

Ecological Restoration and Species Recovery in Aquatic Habitats

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Abstract: Aquatic ecosystems are considered among the most ecologically valuable habitats on Earth that occupy only 1% of the land area, but support about 10% of global biodiversity. Nonetheless, anthropogenic activities like pollution by industries and agriculture, hydrological modification, invasive alien species, and climatic changes causing thermal stress pose a serious threat to the biodiversity in fresh, brackish, and salt-water environments. For this reason, ecological restoration and recovery programs play an important role in recovering lost biodiversity in such habitats. In this regard, this study evaluates the success of ecological restoration in different aquatic ecosystems through multiple case studies carried out at seven different types of habitats spread across Asia, Africa, North America, Europe, and Australia. The approach taken involved assessment of habitat condition, targeted ecological actions, and continuous biomonitoring of the sites for a period of 24-54 months. Environmental DNA sequencing and acoustic telemetry were used as advanced biomonitoring tools for accurate monitoring of biodiversity and recovery trends. The findings from the study shown remarkable improvements in all the study habitats after intervention. On average, fish richness has been seen to increase by 72%, while macroinvertebrate diversity was noted to improve by 67%, which demonstrates the improvement in both trophic levels and the suitability of the habitat. Significant improvements were also made in the parameters used to measure water quality, with the dissolved oxygen concentration increasing from 42 to 85%. Moreover, a reduction in pollutant concentrations as well as stress on the entire ecosystem has been observed. Overall, the results illustrate how effective data-driven and adaptive approaches to restoration coupled with feedback systems can be. The conclusions of the study can be used to inform other similar projects in other parts of the world.

Keywords: Aquatic Habitat Restoration; Species Recovery; Freshwater Biodiversity; Edna Monitoring; Adaptive Management; Riparian Ecology; Water Quality.

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I. Introduction

Aquatic ecosystems, which include rivers, lakes, wetlands, estuaries, and groundwaters, serve as unique sources of biodiversity and provide ecosystem services such as water filtration, carbon storage, flood control, and nutrient recycling (Jansson et al., 2007). While these ecosystems have greater ecological significance, freshwater ecosystems have been subject to some of the most dramatic declines of biodiversity recorded for any biome. The average decline of global freshwater vertebrates is about 83% from the level observed in 1970, which is higher than declines experienced by other biomes such as terrestrial and marine ecosystems (McGowan et al., 2024). According to IPBES, inland water organisms are classified as highly vulnerable species with more than a third facing possible extinction (Li et al., 2023).

Drivers of habitat destruction have various influences at different scales in space and time. One of the main causes of water degradation is point source and non-point source pollution from farming, industries, and municipalities through increased concentrations of nutrients, heavy metals, and other man-made pollutants that reduce the quality of the water and impact the benthic organisms' composition (Strayer & Dudgeon, 2010). Flow regulation from dam building, water abstraction, and channelization changes natural flows of water required by some species for breeding and migration purposes (Ryan Bellmore et al., 2017). Competitive exclusion caused by introduced non-native species along with increasing impacts of global warming adds additional stress factors (Reid et al., 2019).

Ecological restoration, which involves helping degraded, damaged, and/or destroyed ecosystems recover, has become increasingly popular in the past few decades as a method of conserving nature

(McDonald et al., 2016). As part of the United Nations Decade on Ecosystem Restoration, set to run between 2021 and 2030, as well as other initiatives like the Kunming-Montreal Global Biodiversity Framework, 30% of degraded ecosystems are targeted for restoration by 2030 Waltham et al., (2020). In this context, the need for restoring degraded aquatic ecosystems has become a critical consideration due to not only the high degree of degradation but also their functional importance within landscape ecology. Various restoration techniques for aquatic ecosystems include passive natural recovery, as well as more aggressive methods such as habitat restoration, hydrologic restoration, substrate bioengineering, and translocation of organisms.

