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Climate Change-Induced Alterations in Freshwater Ecosystems Through Hydrological Variability Biodiversity Loss and Conservation Strategies

[1] Roohee Khan, Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.

E-mail: ku.roohee.khan@kalingauniversity.ac.in, Orcid: https://orcid.org/0009-0009-8960-8840

[2] Ashu Nayak, Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.

E-mail: ku.ashunayak@kalingauniversity.ac.in, Orcid: https://orcid.org/0009-0009-6363-1591

Abstract: Freshwater ecosystems represent some of the most vulnerable biomes on Earth; climatic changes are affecting the distribution and movement of water in rivers, lakes, and wetlands. This paper sought to explore how changes in climate, precipitation, and water availability affected the conditions and biodiversity of freshwater ecosystems in six sample sites comprising river sections, a floodplain wetland, a lake, and a reservoir. The study employed a comparative research design comparing the two decades of 2005-2014 and 2015-2024 using hydrological data, seasonal sampling of water quality and biodiversity, and local conservation activities. The mean annual rainfall decreased by about 8%, the mean annual river discharge decreased by about 14%, the number of zero-flow days in the lower river increased by more than 100%, while the dry-season lake area decreased by about 22%. In all the sites, the dry-season dissolved oxygen level fell below the critical value for the floodplain wetland biota. Total richness of all species in terms of fish, aquatic invertebrates, amphibians, and aquatic plants decreased by about 27% from 2006 to 2024, and amphibians experienced the greatest drop in richness. Warming during the dry season was significantly associated with low fish richness. For conservation actions, environmental flows, habitat protection zones, and riparian buffer plantings resulted in the greatest positive effects on ecosystem health. The results suggest that hydrologic variability is a key mechanism for climate change impacts on freshwater biodiversity, and conservation efforts based on flows, habitats, and communities have the greatest potential for sustaining healthy freshwater ecosystems.

Keywords: Climate Change; Freshwater Ecosystems; Hydrological Variability; Biodiversity Loss; Water Quality; Conservation Strategies; Climate Adaptation.

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I. Introduction

Background of Climate Change and Freshwater Ecosystems

Global warming has transitioned from being an issue of the future to an event currently affecting the natural environment in all parts of the globe. Increases in air temperatures, changes in rainfall distribution, and increased frequency of climatic events have resulted in changes in the fundamental operating conditions for ecosystems. Aquatic ecosystems, which consist of rivers, streams, lakes, ponds, reservoirs, and wetlands, cover less than one percentage of the Earth's surface, but they are home to a significant proportion of the known species. Since these environments are dependent on water, even the slightest change in temperature or rainfall will affect the ecosystem.

Importance of Freshwater Ecosystem Health

Healthy freshwater ecosystems support the provision of drinking water, irrigation, fisheries, flood management, nutrient cycling and recreation to human populations. Many millions of people, especially in rural and developing countries, depend upon inland fisheries for food and livelihoods. Wetlands store floodwaters and replenish groundwater, whereas rivers carry sediment and nutrients necessary for maintaining productive floodplains. As freshwater ecosystem health deteriorates, the benefits become less effective, leading to impacts on food security, health, and the economy. The maintenance of ecological integrity of freshwater ecosystems is thus not just an environmental issue, but also a socio-economic one.

Major Climate-Related Pressures

Climate stressors impacting freshwater ecosystems include surface warming, decreasing and more variable precipitation, extended and more severe drought periods, flash floods and lower dry-season flows. Warming increases water temperature, thereby reducing its ability to retain oxygen and increasing algal growth; low flow rates lead to the concentration of pollutants and habitat fragmentation. Climate stressors do not usually affect freshwater ecosystems separately; rather, they interact with other anthropogenic stressors such as water abstractions, dam construction, water pollution, land use changes, and the spread of alien species.

Study objectives

1. To analyze the changes in hydrological regimes between the two decades 2005-2014 and 2015-2024.
2. To analyze the changes in water quality and freshwater ecosystems in general.
3. To measure the changes in the number of species and analyze their correlation with climatic variables.
4. To assess the effectiveness of existing conservation policies and suggest some approaches for the protection of freshwater.

