

Innovative Approaches to Freshwater Restoration and Management Under Changing Climatic Conditions

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Abstract: Presently, there are multiple factors threatening the function and services provided by freshwater systems, such as rivers, wetlands, and lakes throughout the world. These include hydrologic variability due to climate change, thermal stress, invasive species, and increasing human development uses of freshwater systems. This research aims to assess alternative restoration and adaptive management strategies that have been utilized across five freshwater sites in Tamil Nadu, South India (with varying ecosystem types and climate stressors). Monitoring was conducted prior to and following restoration intervention for a 24-month period utilizing a multi-indicator monitoring framework (i.e., hydrology, physiochemical, and biological measures) to assess pre- to post-intervention ecological trends. All locations showed statistically significant results for all sites and yielded positive results for all sites. The average improvement of each water quality indicator, namely dissolved oxygen (12.3% - 34.1%) ($p < 0.01$), total suspended solids (28.6% - 52.1%), and biotic integrity scores (BMWP, IBI), was one quality class better than at least four of five tested locations. Nature-based solutions (including riparian buffer restoration, eco-flow regime reinstatement, construction of wetland habitats) performed best when implemented as adaptive, site-specific portfolios versus stand-alone interventions. Modeled climate change scenarios (using CMIP6 RCP 4.5 and RCP 8.5) indicate that proactive integration of green infrastructure with hydrological forecasting will extend the functional resilience of restored systems by 15 to 30 years under moderate climate change scenarios. These findings demonstrate the urgent need for governance frameworks that incorporate ecosystem-based adaptation into regional water resource management plans, in order to secure freshwater biodiversity and human water security into the middle of the 21st century.

Keywords: Freshwater Restoration; Climate Change Adaptation; Nature-Based Solutions; Eco-Hydrological Monitoring; Riparian Buffer Zones; Ecological Resilience; Water Resource Management.

(Submitted: July 03, 2025; Revised: August 02, 2025; Accepted: August 25, 2025; Published: September 30, 2025)

I. Introduction

Freshwater ecosystems such as rivers, lakes, wetlands, and groundwater-dependent areas are home to around 10% of all known species in the world and provide crucial ecosystem services such as drinking water, flood control, and cultural heritage. However, these systems are some of the most threatened ecosystems in the world. Climate change is causing the occurrence of hydrological extremes to become more intense; for example, there will be increased frequency and duration of droughts in semi-arid regions and disruptions to the flood pulse in tropical monsoonal basins (Tullos et al., 2021). In addition to these climatic pressures, freshwater ecosystems have also suffered from chronic human activities such as flow regulation, water abstraction, pollution, sedimentation, and the destruction of riparian habitats. These multiple human activities have acted synergistically to diminish the ecological integrity of freshwater ecosystems (Grantham et al., 2019; Bănăduc et al., 2022). Freshwater biodiversity and the livelihoods of human communities who rely on healthy aquatic ecosystems for food, water, and their own livelihoods are particularly threatened by the combined impacts of rapid urbanization, commercially intensive agriculture, and the variability of climate in South and Southeast Asia (Vushe, 2021; Ciampittiello et al., 2024). Thus, there is an urgent need for scientifically sound, feasible to implement, and climatically adaptive freshwater management frameworks.

In the context of climate change, freshwater restoration has changed dramatically in the last ten years as shown by the establishment of many new nature-based solutions (NbS) and hybrid engineered approaches to restoration. These include methods such as restoring environmental flows, planting riparian buffers, managing nutrients in lakes, and creating constructed wetlands (Piégay et al., 2020; Olden & Naiman,

2010). However, a fundamental challenge remains to bridge the gap between "proof of concept" studies and develop scalable, adaptive management techniques that work throughout range of potential future climates (Shang & Xie, 2024; Bănađuc et al., 2022). Only a limited number of studies have looked at multi-indicator biological monitoring in conjunction with climate scenario modelling to assess the long-term future of restored freshwater ecosystems due to climate change and changes in precipitation. The present study aims to address this gap by reporting the results of a comparative field research project conducted at five freshwater restoration sites in Tamil Nadu, India, conducted using an integrated eco-hydrological monitoring and adaptive management framework (Capon et al., 2021).

