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Restoration Ecology Strategies for Reviving Degraded Aquatic Habitats and Enhancing Ecosystem Resilience

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Abstract: The objective of this study is to assess restoration strategies that can be employed in reviving degraded aquatic ecosystems in order to increase ecosystem resilience. In this study, efforts were made to improve habitat structures, water and sediment quality, biodiversity, ecosystem functioning, and resilience of the ecosystems. This study employed the "before and after restoration" approach to assess the degraded aquatic ecosystems by comparing the ecosystem against an undisturbed reference site. Measures adopted in restoration include establishing native aquatic vegetation, sediment manipulation, habitat restoration, hydrologic connection enhancement, establishment of riparian vegetation, and nutrient load reduction. Indicators of physico-chemical, habitat, vegetation, macroinvertebrate, microbial, ecosystem functioning, and resilience were analyzed before and after restoration. The ecological condition index was raised from 42.6 ± 6.8 to 71.8 ± 7.4, whereas the resilience index was raised from 0.43 ± 0.08 to 0.72 ± 0.07. The amount of dissolved oxygen was raised from 4.2 ± 0.8 to 6.8 ± 0.9 mg/L, while the amount of turbidity was reduced from 28.6 ± 7.4 to 13.2 ± 4.1 NTU. The percentage of vegetation cover was raised from 21.4 ± 6.3% to 56.8 ± 8.1%, while the richness of macroinvertebrates was raised from 24.3 ± 4.6 to 38.7 ± 5.2 taxa. Ecological recovery was achieved at 76.2%, including the recovery of 82.9% for habitat complexity and 82.4% for dissolved oxygen. The application of the integrated restoration led to significant improvements in terms of ecological state, biodiversity, ecological functioning, and resilience.

Keywords: Aquatic Habitat Restoration; Restoration Ecology; Ecosystem Resilience; Biodiversity; Water Quality; Habitat Recovery; Adaptive Management.

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I. Introduction

Aquatic ecosystems play a very significant role in maintaining biodiversity, biogeochemical cycles, water balance, food security, and human welfare; however, the continuous degradation of their habitat has considerably hampered their ecological functioning and resilience. Rivers, wetlands, lakes, estuaries, coastal ecosystems, and marine environments have been subject to pollution, manipulation of hydrological regimes, fragmentation of habitats, overutilization, invasion of exotic species, sedimentation, and environmental disturbances caused by climate change. This has led to modifications of habitat structures, decreased diversity of species, changes in ecological interactions, and a reduction in their capacity to recover from disturbances. Consequently, habitat restoration has become one of the key elements of aquatic ecosystem management in recent times, with greater emphasis being placed on the restoration of ecological processes rather than habitat condition itself (Geist & Hawkins, 2016; Banks-Leite et al., 2020). Recent studies have provided evidence of the serious impacts that degradation can cause to fish populations due to the loss of spawning, foraging, nursery, and refuge habitat (Huang & Han, 2025).

The aim of this research is to analyze the restoration ecology methods that can be used to recover degraded aquatic habitats and enhance their resilience. In particular, attention is paid to the holistic methods that incorporate habitat restoration, ecological engineering, biodiversity increase, biological restoration, water quality improvement, and nature-based solutions. Restoration technologies in rivers have shown the ability to increase biodiversity and ecosystem functionality, and new biological methods of restoration, in turn, open up new opportunities for the management of nutrients, water quality improvement, and ecological restoration (Li et al., 2022; Rajenthiram et al., 2026). The restoration process should take into account the ability of aquatic ecosystems to tolerate disturbances, re-organize ecological relationships, and perform their functions despite the changes in the environment (Pelletier et al., 2020; Imoobe et al., 2024).

Nevertheless, certain research problems exist despite considerable advances made in the field. In particular, restoration methods usually pay attention to individual habitats, species, and environmental factors but not to ecological processes, social aspects, resilience, and climatic disturbances. The restoration process can also face limitations such as the lack of consistent assessment criteria, ecosystem valuation, ecological trajectory uncertainty, and extreme climatic disturbances (Zabin et al., 2022; Abelson et al., 2016; Basconi et al., 2019). Moreover, restoration strategies created for specific ecological contexts might not achieve similar results in other types of aquatic ecosystems since recovery depends largely on the existing ecological conditions and disturbances in each ecosystem. Recent ecological theories indicate the necessity of designing restoration based on interactions in the ecosystem, feedbacks, and unique processes in the ecosystem instead of using conventional intervention techniques (Silliman et al., 2024).