Section 1 gives information about the research background, significance of freshwater ecosystems, climatic stressors, and objectives of the research. Section 2 covers the review of the literature related to climate change, hydrological variations, freshwater biodiversity, conservation methods, and research gaps. Section 3 describes the research methodology in detail, including information about research design, study area, data gathering, hydrology and biodiversity assessments, ecosystem evaluation, and data analysis. Section 4 highlights the results about hydrological variation, water quality, biodiversity losses, relationship between climate and biodiversity, and effectiveness of the conservation methods, while Section 5 discusses these results. Section 6 highlights the conservation methods and management techniques. Section 7 concludes the paper, highlighting the main findings of the research.

II. Literature Review

Climate Change Effects on Freshwater Environments

Biodiversity in freshwaters is currently diminishing at a faster rate compared to biodiversity in terrestrial and marine ecosystems, and climate change is increasingly acknowledged as an important threat to the survival of species alongside habitat destruction, pollution, and alterations to the natural flow (Albert et al., 2021; Maasri et al., 2022). Lakes are warming, deicing, stratifying, and exhibiting shifts in the timing of seasonally dependent processes, which are affecting their food chains and overall water quality (Woolway et al., 2022). In addition, warm spells in lakes, known as lake heat waves, will be intensified by future warming trends, leaving organisms within lakes vulnerable to such conditions for longer periods of time (Woolway et al., 2021). Another effect of warming in lakes is deoxygenation, as historical data from more than 300 temperate lakes indicates decreasing dissolved oxygen levels in both epilimnion and hypolimnion, related to warming and decreased clarity of the water (Jane et al., 2021).

Changes in Rainfall, Temperature, and Water Availability

Trends in river flows from thousands of gauging sites have been found to indicate that changes in climate have resulted in shifts in both mean and extreme flows; there are drying trends evident in several parts of the world (Gudmundsson et al., 2021). Streams and rivers that experience interruptions in flow for some period during the year are commoner than is believed, and there is an expectation of an increase in the number of non-perennial watercourses due to variability in precipitation levels and warming (Messager et al., 2021). There is evidence from satellite observation that there has been a reduction in water storage in major natural lakes and reservoirs, with rising temperatures and evaporation levels being one of the causes

apart from usage by humans (Yao et al., 2023). The smaller lakes that represent only a small proportion of the total surface area of lakes in several parts of the world are major sources of variability in lake extents (Pi et al., 2022). Warming results in changes in thermal habitat for aquatic life, with lack of temperature overlap being a major issue in several lake species (Kraemer et al., 2021).

Effects on Freshwater Biodiversity

Projections for freshwater fishes suggest that there will be significant numbers of species that will experience temperatures and flows outside of their historical range in the future due to climate change, and this will happen increasingly for greater levels of climate change (Barbarossa et al., 2021). When studying decapod crustaceans, fishes, and odonates from across the world, it was discovered that about a quarter of these species will become extinct because of pollution, dams, water abstraction, agriculture, and invasive species (Sayer et al., 2025). Country-specific studies reveal similar trends, suggesting that a considerable number of species are under threat, whereas a lot of them have been poorly studied (Desforges et al., 2022).

Existing Conservation and Management Approaches

Biodiversity of fresh waters provides for food security, livelihood needs, culture and overall well-being, making the protection of this biodiversity a matter of common societal interest rather than just an environmental concern (Lynch et al., 2023). According to experiences from regional policies, the protection of freshwaters can be enhanced by having well-defined objectives, river basin planning, restoring natural water flows, and strengthening connections between biodiversity and water policies (Van Rees et al., 2021).

Research Gap

Research and conservation funding related to freshwater biodiversity continue to lag behind other areas, and important areas of focus for future efforts include enhanced monitoring, infrastructure improvements, and knowledge regarding multiple stressors, along with better integration between science and management. Little research has linked the effects of climatic variability on hydrology, water quality, multi-taxon biodiversity, and conservation effectiveness into one cohesive evaluation. This research addresses that void by integrating those factors in diverse freshwater environments.

III. Methodology

Research Design

A comparative mixed-evidence study design was used. Comparisons were done for two different periods: one period known as the baseline period (Period I 2005-2014) and another period known as the current period (Period II 2015-2024). Long-term hydrological and climatic data were used in combination with on-site water quality testing, repeated biodiversity assessments, and conservation efforts. The entire process flow diagram is shown in figure 1.