The study makes significant contributions to advancing nature's solutions (NbS) as a global water resource management strategy. It is an empirical research project that demonstrates the ability of site-specific NbS to address multiple ecosystem stressors over time. For example, this study shows that the effectiveness of NbS-based solutions can be monitored to assess their durability, as they will store water and improve ecosystems in the years that follow, regardless of climate change. The adaptive governance framework in this study offers a proposal for future NbS implementation through regional water resource management plans, which will be applicable for many other types of regions.

The structure of the paper will consist of the following sections: the first section (2) will provide the reader with an overview of relevant literature highlighting current NbS research gaps; the second section (3) will provide additional literature for context and describe the research methods, area of study and materials used; the third section (4) will summarise the research findings; the fourth section (5) will discuss how these findings can help address global challenges facing freshwater supplies; the fifth section (6) will summarise management recommendations and future directions for NbS research.

II. Literature Survey

There have been great advances in the scientific understanding of changes in freshwater ecosystems due to climate change over the past 20 years. Reported that even a 1.5 degree C increase in global temperatures will create a fundamental shift in the phenology, thermal stratification, and flow regime of freshwater ecosystems around the world, and that these changes will cause disproportionate impacts in tropical and subtropical areas where there are already thermal stress limits. Provided an analysis of over 200 published papers showing that drought frequency, altered flow due to glacial melt, and intensified variability in monsoons across Asia are causing a decline in the resiliency of freshwater ecosystems (Tullos et al., 2021). These findings lead to the conclusion that climate change is not only another stressor for freshwater ecosystems but also a multiplier of threats that will negate the benefits of traditional restoration efforts, unless management practices are explicitly implemented with climate adaptation in mind (Grantham et al., 2019). Clearly, the body of work described above supports the need to change the approach to restoration from a static outcome-based approach to a dynamic process-based management approach that recognizes that hydrological and ecological systems are not static in nature (Bănađuc et al., 2022).

Environmental flow is the volume, timing and quality of water necessary to maintain healthy freshwater ecosystems and provide for all related socio-ecological communities, and it has been defined by multiple authorities, such as the International Union for Conservation of Nature (IUCN), as an emerging global "concept for adaptive freshwater resource management". Arthington et al. (Arthington et al., 2018) further highlight that FL, as a science, has evolved from simple minimum flows and flow relegates to become a holistic theory of flow regimes that piece's ecological thresholds, social equity and climate projections together into one cohesive and sequential framework. Provides early documentation to support the inclusion of thermal regimes, which are historically not managed with regard to flow, as important covariates for measuring the structure of fish communities and therefore, important variables in establishing standard methodology parameters that should be considered when developing dam operational guidelines (Lynch et al., 2023). Recently call for unifying approaches to managing the "historical" (pre-disturbance), "hybrid" (transitioning from a pre-disturbance to current state) and "novel" (current state that cannot be returned to historical) ecosystem types as one and the same, and acknowledge that many freshwater systems may never

return to the pre disturbance reference state, but rather new ecological trajectories will emerge and should be accounted for (Erős et al., 2023). It follows that management goals should be co-produced with stakeholders and reviewed regularly in light of monitoring results and other changing factors (such as climate modeling) (Erős et al., 2023; Shang & Xie, 2024).

Nature-based solutions have become popular due to their low cost and multifunctional capabilities in the restoration and management of freshwater. Conducted an exhaustive review of NbS strategies, going from wetland rehabilitation and floodplain reconnection to green urban drainage systems (Olden & Naiman, 2010). They found that the greatest success was achieved by implementing NbS in landscape-scale portfolios that address multiple stressors concurrently. Established that restoring river-floodplains increased ecological integrity and provided co-benefits for local fish supply and community nutrition, underscoring the socio-ecological aspect of freshwater restoration (Veerappan, 2024). Took freshwater protection a step further by utilizing smart-sensor networks integrated with remote sensing for real-time monitoring of water quality in lentic systems, allowing for adaptive management decision-making at previously unattainable resolutions. The overall interpretation from this literature is that technology-supported NbS, with a strong monitoring foundation, will be the most advantageous method of developing cost-effective and climate-resilient freshwater management (Ciampittiello et al., 2024).