The major innovation of the paper under consideration is the development of a framework for restoration that focuses on the interrelation between recovery of habitats, increasing biodiversity, proper functioning of the ecosystem, and resistance to disturbances in the future. Thus, the paper indicates the significance of integrating ecological restoration techniques with adaptive management, ecological theory, biological intervention, and climate-resilient strategies.

This paper is divided into six sections as follows: Section 1 discusses degraded aquatic ecosystems and research objectives; Section 2 covers the integrated restoration literature review; Section 3 describes the research methodology and assessment criteria; Section 4 provides empirical data on the recovery process; Section 5 discusses results and limitations; and finally, Section 6 concludes the paper.

II. Literature Review

Aquatic Restoration Ecology has gradually moved from an emphasis on single-habitat restoration to strategies that focus on restoring the structure and functioning of ecosystems. Early restoration studies focused on the restoration of the physical habitat itself, but modern approaches have come to realize the importance of studying interactions between hydrology, habitat complexity, diversity, ecosystem processes, and other pressures. Reviews of aquatic habitat restoration show that restoration efforts have come a long way, but still face problems related to ecological uncertainty, scale, monitoring, and anthropogenic pressures (Geist & Hawkins, 2016). The effects of habitat degradation are especially significant for aquatic organisms since it can affect the abundance and composition of populations by affecting their breeding, feeding, migration, and refuge habitats (Huang & Han, 2025).

The technologies used for ecological restoration have proved to have great potential in improving the health of the aquatic ecosystem. River restoration technologies are effective in increasing habitat complexity, connectivity, and the support of biodiversity and ecosystem functioning (Li et al., 2022). On the other hand, the idea of ecological restoration is not that of taking the ecosystem back to its historical condition, but rather that of rebuilding its resilience. The resilience of the aquatic ecosystem is associated with the ability of an ecological system to withstand disturbances, re-organize after the disturbance, and provide its functions (Pelletier et al., 2020).

Climate change adds additional weight to the importance of such restoration. Climatic extremes may jeopardize the efforts in ecological restoration by creating disturbance in the form of heat stress, flooding, droughts, storms, and other rapid changes in the environment. Therefore, any restoration program should be ready for the future disturbance regime and include properties to increase resistance and recovery from extreme events (Zabin et al., 2022). Ecological theory plays a key role in enabling this transformation due to its focus on species interaction, ecological networking, feedback, succession, and context-based recovery mechanisms. Utilizing such concepts can enhance restoration practices and help avoid the use of one-size-fits-all approaches which do not necessarily reflect the actual ecological situations (Silliman et al., 2024).

Marine restoration research, in a similar manner, illustrates the significance of combining ecological and social aspects. Restoration is not only determined by the ecological aspect of restoration but also by the issues of governance, stakeholder involvement, ecosystem services, socio-economic issues, and relevant

valuation processes (Abelson et al., 2016). Restoration can bring various additional benefits beyond biodiversity through improved ecosystem services and human well-being (Aronson et al., 2016). Habitat restoration research further highlights the significance of considering all three aspects of habitat destruction - loss, fragmentation, and degradation at the same time (Banks-Leite et al., 2020). New approaches in the field of restoration make it possible to use more possibilities to tackle complex types of degradation. Restoration of aquatic ecosystems with the help of microalgae is studied now as a possible solution due to the benefits of such restoration in terms of the removal of nutrients and pollutants, production of biomass, and water quality improvement despite the problems that are still present (Rajenthiram et al., 2026). Experience of restoration projects from other fields shows that biological methods can be used for tackling degradation issues (Gufwan et al., 2025). However, restoration is highly dependent on the choice of correct assessment tools, proper ecological goals, ecosystem valuation, monitoring, and management. The marine restoration field emphasizes the lack of proper approach selection, evaluation, and valuation as the main obstacles in the restoration process (Basconi et al., 2019). Overall, the literature demonstrates the need for moving to more integrated and resilient approaches to ecosystem restoration that can handle current and future environmental challenges.