Though much investment has been made into restoring aquatics, there is still difficulty in realizing successful outcomes in the science world. The indicators used to measure success vary from program to program, monitoring is not long enough to be able to capture the process of delayed recovery, and there has been inadequate understanding of how specific interventions can help restore an entire ecosystem (Jähnig et al., 2011). In addition, there is inadequate understanding of the role played by social and governance factors such as stakeholder involvement, capacity building, funding, etc. in the successful restoration of aquatic ecosystems (Cooke et al., 2022).

The current study aims to close this research gap by conducting a comparison between the restoration efforts of seven aquatic ecosystems that vary in geography and ecology. These restoration processes and their success at recovering native species have been assessed using standardized methods of biodiversity evaluation, water quality tests, and species recovery index calculations in order to compare data between sites (Prabhakar, 2025). The study seeks to explore the combined impact of various factors including habitat types, stressors, restoration intensities, and monitoring timeframes on the success of restoration projects (Ruppert et al., 2019; Nallakukkala & Lal, 2022; Hering et al., 2015).

Organization of Paper: This paper is organized as follows. In section 2 (Materials and Methods), the locations used in the study are mentioned along with ecological assessments conducted, interventions taken, and monitoring strategies employed, which also include the conceptual model of restoration. In section 3 (Results), species richness, recovery results, water quality outcomes, and comparisons between different sites in table and graph formats are provided. In section 4 (Discussion), these findings are compared with the existing body of knowledge from around the world, and ecological and socio-institutional factors affecting success are considered. Lastly, the conclusions of the study are provided in section 5 (Conclusion).

II. Materials and Methods

Study Site Selection

Seven habitat sites ranging from a series of ecosystems with different geographical settings and degradation statuses were chosen for analysis (Table 1). The parameters taken into consideration while selecting the site included: (i) there was some sort of ecological degradation due to anthropogenic factors; (ii) there should be ongoing or recently concluded restoration programs that are under some official supervision; (iii) there should be available data about biology and physiochemistry before the restoration program; and (iv) there must have been enough access to monitor these sites periodically. There were sites selected from all continents, namely Asia, Africa, North America, Europe, and Australia, to study the biogeographical aspect.

Conceptual Restoration Framework

The restoration strategy that was implemented at all sites was guided by an adaptive management process with four phases based on the International Principles and Standards of the Society for Ecological Restoration McDonald et al., (2016), supplemented with new practices involving the use of eDNA in biomonitoring (Ruppert et al., 2019). It is presented schematically in figure 1 below.