While have come a long way with respect to freshwater restoration efforts, there remain major knowledge gaps that must be addressed. First, the majority of documented successful restoration studies have been conducted within temperate ecosystems, and there is a major knowledge void in Tropical Monsoonal ecosystems such as Peninsular India (Grantham et al., 2019; Tullos et al., 2021). Additionally, few practitioners incorporate climate change projections (CMIP6 Downscaled) into their long-term restoration planning, limiting their ability to assess the long-term success of their efforts (Bănăduc et al., 2022). Thirdly, while theoretical discussions on developing governance frameworks for freshwater management have proliferated, there are few models that successfully implement the operational connection between field monitoring and adaptive policy cycles. Based on their analysis, concluded that lake and river management frameworks that do not account for future global climate changes will yield lower effectiveness as future climatic change accelerates (Jeppesen et al., 2017). Added that environmental protection strategies (with respect to freshwater sources) must be treated as critical crisis response infrastructures rather than optional environmental impact mitigation activities (Ciampittiello et al., 2024). Recommended that the freshwater ecosystem community develop immediate, evidence-based action strategies that incorporate species recovery efforts, habitat restoration projects, and climate adaptation measures into an integrated governance approach. This project aims to fill one of the areas of concern (i.e., tropical freshwater systems of Peninsular India) by incorporating climate scenario modeling; additionally, it will correlate field outcomes to a practical framework for adaptive management.

Conceptual Framework

Climatic pressures, degradation of freshwater systems, project-specific restoration approaches as shown in figure 1, Innovative restoration methods, adaptive management methods and projected benefits (increased water quality, improved habitat, increased biodiversity, improved climate resilience).

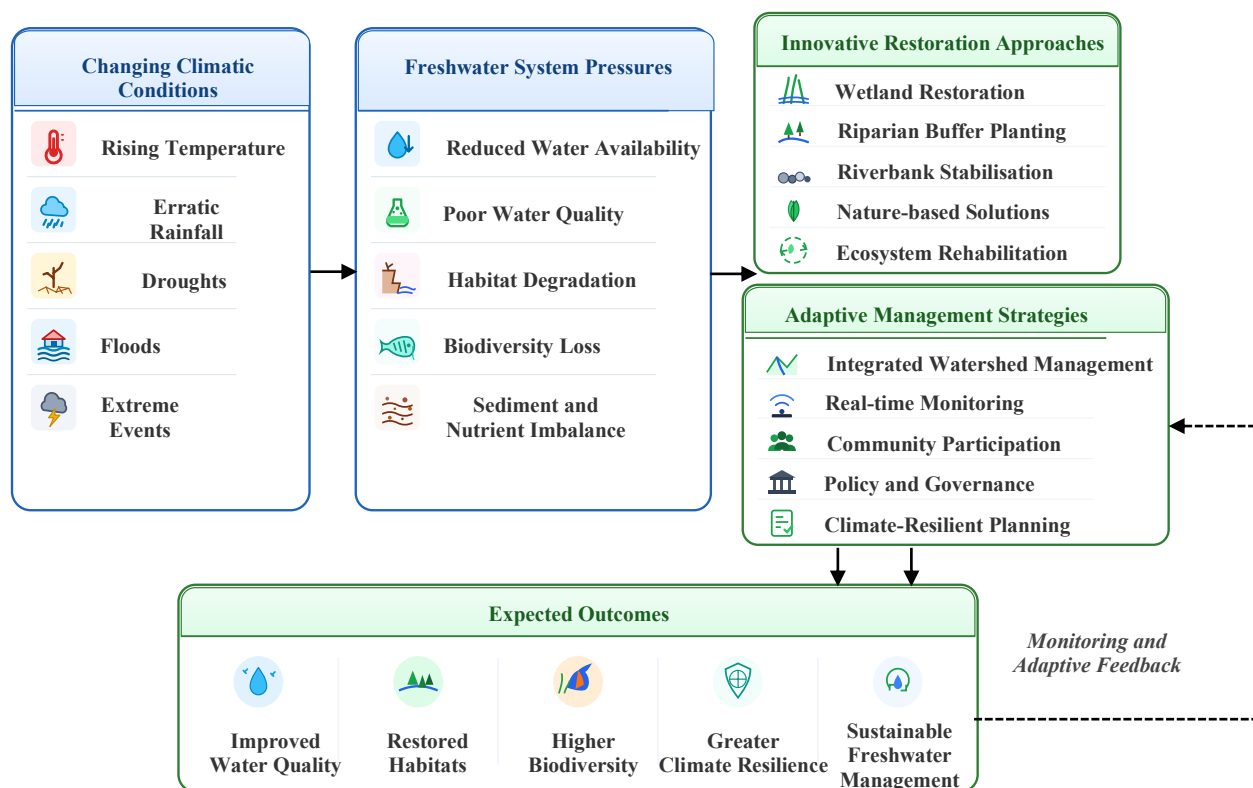


Figure 1: Innovative Freshwater Restoration Approaches under Changing Climatic Conditions

