, with data grouped by seasons: rainy (February to May) and dry (August to November). Sampling is conducted in three zones of the Reservoir: the inlet, valve area and outlet point, based on their characteristics and water availability. The aim is to document the occurrence of exotic species, analyse their abundance and assess the influence of hydrological factors on their distribution. Local fishermen participate in the sampling process, while fish markets and landing sites near the reservoirs provide additional data points. Specimens are collected using standard inland fishing equipment, including cast nets, gill nets and traps made of nylon monofilaments, with mesh sizes ranging from 65 to 130 mm. These nets are deployed in the early morning and left to soak for two to three hours at each sampling site. Following the assessment of fish populations, immediate measurements are taken of the water conditions and the physical attributes at each location.

2. 4 Water sampling

Variables at each sampling location are examined by evaluating fifteen parameters mentioned with codes (Table 1): pH, temperature, turbidity (Tur), ammonia (Nh), boran (Bo), iron (Fe), total dissolved solids (Tds), calcium (Ca), chloride (Cl), fluoride (Fl), magnesium (Mg), nitrate (No), sulfate (So), alkalinity (Alk) and hardness [20]. Water temperature (Tmp) (^{o}C) is measured with a digital thermometer placed one-foot deep in the water. pH is determined with a pH meter, while Total dissolved solids were measured using a TDS meter. Chloride and hardness are analysed via the titration method, whereas sulfate and fluoride levels are assessed using atomic absorption spectrometry. The alkalinity of a water sample is established through titration with a strong acid (H2SO4) using methyl orange as an indicator. Additional samples (100 ml) intended for cation analysis are preserved with HNO3 (for example, 0.3 ml of HNO3 is added to a 200 ml water sample) and delivered to MSV Analytical Laboratories for the examination of major cations (such as calcium and magnesium) and minor/trace metals (including ammonia, boron, iron, and nitrate). Inductively coupled plasma mass spectrometry is used for the analysis.

2. 5 Data analysis

The statistical analysis of fish species is conducted to categorise different assemblage clusters based on abundance using Python. Fish species and water variables are analysed through a multivariate analysis tool. Given that our datasets are abundance-based species exhibiting linear responses to environmental factors, Redundancy Analysis (RDA) is selected [23, 24, 25, 26] to describe the association between species abundance and hydrological variables. Therefore, a direct multivariate ordination method based on the linear response of species to hydrological variables is applied by using Python 3.8. Several libraries are utilised, including pandas for data manipulation, NumPy for numerical calculations and linear regression and Matplotlib for visualisation. Prior to RDA, spearman correlation coefficient analysis (SC) is conducted to examine the correlation between water variable concentrations. The relationships among 15 different physio-chemical characteristics are evaluated using Spearman Correlation, represented in a

Heatmap Cluster Analysis (HCA) [27]. Table 1. illustrates the identified relationships among the fifteen water variables, including physio-chemical parameters in the study area and their potential sources. All data analysis and visualisation are carried out using Python, while maps are generated using QGIS software (version 3.16.4).

3. RESULT AND DISCUSSIONS

The investigation conducted in the Chandil Reservoir (India) highlights the connection between fish assemblages and water quality, which is a key factor in developing strategies for conserving aquatic fish diversity [28, 29]. A total of seven exotic fish species, belonging to four families, are recorded from Thippagondanahalli Reservoir. Biplot scores for constraining variables and the axes are presented in Table 1 and Table 2.

Table 1. Hydrological variables analyzed from the Thippagondanahalli Reservoir including code, mean, and standard deviation (SD).