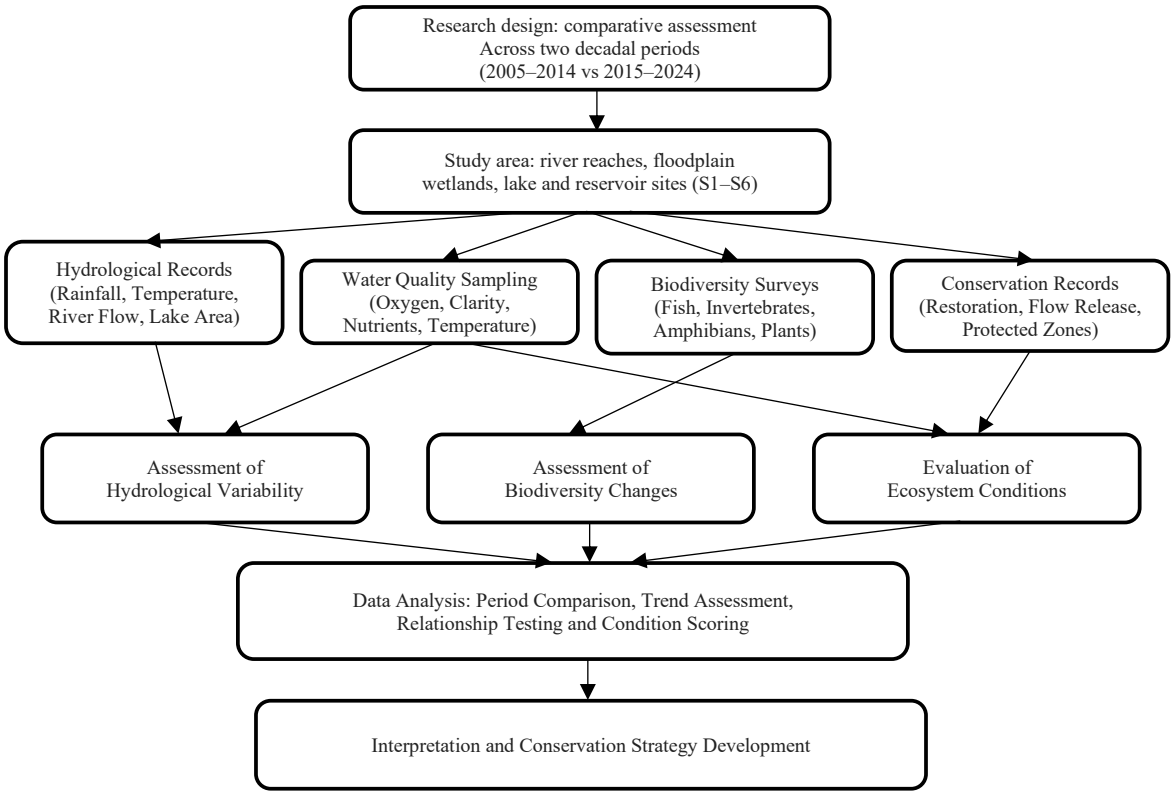


Figure 1: Methodological Framework of the Study

Study Area and Data Collection

Six sampling locations were identified in order to capture the different types of freshwater habitats found in a tropical river basin with a pronounced wet season and dry season. The sampling locations included an upstream reach of the river (S1), a midstream reach of the river (S2), a downstream reach of the river (S3), a floodplain wetland (S4), a natural lake (S5), and a reservoir (S6). The sampling sites have been chosen to encompass a gradient of anthropogenic effects, water permanence, and habitat complexity. Data were collected from four different sources: rainfall and air temperature data and river flow data from regional monitoring stations; periodic water quality data collected during the pre-monsoon dry season and post-monsoon seasons at each location; biodiversity surveys that were conducted in 2006, 2010, 2014, 2018, 2022, and 2024; and records of any conservation and restoration activities from local authorities.