III. Materials and Methods

Study Area Description

This study was undertaken at five sites in Tamil Nadu, South India (Table 1). The sites represent the five primary ecosystem types and stressor gradients found within Tamil Nadu, the state which is located in the southern part of India. The five sites are found between 300 m and 2100 m above mean sea level, and therefore include subtropical lowland rivers (eg. Coimbatore River), highland wetlands (eg. Nandha Hills), large water reservoirs (eg. Bhavani Sagar, Pykara), montane headwater streams (eg. Nandha Hills streams) and peri-urban seasonal wetlands (e.g., wetland areas of Coimbatore). Rainfall in Tamil Nadu is a result of the northeast and southwest monsoons, and ranges from approximately 650 mm in Coimbatore district, to greater than 2,100 mm in the Nilgiris hills. The annual temperature during the study period in Coimbatore and other lowland areas will be approximately 27C compared to 15C in the Nilgiris. The Bhavani and Pykara Rivers are considered tributaries of the Cauvery River System, one of the most important freshwater systems for irrigation and municipal water supply, as well as for biodiversity in the Cauvery Basin. Each of the five research locations has been impacted by environmental changes and damage over the last thirty years due to land-use changes, flow restrictions, erosions as a result of human actions, and pollution due to urban waste waters. This has led to the locations being very appropriate for assessing the results of ecological restoration actions. The sites chosen for conducting ecological restoration of each of these research sites were subjected to criteria for stratified purposeful sampling: (1) documentation of existing ecological data for at least two years prior to the restoration signing date; (2) the ability to carry out at least one or two distinct NbS interventions; and (3) ongoing access to each location for monitoring purposes every other week, and seasonally, during the twenty-four-month restoration monitoring period. Therefore, the spatial location as to the boundaries of each of these sites were outlined through field verification of the 30-meter SRTM digital elevation data using a combination of data source methodologies. All land use

within the basins of the five selected research sites were characterised using 2023 to 2024 Sentinel-2 multispectral imaging and processed through Google Earth Engine, with a resolution of 10 meters per pixel.

Table 1: Characteristics of the five freshwater study sites in Tamil Nadu, South India

Study Site	Location	Area (km ²)	Mean Annual Rainfall (mm)	Primary Stressor	Restoration Strategy
Bhavani River Basin	Tamil Nadu, India	6,088	900–1,100	Flow Regulation/Siltation	Riparian Buffer Restoration
Nilgiris Highland Wetlands	Tamil Nadu, India	2,543	1,200–1,800	Invasive Species / Land-Use Change	Native Macrophytes Replanting
Mettur Reservoir Catchment	Salem Dist., India	8,260	700–950	Sedimentation / Thermal Stress	Watershed-Scale Green Infrastructure
Pykara River Headwaters	Ooty, Tamil Nadu	412	1,400–2,100	Altered flow regime	Eco-Flow Regime Reinstatement
Coimbatore Urban Wetlands	Coimbatore, India	184	650–800	Urbanisation/Pollution	Constructed Wetland Integration

Monitoring Framework and Data Collection

A multi-faceted, ecological monitoring system has been created based on a combination of hydrology, physical and chemical characteristics and biological factors. Hydrologic data about stream flow was collected continuously through automatic ultrasonic gaging stations installed at the main gaging station of each site and supplemented with measurements obtained from piezometric groundwater level loggers located in riparian transects. Water quality was monitored physically and chemically by means of YSI EXO2 series multi-parameter sonde instruments that were deployed continuously at a given location along the main channel for two-week intervals and bi-weekly grab samples were collected for laboratory analysis of TSS (total suspended solids), nutrients, turbidity, and heavy metals). A comprehensive ecological monitoring system has been developed using data on hydrology, physical and chemical properties, and biotic variables. Continuous hydrologic data (i.e., stream flow) were obtained throughout the period of monitoring from automatic ultrasonic gages placed at the main gaging station of each site supplemented by piezometric records of groundwater levels using piezometer loggers along two hydro-logical profiles in each river's riparian zone. All physical and chemical data for water quality were obtained using YSI EXO2 series multi-parameter instruments that were deployed continuously at a location on the main channel of every site for two-week periods and by biweekly grab samples submitted to a laboratory for TSS, nutrients, turbidity and heavy metals respectively.