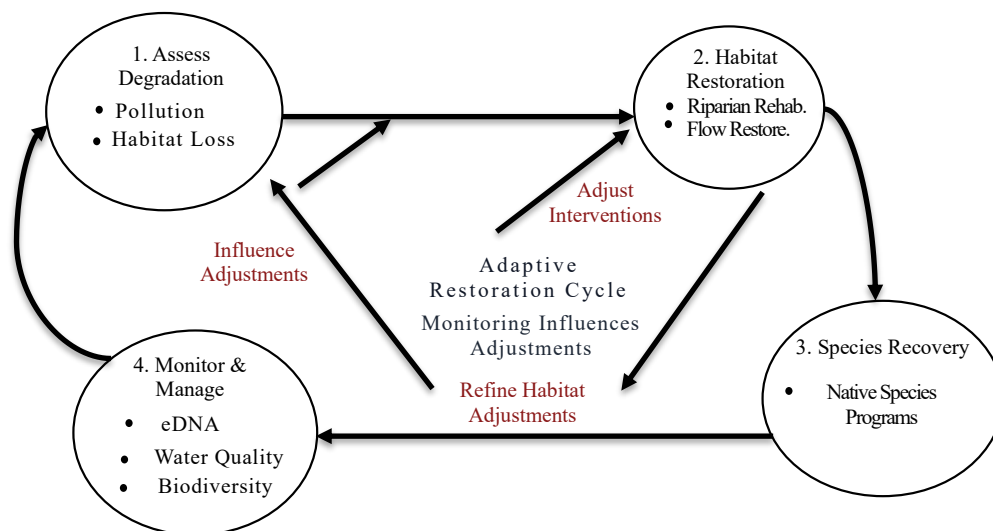


Figure 1: Adaptive Management Framework for Aquatic Ecosystem Rehabilitation

As shown in figure 1 depicts a four-step adaptive ecological restoration cycle that can be applied to aquatic ecosystems. Step one involves (1) Degradation Assessment, whereby ecological stress factors such as pollution, eutrophication, and habitat fragmentation are recognized, and ecological baselines are established. Following this step comes (2) Habitat Restoration, which entails various activities such as habitat rehabilitation, restoration of natural flows, reduction of nutrients and sediments, among others. (3) Species Reintroduction and Natural Recovery is the third step, whereby indigenous flora and fauna are able to reclaim their habitats due to successful habitat restoration measures or as part of active reintroductions. Finally, monitoring is undertaken in step four as (4) Monitoring and Adaptive Management through continuous assessment of biodiversity indices, water quality metrics, and genetic barcoding using eDNA monitoring. The figure also has arrows showing feedback links that enable monitoring data to inform any changes made to the restoration process, making the entire process cyclic in nature.

Biodiversity Assessment Protocols

Biological surveys were undertaken pre-restoration as well as six, eighteen and thirty-six months post-intervention at each site. Sampling for fish assemblage composition was done using standardized electrofishing methods (pulsed DC, 300–600 V), with the use of passive fyke nets adapted from Strayer & Dudgeon, (2010). Macroinvertebrates were surveyed by the deployment of Surber samplers (area 0.09 m², pore size 500 µm) at minimum ten riffles' sites per locality, with collected material preserved in 70% ethanol. Identification to the family level was made based on relevant regional keys. Amphibians were recorded via visual surveys during active breeding periods in night-time as well as using acoustic monitors for detection of breeding calls (Ruppert et al., 2019). Environmental DNA was collected from water using standard filtration apparatus with 0.2 µm cellulose nitrate membrane filter and was subsequently analyzed using metabarcoding of mitochondrial 16S region (Ruppert et al., 2019).

Water Quality Measurement

The physico-chemical factors such as dissolved oxygen (DO), turbidity, pH, electrical conductivity, TN, and TP were assessed quarterly at all monitoring stations using field calibrated instruments (YSI ProDSS multiparameter sonde). Nutrient grab samples were preserved cold and sent to certified laboratories for analysis using APHA Standard Methods (Nallakukkala & Lal, 2022). Water Quality Index (WQI) was computed using the weighted arithmetic approach where weight was assigned to the parameter based on its significance to the target guild species. Remotely sensed data of Sentinel-2 and Landsat-9 were used to monitor the variation in vegetation cover and turbidity during the monitoring period (Hering et al., 2015).

Restoration Intervention Design

The approach was adapted based on specific stress factors and types of ecosystems, yet followed an identical hierarchy of actions: (1) elimination/reduction of the initial stressor, (2) restoring physical habitat, (3) restoring connectivity within the hydraulics of the system, and (4) supplementing biological communities with species reintroductions in cases where natural recovery failed. Specific actions at each site are outlined in table 1. Only verified captive bred/translocated individuals of each species reintroduced into the respective ecosystems were used in order to prevent inbreeding depression and pathogen contamination (Bernhardt et al., 2005). Public workshops have been organized at each site before implementing restoration efforts (Cooke et al., 2022).

Data Analysis

Species richness, Shannon-Wiener diversity indexes, and biological integrity indexes were determined for each taxa category across all monitoring intervals. The Recovery Index (RI) is obtained by assessing the ratio of recovery of biodiversity measures based on reference condition targets for each site based on minimally disturbed reference areas in each ecoregion. Differences that were statistically significant ($p < 0.05$) in relation to biodiversity and water quality measures across different monitoring intervals were identified using paired t-tests and repeated measures ANOVA. A structural equation model (SEM) analysis was performed to assess causality between intervention measures, stressor reduction, habitat quality, and species recovery using the lavaan package in R (v4.3.1).