Variable	Code	Mean	±SD	RDA1	RDA2
pH	ph	7.41	0.364527	-0.486569	0.960555
Temperature	tmp	25.55	1.060736	-0.518393	-0.896783
Turbidity	tur	0.34	0.093808	0.785240	-0.572293
Ammonia	nh	0.044	0.008	-0.653241	-0.495483
Boran	bo	0.156	0.034409	-0.653241	-0.495483
Iron	fe	0.052	0.020396	-1.089568	-0.002728
Total dissolved solids	tds	499.6	23.64403	-1.101585	-0.130214
Calcium	ca	46.12	7.878426	0.156579	-1.102693
Chloride	cl	72.9	14.79189	-1.100031	0.093376
Fluoride	fl	0.18	0.021909	-0.653241	-0.495483
Magnesium	mg	4.368	1.776101	-1.078998	0.019140
Nitrate	no	0.3	0.075895	-0.096243	-0.321728
Sulfate	so	6.348	1.345666	-1.078998	0.019140
Alkalinity	alk	113.28	17.68823	-1.065758	-0.17143
Hardness	hdn	97.3	12.46627	-0.653241	-0.495483

Table 2. Invasive alien species recorded in the Thippagondanahalli Reservoir detailing with common name, family name, native range, RDA code, and loading values of RDA1 and RDA2.

Species	Common name	Family name	Native range	Code	RDA1	RDA2

Oreochromis mossambicus	Mozambique Tilapia	Cyprinidae	Tropical and subtropical Africa	**orms**	-1.561060	2.161300
Oreochromis niloticus	Nile Tilapia	Cyprinidae	Africa	**ornl**	-0.633728	0.631933
Gambusia affinis	Mosquito Fish	Poeciliidae	North and Central America	**guaf**	-2.037213	2.853592
Clarias gariepinus	North African Catfish	Clariidae	North America	**clga**	-0.881482	1.024389
Pterygoplichthys pardalis	Sailfin Cat fish	Loricariidae	South America	**ptpa**	1.276630	0.077532
Cyprinus carpio	Common carp	Cyprinidae	Europe to Asia	**cyca**	-0.749318	-0.490131
Ctenopharyngodon idella	Grass carp	Cyprinidae	Pacific east	**gras**	-0.154563	-0.191931

The first two axes (RDA1 and RDA2) explain 82.2% of the total variance in the distribution of seven exotic fish species in relation to eleven hydrological variables (variance proportion explained: RDA1=57.7 %, RDA2=24.5%) (Figure 4). The RDA biplot scores suggest that the model effectively represents ecological relationships supported with the explained variance. The RDA1 highlights Tur as primary driver and RDA2 emphasises the highest loading variable. Whereas *Gambusia affinis* indicates the highest loading in species score (RDA2= 2.85), which is also indicated by the longest vector on the RDA plot (Figure. 3). *G. affinis* are found resilient to a range of environmental conditions and pH plays a vital role in their habitat suitability, preferring pH level of 7.0 to 8.5 [30], which aligns with observed value 7.41 ± 0.36 (Table 1.) Similarly, *Oreochromis mossambicus*, *Clarius gariepinus* and *Oreochromis niloticus* can flourish in water with elevated Ph and can tolerate nutrient-rich, alkaline environments common in reservoirs [31, 32]. *Pterygoplichthys pardalis* also shows distinctively high loadings on the RDA axes (RDA1= 1.27, RDA2=0.07) with a positive correlation to Tur on RDA1. On the other hand, *C. gariepinus* displays significant loading on both axes (RDA1=-0.88, RDA2=1.02) and shows a strong preference for habitats with Mg, So, hardness, Alk, Cl. This pattern suggests affinity of the species for ion-rich, mineral-loaded aquatic environments [33]. The RDA results reveal a strong collinearity between *Cyprinus carpio* and tds followed by Tmp, as evident from the angle their vectors share in the RDA plot (Figure. 4). This suggests a positive relationship, where *C. carpio* favours warmer, high nutrient water bodies, found in eutrophic or disturbed freshwater ecosystems [34]. *C. carpio* shows an exhibited preference for habitats with elevated Mg, So, hardness, Alk, Cl, which are clustered along the RDA2 axis, reflecting its adaptation to mineral-rich environments [35].