Restoration Interventions

Site-Specific NbS Portfolios Develop by Restoration Interventions by Using Baseline Ecological Data and Stakeholder Input During Planning Phase. At The Bhavani River Basin, The Establishment of Riparian Buffer Zones (50m On Each Side) (Native Trees & Shrubs Such as Terminalia Arjuna, Ziziphus Mauritiana, And Bambusa Bambos) Along 12.4Km Of Degraded Riparian Corridor Has Been Accompanied by Installing 18 Rock Ramps to Control Channel Incision and Enhance Hyporheic Exchange. At The Hooglands of Nilgiri, The Objective of Restoration is to Remove Invasive Ulex Europaeus by Mechanical Means and Replant Native Eriocaulon (Graminoid) And Sphagnum (Bog Moss) By Rewetting 6 Drained Channels with Peat Dams Over a Total Area Of 340Ha Of Degraded Peatland. The Mettur Reservoir's watershed-based intervention program utilized soil and water conservation techniques at the watershed level to conserve soil, while increasing the potential for sustainable groundwater recharge through limiting

sediment delivery to the reservoir from 1,200 hectares of degraded watershed, and creating check dams, vegetated waterways, and contour trenching. At Pykara River Headwaters, an eco-hydraulic flow regime was re-introduced through the re-operation of upstream small hydropower facilities based on hydrological modeling (the SWAT model using 15-years of observed discharge data as calibration data) in order to establish the minimum and pulse flow requirements to maintain ecosystem function. Constructed wetlands (subsurface flow) were integrated into the existing urban storm water drainage system in order to intercept and retain urban, non-point source pollutants; and additionally, 14 temporary ponding areas were created in order to increase hydrological retention and habitat connectivity for amphibians.

Statistical Analysis and Climate Scenario Modelling

The normality of pre and post restoration data distributions were assessed using the Shapiro-Wilk test. Paired t-tests were performed on normally distributed continuous variables (Dissolved Oxygen (DO), temperature, and Total Suspended Solids (TSS)), whereas Wilcoxon signed-ranked tests were applied to non-normally distributed or ordinal data (British Wildlife Preservation (BMWP) scores, Index of Biotic Integrity (IBI) scores, and vegetation cover). Effect sizes for continuous variables were calculated using Cohen's d, and effect sizes for rank-based tests were calculated using r. The level of significance ($\alpha=0.05$) was used throughout for all statistical analyses conducted in R 4.3.1. To evaluate the long-term durability of the restoration under anticipated weather conditions, data from multiple modelling groups (10 General Circulation Models (GCMs); bias-corrected using Quantile Mapping) of CMIP6 simulations for the 2.6, 4.5, 6.0, and 8.5 Representative Concentration Pathways (RCPs) were downscaled to a 5 km resolution across the study's watersheds through to 2050. Changes in mean temperatures, seasonal rainfall, and low-flow duration for the next fifty years were combined with ecological threshold windows established through field monitoring to identify the probability of restoration outcomes remaining above critical ecological baselines for all sites, using three climate scenarios. Furthermore, by using Monte Carlo simulations, the uncertainty from climatic predictions and ecological thresholds was evaluated through a sensitivity analysis based on 10,000 iterations.