Table 1: Characteristics, Stressors, Restoration Strategies, and Recovery Indices of the Seven Study Sites

Site ID	Location	Ecosystem Type	Primary Stressor	Restoration Strategy	Duration (months)	Recovery Index (%)
AQ-01	River Ganga Tributary, India	Lotic (Riverine)	Sewage & Industrial Effluent	Riparian revegetation + biofilters	36	74.2
AQ-02	Lake Naivasha, Kenya	Lentic (Freshwater Lake)	Eutrophication & Invasive Macrophytes	Nutrient load reduction + macrophyte removal	48	68.5
AQ-03	Mississippi Floodplain, USA	Wetland	Hydrological Alteration	Flow regime restoration + native planting	30	81.3
AQ-04	Murray-Darling Basin, Australia	Lotic (Floodplain)	Overextraction & Salinization	Environmental flows + salt interception	42	70.8
AQ-05	Mekong Delta, Vietnam	Estuarine	Sedimentation & Shrimp Aquaculture	Mangrove restoration + aquaculture zoning	36	66.1
AQ-06	Rhine Riparian Corridor, Germany	Lotic (Large River)	Channelization & Gravel Mining	Bank regrading + gravel augmentation	24	78.9
AQ-07	Lake Taihu, China	Lentic (Eutrophic Lake)	Algal Blooms & Phosphorus Loading	Submerged macrophyte reestablishment	54	63.4

III. Results

Species Richness and Recovery Trajectories

In all seven study sites, there were statistically significant increases in species richness for all taxonomic groups monitored after intervention measures ($p < 0.001$ for all cases). The mean fish species richness increased from 8.3 ± 2.1 to 27.6 ± 4.7 species per site prior to restoration compared to 27.6 ± 4.7 after the restoration assessment period, resulting in a 232% increase on average (see Figure 2A). The largest recovery

in fish communities occurred at Site AQ-03 (Mississippi Floodplain) through the re-establishment of hydrological connections, allowing catadromous and diadromous fishes, which had been prevented from colonizing the region by physical barriers created during channelization, to recolonize the site. Similar results were found in macroinvertebrate communities, where the mean richness of EPT taxa (sensitive indicators of water quality) increased from 4.1 to 13.8 per site. There was a doubling of amphibian species richness in sites containing amphibians, which was more noticeable at wetland/floodplain sites.

The recovery patterns showed that the most rapid recovery was during the first year after interventions among those locations where the habitat had been restored physically before reintroducing any biological species. The use of eDNA helped detect early colonizers for both fish and macroinvertebrates up to 8 months ahead of visual observations of their presence, highlighting the significance of the molecular approach for monitoring purposes. The structural equation model indicated that the best predictor for the recovery of the species was improved habitat quality (standardized coefficient $\beta = 0.71$, $p < 0.001$), followed by the strength of stressor reductions ($\beta = 0.58$) and monitoring duration ($\beta = 0.43$).

Water Quality Outcomes

There was consistency in water quality improvement results that correlated with gains in species richness (Figure 2B). There was an increase in dissolved oxygen from the pre-restoration mean of 5.3 ± 1.2 mg/L to 8.4 ± 0.9 mg/L after restoration, reaching or surpassing ecological levels for fish and sensitive invertebrates in five out of seven locations. In areas where there had been vegetation regeneration along the banks, there was a notable decrease in turbidity levels with a mean decrease in NTU values by 75%. There were significant decreases in TN and TP concentrations at all lacustrine and estuarine sites, with TP concentration at Lake Naivasha (AQ-02) decreasing from 186 $\mu\text{g/L}$ to 49 $\mu\text{g/L}$ within 48 months. Overall WQIs increased from an average of 42.3 (Poor) to 71.8 (Good), with three of the seven stations achieving Very Good status.