As it is a bottom-dweller, the species benefits from elevated hardness and alkalinity for osmoregulation and metabolic support. In contrast, *P. pardalis* do show a preference for Tur, due to its detritivore nature favouring a turbid, less mineral-rich habitat. Finally, *G. affinis, O. mossambicus*, *C. gariepinus* and *O. niloticus* demonstrate a strong correlation with Ph and a negative correlation with Tur, suggesting a low preference of turbidity in the environment. Environmental variables, nitrate content and species *Ctenopharyngodon idella* appear negligible in the biplot, as their vector representation is minimal in the axes. This suggests that their importance in determining variation and their impact can be considered negligible.

The dendrogram clustering reveals three distinct clusters. The first clusters (Mg, Ca, Hdn, So, Cl, Alk) represent significant parameters that may share common origins or behaviours within the reservoir. It is likely that these parameters contribute to buffering capacity, mineral content, geogenic processes and nutrient supply [36]. Previously noted, all these parameters are depicted in the heatmap with strong correlation with Spearman correlation coefficients (r), value<0.90. (Figure. 3.) The second cluster (Bo, No, Tmp, Tds) includes parameters that exhibit a distinct pattern from the first group. These parameters may be associated with industrial discharges, sewage discharge, pollution, or other human activities. The third cluster (Fe, Fl, Nh, Tur) highlights the strong association between Fe and Fl, as well as between Nh and Tur.

Parameters linked at shorter distances are more similar to each other. For example, Fe and Fl are closely linked and may indicate natural leaching from sediments or geochemical interactions in anaerobic conditions. Nh and Tur linkage may reflect events, such as sediment disturbance, low oxygen zones, or runoff after rainfall [37, 38] (figure 3).

The relationship between various water parameters and heavy metals provides valuable insights into their movement within the reservoir. At a significant level of Spearman, correlation matrix is observed. Specifically, the highest positive correlation between Mg and Ca (r=0.99) is followed by Alk, Cl, So (r=0.98). Similarly, positive correlations are detected between Hdn and Mg (r= 0.98), SO and Cl (r=0.96), suggesting a shared origin from natural weathering processes and anthropogenic sources, such as sewage discharge and agriculture runoff [39]. Moderate positive relationships are observed between Tds and Tmp (0.39) and Bo and pH (0.30). Additionally, correlation between Fe and No (r= 0.69), Tur and Fe (r=0.67) and Ca and Tds (R=0.71) indicate strong positive relationships. For example, the correlation between Cl and Ca suggests a strong association.

Meanwhile, the lowest correlation is observed between pH and Fl (r =-0.93). Their presence might be influenced by different factors and they may not exhibit strong interdependencies with other parameters. The correlation between Ca and Cl (r=0.93) indicates a strong association, suggesting their interconnection within the reservoir. In water treatment processes, for instance, Ca and Cl ions are often considered related due to their potential involvement in combined reactions for specific treatments. Comparative studies [40] show that these changes can impact freshwater ecosystem dynamics and health. Mg and Ca are the primary contributors to Tds, given their correlation (>0.50). Mg shows a correlation with Ca and So consistent with global observations [41]. Our RDA results indicate that Mg, So, Hdn, chloride and Alk have a negative correlation with *P. pardalis*. Similarly, a study [42] reports a gradual reduction of So, Ca, Mg in presence of *P. pardalis,* because of its capacity to remediate dairy effluents.

Though the species show positive correlation with several invasive species, including *G. affinis, O. mossambicus, C. gariepinus,* and *O. niloticus,* a study [43] finds that the correlation between environmental parameters and fish abundance indicates pH as the most significant factor influencing abundance, which aligns with our findings. Although No is an important parameter for fish abundance, its influence in our research appears negligible. This aligns with a study showing that the invasive fish species Gambusia sp. exhibits greater tolerance to nitrate pollution, potentially explaining the minimal effects on these invasive species. Past research also shows that assimilation by algae, dense macrophyte growth and microbial activity metabolise nitrate accessible for uptake [43].