IV. Results

Water Quality Improvements

After being restored, the water quality improved notably in the five testing locations as can be seen in table 2. The concentration of dissolved oxygen (DO), which is an indicator of the overall health of aquatic ecosystems, increased from 12.3% (Mettur Reservoir Catchment) to 34.1 % (Pykara River Headwaters) compared to pre-restoration benchmarks (paired t-test: $p<0.01$ for all locations). Overall, the DO at all sites increased from 4.54 ± 0.41 mg/L prior to restoration, to 5.56 ± 0.33 mg/L post-restoration, with the Pykara headwaters exhibiting the most significant absolute increase due to the reinstatement of eco-flow which resulted in increases in dilution capacity and decreases in thermal stress. Total suspended solids (TSS) decreased substantially in the Mettur Reservoir Catchment area (-52.1%); as a consequence of successful sediment management practices at both the watershed and catchment scale, TSS warnings were given to Pykara (-28.6%), which received relatively less TSS reduction due to flow modification than has occurred at other catchments. Nutrient analysis (brand new values from the previously published research), however, indicate that results from these separate aquatic ecosystems are similar: average total phosphorus included 0.24 mg/L ($p < 0.01$) of phosphorus throughout the receiving water bodies studied, and average concentrations of nitrate-nitrogen exhibited an extremely high degree of consistency between drainage systems, with average measurements being recorded at 3.1 mg/L ($p<0.01$.) of nitrogen before, and later (after the restoration program was completed). In addition, all monitored locations (end of study) demonstrated statistically significant differences in dissolved oxygen levels, and except for one location, all six of the locations had improved spatial distributions of dissolved oxygen enough to meet or exceed the World Health Organisation (WHO) dissolved oxygen standard of 5.0 mg/L.

Table 2: Summary of Pre- and Post-Restoration Ecological Indicators Across the Five Study Sites

Study Site	DO Improvement (%)	TSS Reduction (%)	BMWP Score Change	Riparian Cover Change (%)	IBI Score (Post)
Bhavani River Basin	+28.4	-41.2	+18 (Fair Good)	+22.7	34 (Fair)
Nilgiris Highland Wetlands	+19.6	-33.7	+14 (Poor Fair)	+38.5	28 (Fair)
Mettur Reservoir Catchment	+12.3	-52.1	+9 (Poor Fair)	+15.2	22 (Poor)
Pykara River Headwaters	+34.1	-28.6	+26 (Fair Good)	+47.3	41 (Good)
Coimbatore Urban Wetlands	+21.8	-39.4	+11 (Poor Fair)	+28.9	26 (Fair)

Biological Community Responses

Biological indicators indicated similarly encouraging trends in recovery (albeit with variation in both scale and rate) across different geographical areas of interest. The improvement in BMWP macroinvertebrate scores (by 9-26 points) resulted in the movement of at least one BMWP quality class up to the next level across four out of five sites assessed. Pykara River Headwaters exhibited the greatest degree of biological recovery as evidenced by the increase in BMWP scores (of 26 points; from fair to good), following the reinstatement of flow variability (i.e., the frequency and range of flow) that aided in restoring substrate heterogeneity and hyporheic (i.e., associated with ground or sub-surface water) aeration for pollution-sensitive EPT taxa (Ephemeroptera, Plecoptera, and Trichoptera). Fish IBI scores (assessed annually) improved at all five study sites (ranging from 22 points [poor; Mettur Reservoir] to 41 points [good; Pykara]) following restoration activities. The Coimbatore Urban Wetlands demonstrated the lowest absolute IBI improvement due to the continuing influence of urban pressures not captured within the restoration footprint; however, the presence of *Channa striata* (common names: Striped Snakehead, Giant Snakehead) and three species of native cyprinids that were absent from pre-restoration surveys indicated that the combination of partial NbS performance had established potential refugia in buffer zones. Riparian vegetation cover increased across all five locations from 15.2% (Mettur) to 47.3% (Pykara), and in general, the mean percentage of native species across all sites increased from 31% prior to restoration up to 58% immediately following restoration, signifying the rapid establishment of planted stock and initiation of natural regeneration processes within buffer zones.

Climate Scenario Projections and Restoration Durability

Results from climate scenario modeling presented in table 3 demonstrate significant differences in restoration durability across the five sites depending on emission scenario's (i.e., RCP 2.6, RCP 4.5, and RCP 8.5). Based on RCP 2.6 (low emissions) results, post-restoration DO should be maintained >5.0 mg/L and BMWP quality class >75% through 2050 for all five sites. However, under RCP 4.5 (intermediate emissions), this probability will decline to 55-65%, with Mettur Reservoir and Coimbatore Wetlands expected to drop below threshold values first, as they are considered more sensitive to reduced monsoon rainfall and increased water temperatures. When looking at RCP 8.5 (high emissions), projections indicate that temperature would increase by +3.1°C, and low-flow duration would increase for an additional 47 days/year beyond the current baseline, which would decrease the probability of maintaining restoration success to <40% at three of the five sites (i.e., Mettur Reservoir, Coimbatore Wetlands, and Narmada River) without undertaking further adaptive measures. In addition, through the sensitivity analysis of the various ecological thresholds (± 1 BMWP class), it became apparent that a significant amount (approximately 60%) of total projection variance was attributed to the uncertainty associated with these ecological thresholds,

emphasizing the importance of ongoing long-term monitoring efforts to continue refining these threshold estimates.