Assessment of Hydrological Variability

Variability of hydrology was established through the comparison of rainfall received annually, average air temperature, average water during the dry season, average discharge of rivers annually, the number of days in which there was zero flow of water in the lower river, number of floods, and the surface area of the lake during the dry season. The surface area of the lake was calculated from free satellite images at the end of each dry season. The values were then averaged per period, and percentage change was determined.

Assessment of Biodiversity Changes

For each of the four taxonomic groups, namely fish, aquatic invertebrates, amphibians, and aquatic plants, the biodiversity was assessed. For fish, sampling was done through the use of cast nets, gill nets, and visual counts. Sampling for aquatic invertebrates was carried out through hand nets in standardized habitat patches, while that of amphibians was through night-time visual and auditory observations. Sampling for aquatic plants was done in standardized patches on the shorelines. The same methodology

and effort were used in all survey periods to enable fair comparisons. Species richness, which is the number of species observed, and the relative abundance of common species were the key parameters.

Evaluation of Ecosystem Conditions

The assessment of ecosystem condition considered water quality variables such as dissolved oxygen, water clarity, nutrients, and water temperature, and also habitat variables such as riparian vegetative cover, stability of river banks, and invasive species. The individual variable scores were obtained based on a five-level scale ranging from very poor to very good, and the individual variable scores were aggregated to give the ecosystem condition score. Those sites that had conservation actions applied to them during Period II were compared with similar sites without conservation actions to isolate the effects of improvements.

Data Analysis Methods

Data were organized according to sites and period, and differences between periods were assessed using means and percentage change. Examination of trends through years of surveys was done graphically and through use of trend lines. Correlation of climatic factors and biodiversity was established using graph plotting of water temperature and flow conditions against species richness in all site-year combinations. Efficiency of the measures used for conservation was calculated based on percentage improvement in ecosystem condition score as compared to untreated sites.

IV. Results

Changes in hydrological conditions

The hydrological regime was markedly altered between the two periods presented in Table 1. The mean annual precipitation decreased from 921 mm to 846 mm, and the mean annual river discharge decreased from 208 to 178 cubic meters per second. This was accompanied by an increase in temperature, with the mean annual air temperature being higher by +0.9°C (from 28.1° C to 29.0° C) and the mean dry season water temperature higher by +1.4°C (from 28.2° C to 29.6° C). In addition, the number of zero-flow days in the lower reaches of the river more than doubled during Period II, while the number of floods increased, meaning that the regime had become drier and more extreme. The dry season lake area decreased by around 22%. The yearly fluctuations of precipitation and river discharge are demonstrated in figure 2.

Table 1: Comparison of Hydrological Indicators Between the Two Study Periods

Hydrological Indicator	Period I (2005–2014)	Period II (2015–2024)	Change
Mean Annual Rainfall (mm)	921	846	−8.1%
Mean Annual Air Temperature (°C)	28.1	29.0	+0.9 °C
Mean Dry-Season Water Temperature (°C)	28.2	29.6	+1.4 °C
Mean Annual River Discharge (m^3/s)	208	178	−14.4%
Zero-Flow Days Per Year, Lower River (S3)	18	41	+127.8%
Significant Flood Events Per Decade	3	5	+66.7%
Dry-Season Lake Surface Area (km^2)	12.6	9.8	−22.2%