While Fl typically correlates with pH, our research indicates a negatively correlated relationship between the two. This suggests that the relationship may vary based on local geological and hydrochemical conditions. Factors such as the presence of Ca and Mg ions, could influence fluoride behaviour, as these elements can form insoluble compounds with fluoride [44]. The total dissolved solids index is 499.6, which appears to be favourable for *C. carpio* according to the RDA plot. Some invasive fish species exhibit a significant thermal safety margin across acclimation temperatures, suggesting a high thermal resilience [45, 46, 47]. Our study reflects the trend as temperature does not appear to affect exotic species assemblages. Biotic homogenisation is primarily caused by the introduction of non-native species and the decline of indigenous fish species. Recent research [48] confirms that the genetic integrity of native *Clarius batrachus* is deteriorating due to hybridisation with the invasive *C. gariepinus* in Bangladesh. *C. gariepinus* (North African Catfish), a carnivorous species, contributes to the extinction of indigenous species, leading to a subsequent decline in biodiversity [49]. A mixed trophic impact study in Karapuzha Reservoir [50] reveals that *C. gariepinus* is an invasive predator on most of the fish and crustacean species.

A survey conducted among local fishermen reveals that the African catfish poses a significant threat to the native fish population. This species is reported uncommon 30 to 40 years ago but has shown an increase in abundance alongside other introduced species like *Oreochromis* sp, observed in other reservoirs like Karapuzada [50] and Ramsar wetlands [51]. The African catfish can gain weight up to 60 kgs as revealed in a study [50], while our results observe a maximum of 20 kgs each and reports indicate that nearly 1000 kgs of catfish are caught in a single instance. The residents of the village are well aware of the

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invasive tendencies of these fish, demonstrating their understanding of the current invasive status in the area. Exotic fish species have been introduced into many reservoirs. *C. carpio* is introduced in Krishnarajasagar [52], *O. mossambicus* in Amaravathy and *H. molitrix* in Gobindsagar. The introduction of these species has led to significant changes in species assemblages [53]. A study reveals that the introduction of two exotic fishes, *O. mossambicus* and *C. carpio,* into Indian reservoirs has unsatisfactory outcomes. *Hypophthalmichthys molitrix* is introduced accidentally, as well as the establishment of *Catla catla,* one of the Indian major carp (IMC), in Govind Sagar, a Reservoir characterised by a distinct cold-water regime [54].

Research conducted in Kelavarapalli, Tamil Nadu, shows that indigenous catfishes are preyed upon by invasive fish species, such as O. *mossambicus* and C. *gariepinus.* The increasing abundance of *C. gariepinus* also has a negative impact on IMC populations and Pearl spots [55]. An experiment [56] demonstrates that common Carp have a notable, adverse effects on water quality. Specifically, the presence of Common Carp lead to elevated levels of turbidity and suspended solids, with these increases being directly proportional to the biomass of carp present. In a previous study on the same sampling site [57], it is reported that cichlidae family, particularly *O. niloticus and O. mossambicus*, comprise 54%, similarily our research observes that *Oreochromis sp.* contributes to more than half of the total fish biomass, indicating a dominant presence in the reservoir. This suggests that reservoir fisheries in India have the potential for development, provided that scientific management practices are implemented [58].

Overexploitation in fisheries remains the greatest threat to freshwater species. Protection of breeding grounds plays a crucial role in conserving the native fish populations of this Reservoir. Therefore, a well-planned stock enhancement strategy is essential for sustaining self-recruiting fish populations. This approach requires continuous monitoring of water fluctuations, stock enhancement efforts and preventing overfishing in control key areas, developing specific management plans in large reservoirs of tropical regions. Effective monitoring includes techniques such as stock assessment, hydro-acoustic surveys to assess fish biomass, regular water quality sampling (e.g., temperature, dissolved oxygen) and real-time tracking of water levels using remote sensing and in-situ sensors to track environmental changes. Best practices, like adaptive management based on seasonal data and community-led monitoring to mitigate illegal fishing, can optimise these efforts. Engaging local communities in controlling exotic fish inflows and assessing their impact on catch structures can further strengthen conservation efforts.