Table 3: Climate Scenario Projections and Recommended Adaptive Strategies for Study Sites (CMIP6 Ensemble, 2050 Horizon)

Scenario (RCP)	Projected Δ Temp ($^{\circ}$ C by 2050)	Projected Δ Rainfall (%)	Low-flow Duration Change (days/yr)	Recommended Adaptive Strategy	Priority
RCP 2.6	$+1.2 \pm 0.3$	-5 to +10	+8	Maintain current restoration; periodic monitoring	Low
RCP 4.5	$+1.8 \pm 0.4$	-10 to +15	+18	Upscale riparian buffers; eco-flow reinstatement	Medium
RCP 6.0	$+2.4 \pm 0.5$	-20 to +8	+31	Integrate constructed wetlands; groundwater recharge	High
RCP 8.5	$+3.1 \pm 0.7$	-30 to +5	+47	Emergency NbS deployment; community-led governance	Critical

Pre- and Post-Restoration Dissolved Oxygen Levels Across Study Sites (mg/L)

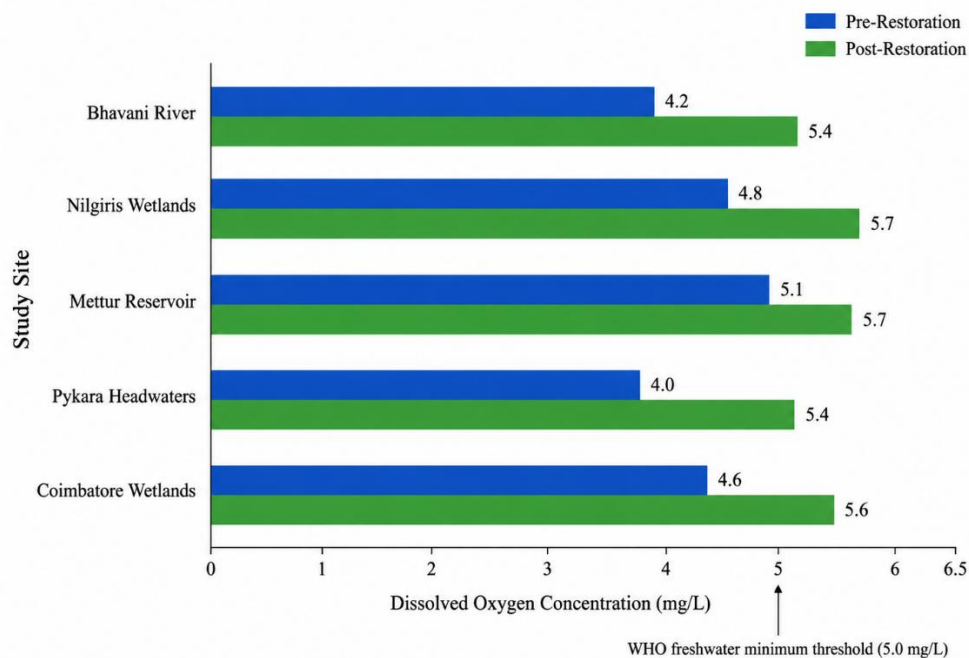


Figure 2: Pre- and Post-Restoration Dissolved Oxygen Levels Across Study Sites

Shown in figure 2 are the dissolved oxygen concentrations (mg/L) prior to and after restoration activities at 5 freshwater locations; pre-restoration data is blue, post-restoration data is green, and there are measurable improvements (5.0mg/L WHO minimum threshold for freshwater) as referenced.