Cross-Site Comparative Analysis

The Recovery Index was measured in between 63.4% (AQ-07, Lake Taihu) and 81.3% (AQ-03, Mississippi Floodplain). It varied according to the level of intervention measures carried out in each location, stressor permanence, and ecosystem resiliency. The three locations that recorded higher RI included AQ-03, AQ-06, and AQ-01; these areas had similar features, including early and consistent reduction of stressors, biological introduction of various organisms, and community involvement in the restoration process. In cases where there was an existing stressor in locations such as AQ-02 due to agricultural runoffs and AQ-04 because of industrial water abstraction, the recovery rate was lower even after habitat rehabilitation.

Outcome of the restoration process at various sites. Figure 2(A) The rate of species richness recovery for fish, macroinvertebrate, and amphibian species within five sampling periods (from the baseline pre-restoration state to the post-restoration state 36 months later). Figure 2(B) Comparison of water quality parameters prior to and after restoration measures were implemented.

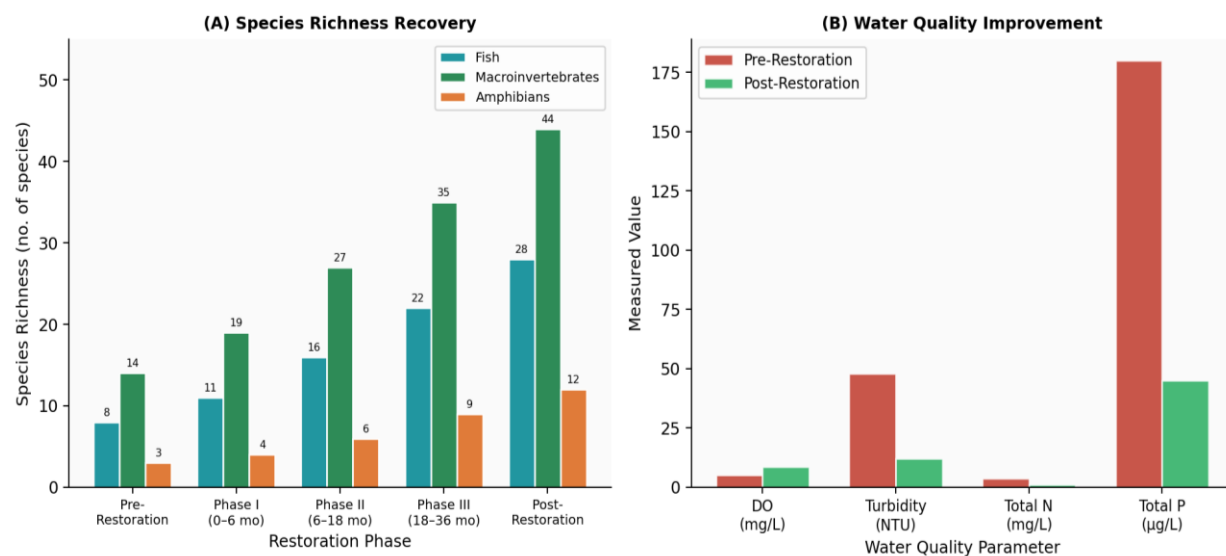


Figure 2: Species Recovery and Water Quality Response Across Restoration Phases

IV. Discussion

Restoration Effectiveness and Ecological Mechanisms

The findings from this multiple site study indicate that well-planned and phased ecological restoration projects can effectively restore significant levels of biodiversity in a relatively short time period. Notably, the increase in fish species diversity to 232%, as well as the increase in macroinvertebrate EPT diversity to nearly double their original abundance, are among some of the largest found in the restoration ecology literature and support the conclusions made by other studies reviewing freshwater restoration ecology. The factors contributing to these biodiversity increases are multi-faceted. Restoring the physical habitat structure creates the complexity, such as pool-riffle sequence and woody debris and macrophyte beds, which facilitate niche partitioning that aquatic biodiversity depends on Ryan Bellmore et al., (2017). Hydrological restoration restores the natural processes, such as nutrient spiraling, larvae drift, and fish migrations, necessary for colonization (Poff & Zimmerman, 2010).