Additionally, mitigating risks to habitats of threatened freshwater species require conservation actions at multiple scales and ecological scales. These may include freshwater recovery programmes, ranging from initiatives targeting individual species to efforts aimed at restoring entire basin faunas. The data generated in this study serves as a benchmark for exploring management practices and provides a scientific foundation, offering a baseline for decision-makers to improve conservation strategies. Furthermore, incorporating data on native species data and control sites would enhance the comparative value in future studies.

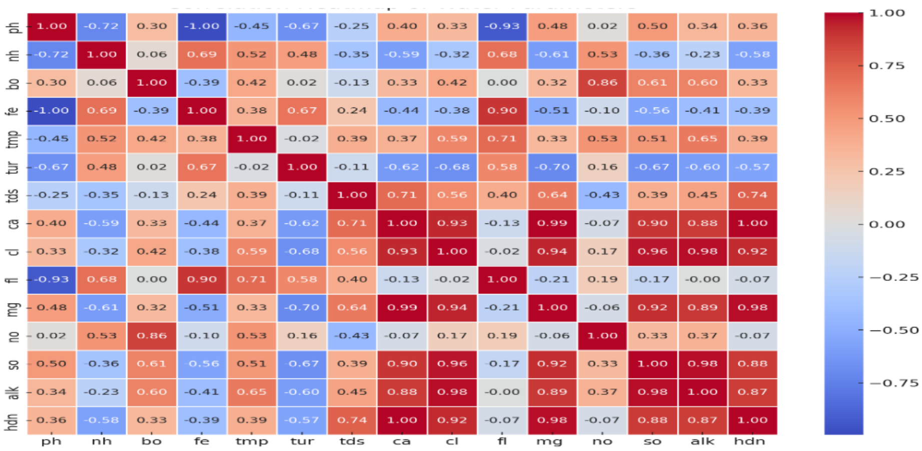

Figure 2. The Heatmap and Spearman correlation illustrate the correlation coefficients between different water parameters. The colors on the heatmap represent the strength of the correlation: red shades indicate

positive correlations, blue shades indicate negative correlations, and color intensity reflect the strength of the relationship. Positive correlations are represented by red squares, with a fold change ranging from 0.02 to 0.99, while negative correlations are shown as blue squares, with a fold change ranging from -0.00 to -0.96.