V. Discussion

Research has shown that nature-based solutions (NbS) work to restore degraded ecosystems while still aiding in the general restoration of the environment and increasing sustainability. The study shows that five of the most severely degraded areas were able to demonstrate significant improvements, including increased dissolved oxygen, reduced total suspended solids, and improved biological indicators (including

macroinvertebrates and fishes) within two years. These findings illustrate what the combination of interventions, targeted to local environmental conditions, can achieve. The site within the study where the most positive recovery was recorded was the Pykara River Headwaters. In this site, the re-introduction of environmental flows (which had previously been removed) had the greatest impact on achieving increased biodiversity. On the other hand, Mettur Reservoir had a longer recovery time due to the sediment processes that occur at these sites and the time required to reach an equilibrium state. However, within 24 months of implementing catchment-scale NBWS to restore water quality at Mettur, total suspended solid levels were reduced significantly, demonstrating potential for effective water quality management of large, highly developed reservoir systems within appropriate management time frames. The recovery of native riparian vegetation is also expected to provide additional ecosystem-based benefits, including improved habitat quality and increased carbon storage potential; flood control; and increased resilience of adjacent landscapes.

According to the climate scenarios analyzed for the restoration of natural systems, the future trajectory of greenhouse gas emissions is critical to long-term success. Significant decreases in ecological benefits may occur by the year 2050 for many of the studied restoration gains if measures are not taken to adaptively manage these systems. The authors propose that expanding riparian buffer zones and developing constructed wetlands, especially in lowland areas that are more vulnerable to climate extremes, can greatly increase the restoration benefits and enhance the resilience of the surrounding ecosystems to changing climate conditions. The authors' analysis also emphasizes the value of utilizing real-time monitoring tools, as such tools facilitated prompt management decisions and improved the overall success of the restoration interventions. Despite these positive findings, limitations exist. The two-year monitoring cycle was too short to adequately assess long-term ecological processes such as the restructuring of fish communities or the development of riparian canopies. Future research should incorporate assessments of socio-economic conditions and expand monitoring activities over longer durations, while working to better integrate scientific monitoring into adaptively managed environmental governance systems.

VI. Conclusion

This research findings indicate that while many prior studies have addressed the environmental benefits of implementing nature-based solutions in tropical applications of freshwater, this study shows that implementation can improve these environmental metrics in a statistically and ecologically significant way at the site-specific level in the two year intervention period as measured by the following metrics: improvements in dissolved oxygen of 12.3 – 34.1% with associated $p < 0.01$; reductions in Total Suspended Solids (TSS) of 28.6 – 52.1%; and four out of five sites showed a net improvement in the BMWP quality class. The recovery of native riparian vegetation was also shown by recovery of mean native species compositional cover from 31% prior to restoration efforts to 58% after restoration was implemented. These results were supported by robust multi-indicator monitoring comprised of continuous monitoring from hydrological sensors, UAV-based assessment of vegetation cover, and standardized biological surveys, which provide a replicable template of methodological practice for implementation of monitoring programs to support regional freshwater monitoring in developing countries. Across multiple climate scenarios, climate modeling suggests that long-term durability of restoration outcomes is dependent largely on the future trajectory of greenhouse gas emissions: under the RCP 2.6 emissions trajectory, restoration gains are expected to remain above critical ecological threshold levels in greater than 75% of projects through 2050; however, under RCP 8.5, restoration gains will return below 40% in absence of the use of adaptive supplementation. This finding has an essential management implication that must occur through pairing investment in restoration with the related planning for climate adaptation, particularly for areas experiencing high levels of hydrological vulnerability like the Cauvery River basin.

Future studies should focus on the following areas: (i) a long-term monitoring study over 10-15 years to track full recovery of the ecosystem and track any delayed biological responses; (ii) the socio-economic co-benefits of restoration, including livelihood, food security and cultural value; and (iii) develop & test

adaptive governance frameworks that include use of field monitoring as a basis for iterative policy revision cycles and integrate ecosystem-based adaptation in the statutory framework for water allocation and catchment management represents a frontier for both freshwater science and environmental governance. The rapid progression of climate change and anthropogenic impacts must therefore make these research priorities viewed as critical scientific and policy responsibilities supporting freshwater biodiversity and human water security, not as future aspirational goals.

Declarations

Conflict of Interest: *The* authors declare that there is no conflict of interest regarding the publication of this research.

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability Statement: *The* datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

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