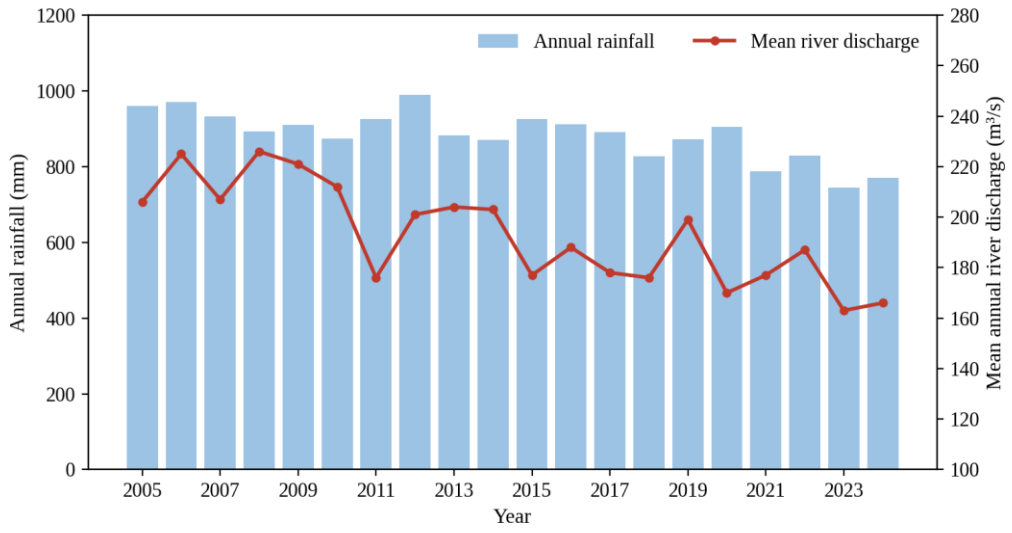


Figure 2: Annual Rainfall and Mean Annual River Discharge from 2005 to 2024

Variations in Freshwater Quality and Ecosystem Characteristics

Water quality was poor at all six locations in the dry season depicted in figure 3. Dissolved oxygen in the dry season fell significantly at the floodplain wetlands site, from 6.2 to 4.3 mg/L. This value is below that required for survival of most aquatic life forms. Water quality at the lower river and reservoirs were close to this value. The observations in the field revealed that there was decreased water clarity, increased incidence of algal bloom in the lake and reservoirs, loss of shore vegetation due to decrease in water depth and increased growth of alien plant species in stagnant water.

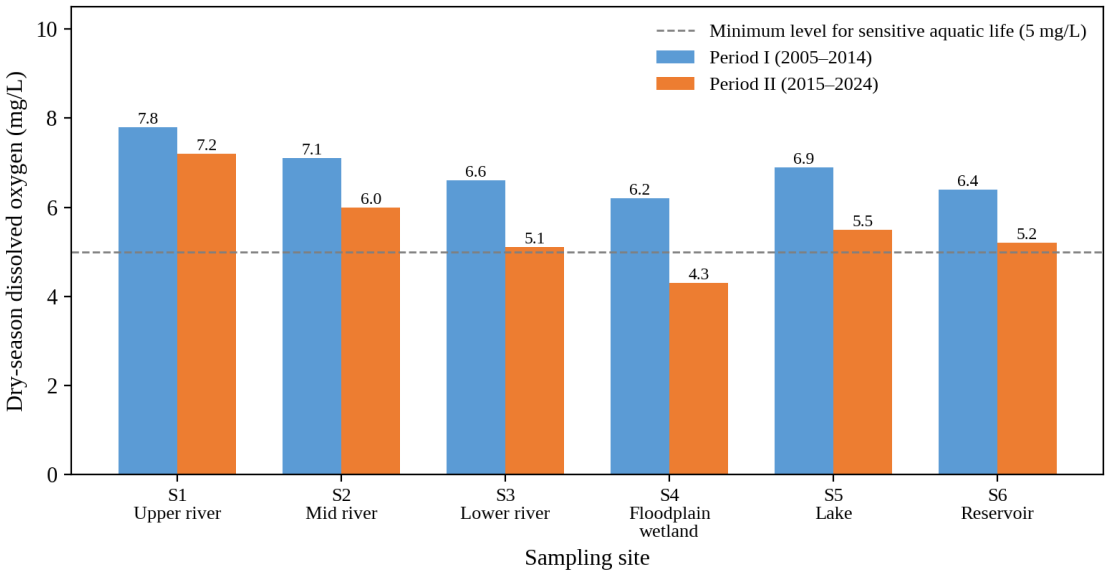


Figure 3: Dry-season Dissolved Oxygen At The Six Sampling Sites In The Two Study Periods

Changes in Species Diversity and Abundance

The number of species in each of the biological groups reduced between 2006 and 2024, as shown in figure 4. Overall, richness reduced from 164 to 120, which is about 27% loss in species richness. Richness

for fish reduced from 46 to 33 species, aquatic invertebrates from 62 to 45, amphibians from 18 to 12 and aquatic plants from 38 to 30. Loss of species richness was relatively low prior to 2014, after which time it accelerated, following the period of more pronounced hydrological change. The highest relative proportion of loss was for amphibians at about one third, and species requiring cool water, flow and high oxygen content such as various minnows and mayfly groups disappeared most often.