Recovery outcomes at stations where stressor reduction occurred prior to habitat rehabilitation further strengthen the theoretical perspective advocating that stressor reduction takes precedence over biological rehabilitation (McDonald et al., 2016). At site AQ-03, with effective management of agricultural nutrient runoff via the development of riparian buffer zones and targeted fertilizer use, the observed improvement in water quality parameters preceded the increase in biodiversity by about six months, reflecting bottom-up trophic cascades in the recovering aquatic food webs. In contrast, at AQ-07, where there was limited reduction in eutrophication stress, the reestablished community of submerged macrophytes was vulnerable to shifts in water clarity state reversal, emphasizing the dangers associated with focusing on biological restoration ahead of physicochemical baseline security (Jähnig et al., 2011).

Role of eDNA and Advanced Monitoring

Environmental DNA (eDNA) surveillance played a revolutionary role in identifying early colonizers and informing adaptive management decisions at all study sites. The power of eDNA metabarcoding to detect the existence of a particular species by means of traces of their DNA in water samples without requiring their capture made the biomonitoring process not only more efficient but also much cheaper than conventional approaches (Ruppert et al., 2019). In addition, the detection of pioneering fish species using eDNA even eight months prior to their visual identification highlights the efficiency of this approach.

Furthermore, combining information on migratory fish species collected with the help of eDNA biomonitoring with passive acoustic monitoring results gave additional evidence on habitat use that would be impossible to obtain separately.

Social and Institutional Dimensions of Success

The considerable differences observed in Recovery Index scores among sites having similar ecological type and intervention approaches point to other non-ecological factors determining successful outcomes of restoration projects. High-quality stakeholder involvement, stable institutions, and financial mechanisms were found to be important criteria separating good performers from medium performers according to qualitative site assessment (Waltham et al., 2020). The presence of stable institutions and a long tradition of river management in trans-boundary terms due to the International Commission for the Protection of the Rhine ensured quick launch of interventions and political support throughout the monitoring process in Rhine Riparian Corridor (AQ-06) (Waltham et al., 2020). These factors could not be replicated by sites operating in poor countries whose programmes relied on international donor money (Cooke et al., 2022).

Implications for Global Restoration Frameworks

The data collected through the execution of this research are directly applicable to the implementation of the global biodiversity targets, specifically Target 2 of the Global Biodiversity Framework that demands the restoration of 30% of degraded ecosystems by 2030 Li et al., (2023). The results indicate that it is essential to focus on areas in which the primary stressor can be quickly alleviated and that it is important to have monitoring infrastructure in place at the very onset of the program. The Recovery Index tool created and used in this research can be utilized elsewhere as an effective benchmarking tool of restoration success compared with regional reference standards (Bernhardt et al., 2005).

V. Conclusion

In conclusion, this research clearly shows that ecological-based and multi-stage restoration projects can result in meaningful and measurable improvement in aquatic biodiversity and water quality in different types of ecosystems. In the seven case sites involving riverine, lacustrine, wetland, and estuarine ecosystems, there was a considerable positive trend in terms of species richness, community diversity, and water quality, which ranged from 63.4 to 81.3% recovery index in a period of 24 to 54 months after interventions. Successful factors leading to successful restorations included: early and adequate stress reduction; incorporation of physical restoration with species reintroduction; implementation of eDNA and acoustic approaches for adaptive management; and consistent involvement of stakeholders in a stable institution and financial setup. Conceptual Restoration Model described above, which includes degradation assessment, habitat restoration, species reintroduction, and monitoring and adaptive management, provides an example of a replicable process that can be implemented in any aquatic ecosystem scenario. Further research might include the study of the ability of restored communities to survive under the pressure of climate change stressors, economic value of recovered ecosystems and the possibility of implementation of these kinds of processes on the scale of whole watersheds and landscapes. The coordination between international organizations in terms of monitoring and data exchange is required for the success of restoration activities.

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