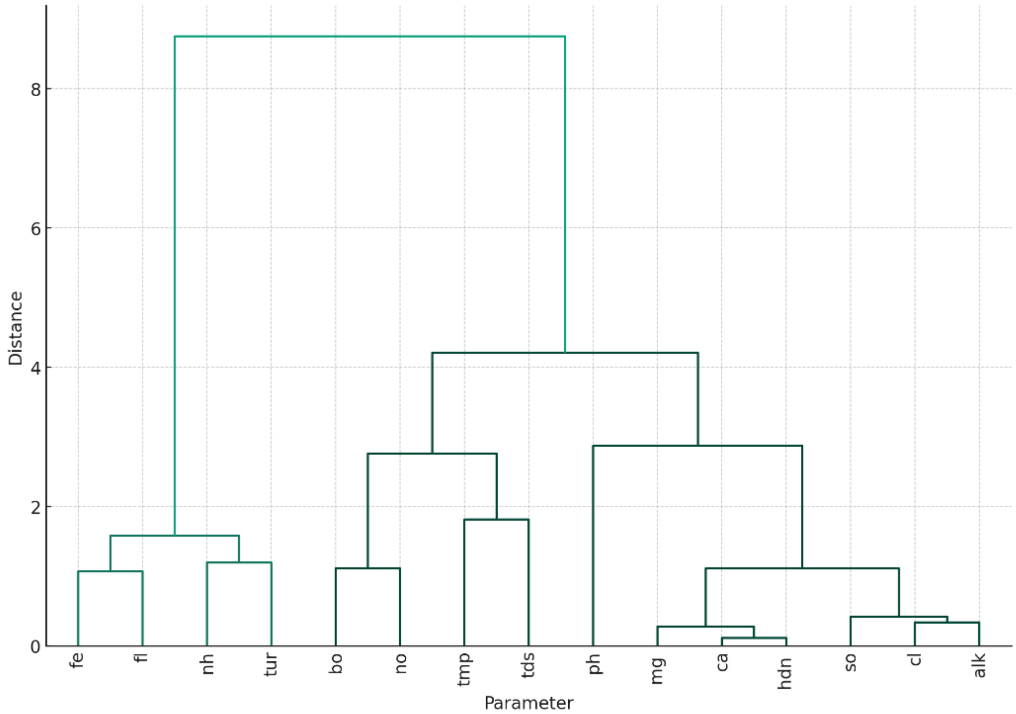

Figure 3. The dendrogram above represents the hierarchical clustering of water quality parameters. The y-axis distance indicates the degree of dissimilarity among clusters, with lower distances signifying higher similarity.

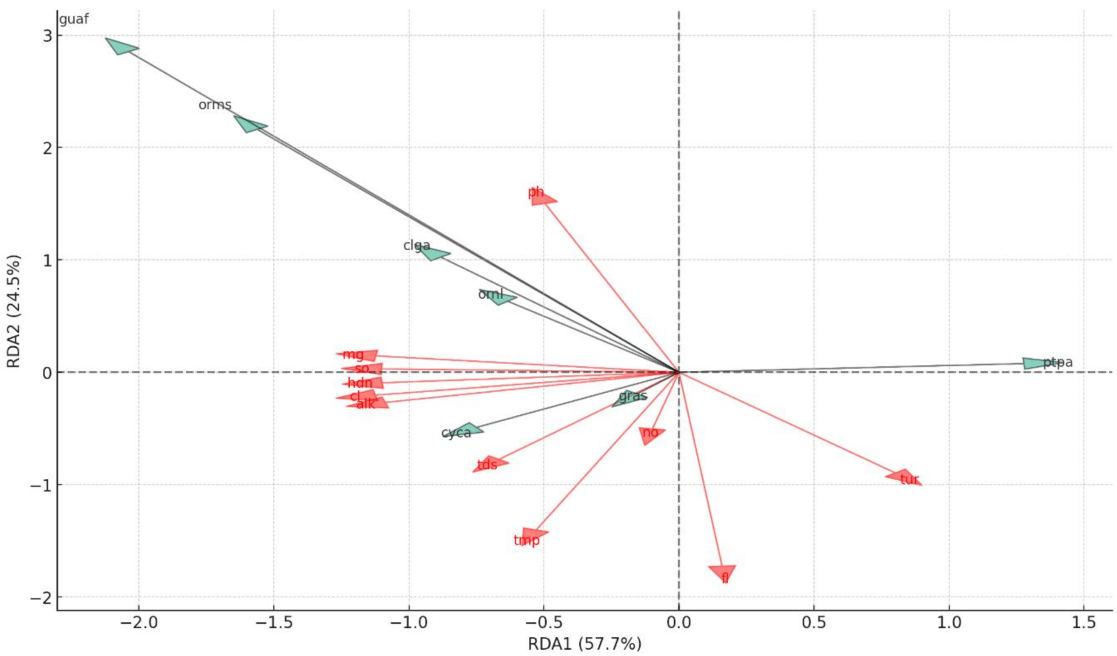

Figure 4. The Redundancy analysis (RDA) biplot illustrating exotic fish assemblages as dependent variables (green arrows) and hydrological variables descriptors (red arrow). Abbreviations are provided in Tables 1 and 2.

CONCLUSION

Our study highlights the crucial interaction between hydrological factors and exotic fish populations, revealing that current hydrology and morphology condition of the reservoir, influenced by anthropogenic activities, is associated with the dominance of exotic fish species. This shift raises concerns about its impact on the ecological balance of the reservoir system. Our analysis shows that exotic species exhibit varied responses to changes in water quality, as discussed earlier. These findings indicate that a dedicated effort is required to restore the natural hydro-morphology affected by damming, invasive alien species. Before making further modifications to river hydro-morphology, it is essential to evaluate habitat suitability and assess the impact of non-native species to implement effective management and conservation strategies. While recognising the role of hydrological factors, our study specifically underscores the critical importance of water quality and exotic fish communities in reservoir ecosystems.

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