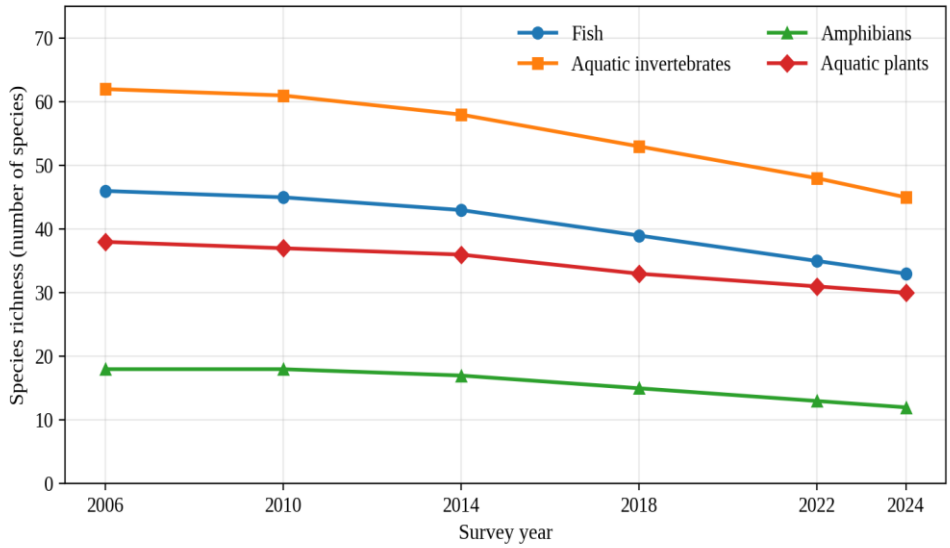


Figure 4: Species Richness Of Four Freshwater Biological Groups Across Survey Years

Relationship Between Climate-Related Factors and Biodiversity Loss

A distinct negative correlation was identified between dry-season water temperature and richness of fish species in all sites-years depicted in figure 5. Warmer water was associated with fewer species of fishes, with an approximate decrease by three species per every degree increase in dry-season water temperature. Similar correlations were evident between the number of zero-flow days and richness of invertebrates in rivers and contraction in lake size and species richness of plants and amphibians along the shore. The correlation shows that warming and decrease in water supply work in tandem as the principal mechanism behind climate change effect on biodiversity.

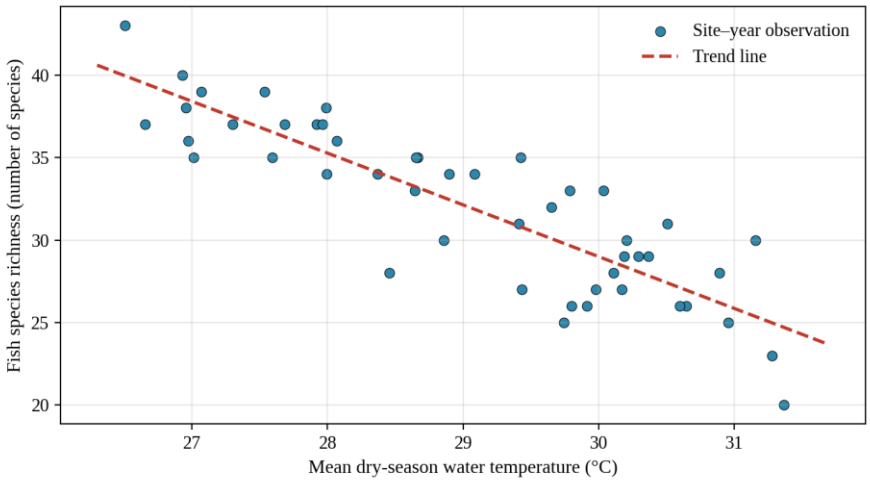


Figure 5: Relationship between Mean Dry-Season Water Temperature and Fish Species Richness

Effectiveness of Conservation Measures

Ecosystem condition improvement through various conservation actions taken in Period II varied as follows compared to those in untreated areas seen in Figure 6. Environmental flows, which were the release of water flows that sustained minimal water flows in the river during the dry period, had the highest rate of improvement at 74%. The protected habitats had the second highest improvement rate at 71%, while riparian buffer planting had the third highest at 68%. Wetlands connecting the river during flooding had an improvement of 61%, while fishing regulations in communities had 55%. Removal of invasive species had the lowest improvement of 47%.

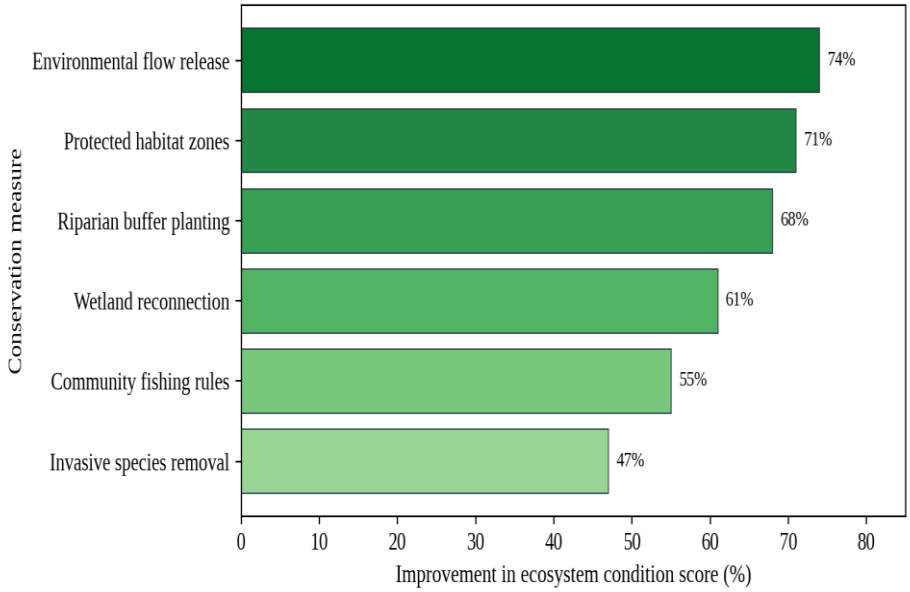


Figure 6: Improvement in Ecosystem Condition Score Under Different Conservation Measures

V. Discussion

Interpretation of Major Findings

Findings indicate an observable order of change in the form of decreased and less predictable rainfall, combined with increasing temperature, led to decreased river flow and lake size; decreased availability of water, along with increased temperature, caused degradation in the quality of water; and poor water quality and habitat destruction led to a general decline in species diversity. Increased pace of species loss following 2014 coincides with the most pronounced changes in hydrology, which is an indication that climatic changes in the water cycle are the main causes of ecological decline, rather than just a backdrop.

Influence of Climate Change on Freshwater Ecosystems

Changes in climate had an impact on the selected ecosystems through two related pathways. First, warming led to increase in the temperature of water, lower oxygen content, and growth of algae and tolerant species. Second, changes in water availability led to reduction in the period of flowing of rivers and wetlands, higher number of zero-flow days, and drying of margins of lakes and wetlands. Floodplain wetland is the most vulnerable ecosystem because it relies on connection with the river on seasonal basis and has shallow water that warms up quickly. Upper river reach is the most resilient ecosystem because it enjoys shade, cooler inflow, and low pressure from humans.

Ecological Consequences of Hydrological Variability

Hydrological variability had implications not only on the volume of water. Prolonged dryness segmented riverbeds into disconnected pools, limiting fish movement and migration of breeding. Frequent floods destroyed the streambed, washing away eggs and young organisms, whereas drying of lake margins limited nursery areas for fish and reproduction places for amphibians. Combined effects of more intense droughts and floods provided an environment to which many indigenous species could not adjust well, making things easier for generalists and exotic species.

Implications of Biodiversity Loss

The loss of species richness has effects that go beyond the extinction of specific species. Invertebrates are involved in organic matter decomposition and serve as a major food source for fish and birds; hence a loss of these species has an impact on the nutrient cycle and food chain. Loss of the native fish has an impact on local fisheries and people who depend on them. There are more losses in amphibian species which is an indication that there is something wrong with the environment since amphibians are environmental stress indicators.

Comparison with Previous Studies

It is clear from the patterns identified above that the observations fit the existing evidence well. Increased warming, oxygen depletion in lakes, reduction of lake storage, increased non-perennial conditions in rivers, as well as an increase in extinction risk for freshwater species, have been reported on regional and global scales, as described in the literature review. The findings presented above contribute by demonstrating that these processes can occur simultaneously in one river basin, and link them with direct measurements of biodiversity decline and conservation effectiveness.

Conservation and Management Implications

The findings imply that the management of the water flow is the primary priority, since many of the impacts discussed above result from hydrological changes. The measures maintaining the water flow and its low temperature, namely environmental flows and riparian shading, proved to be much more effective compared to the other measures targeting the symptoms, such as removing invasive vegetation. Furthermore, the conservation proved to be the most effective when different measures were integrated and people from the local community participated in them.

VI. Conservation Strategies and Recommendations

Freshwater Habitat Protection

Spawning habitats, deep pool habitats, flood plain wetlands, and upstream areas that are cool should be demarcated as protected freshwater systems. This includes riparian corridors and catchments because land use affects water quality and quantity.

Restoration of Degraded Ecosystems

Wetlands that have been degraded should be reconnected to the river system to help restore seasonal flooding and nursery habitats. Riparian vegetation should also be planted along the rivers to help shade the system, stabilise the banks and filter runoff. The removal of old barriers, natural channel formation and desilting of sediment filled water systems would improve habitat quality.

Sustainable Water Management

Environmental flows should be maintained in the rivers, especially during the dry season. This would require coordination of reservoir management and water sharing. Water conservation measures in agriculture and rainwater harvesting would reduce the demand for water from rivers. Wastewater should be treated before discharge to avoid low-flow periods becoming pollution events.

Biodiversity Conservation Measures

Special programmes are necessary for very vulnerable groups such as amphibians and coldwater fish, and may include conservation of breeding areas, captive breeding of species critically under threat, invasive species control and fishing guidelines supported by the local community, for example, opening seasons and protecting breeding stocks. Fishways at barriers can help to restore migration corridors.

Climate Adaptation Strategies

The adaptation strategy needs to identify refuges for species from heat and drought such as shaded, spring-fed or deep-water locations and give priority to their protection. Nature-based solutions, such as wetlands restoration and reconnecting floodplains, can reduce the risks of floods and droughts for humans as well as benefit the biodiversity. Flood and drought management plans need to contain measures to protect aquatic species specifically.

Future Monitoring and Management Priorities

Standardised, long-term monitoring of flow, water temperature, water quality and biodiversity should be introduced at representative sites. Community monitoring and use of easy-to-use online monitoring could increase the area covered by monitoring at low cost. Results of monitoring should provide an input into adaptive management process allowing adjustment of flows, restoration and protection measures due to changes in climate conditions.

VII. Conclusion

The precipitation, increasing temperature and hydrological fluctuations have resulted in reduced river flow, increase in zero-flow events and reduction in lake areas. This has affected the quality of water and particularly the level of dissolved oxygen in shallow water. It has also resulted in about 27% reduction in total number of species across four biological groups, mainly amphibians and cool water species. Warm water has been observed to be highly correlated with decreased number of fish species. The health of the freshwater ecosystems is very dependent on the reliability of the water cycle. Due to the impact of climate change, there is reduced reliability of the water supply, which leads to loss of habitat, quality and species richness in the freshwater ecosystems. Consequently, the functions performed by freshwater ecosystems are affected. Shallow and intermittently connected water bodies are highly vulnerable to climate change effects and need to be urgently addressed. The use of flow regulation, habitat conservation, restoration, and community involvement provides the most promising approach to conserve freshwater ecosystems under future climate scenarios. Further research could involve monitoring in additional watersheds and habitats, including groundwater dependent ecosystems, an analysis of the interaction between climate change and pollution, the evaluation of the sustainability of the effects of restoration projects, and the socio-economic benefits of the conservation of freshwater ecosystems for the community.

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