III. Materials and Methods

An integrative approach of pre- and post-restoration assessment was used to assess the ecological recovery and resilience of degraded aquatic ecosystems in this study. The methodology of the study included the selection of sites, baseline assessment of the environment and biological characteristics, implementation of restoration measures, post-restoration monitoring, and comparison of the results obtained. Such aspects as water quality, habitat characteristics, vegetation, biodiversity, and resilience were analyzed to assess the impact of the implemented restoration measures. The general methodology applied in the study is illustrated in figure 1.

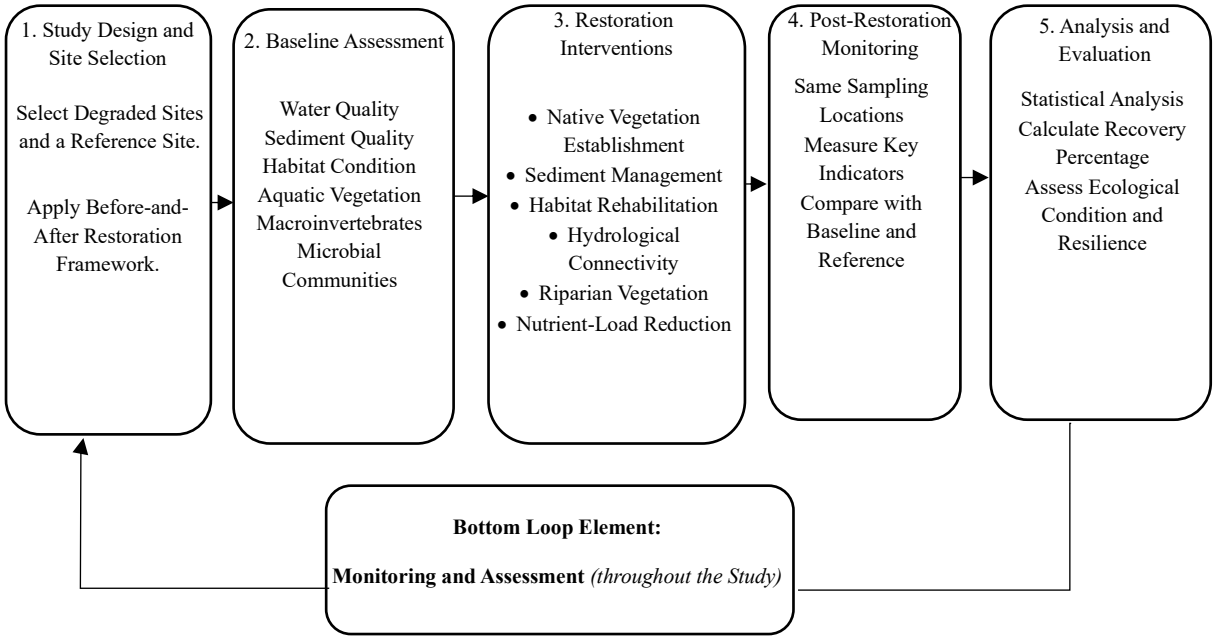


Figure 1: Methodological Framework for Aquatic Habitat Restoration

Figure 1 demonstrates the procedure for carrying out this research from site selection through baseline evaluation, then restoration procedures, post-restoration evaluation, and statistical analysis. This approach includes the consideration of water quality, habitat condition, biodiversity, functioning of the ecosystems, and resilience factors to evaluate ecological recovery.

Study Design and Site Selection

This study aimed at assessing the efficiency of various ecological restoration approaches in enhancing the ecological status of degraded water bodies. The restoration sites were chosen due to habitat degradation, low water quality, sedimentation, decrease in aquatic vegetation, nutrient enrichment, and biological diversity loss. Undisturbed reference sites were selected for determining the benchmark ecological status. This study was based on a before-and-after restoration approach where the ecological status was determined before and after applying restoration approaches.

Baseline Ecological and Environmental Assessment

The baseline conditions were determined using physico-chemical, biological, and habitat-based indicators. Physico-chemical indicators such as water temperature, pH, dissolved oxygen, electrical conductivity, turbidity, total dissolved solids, nitrate, ammonium, phosphate, total nitrogen, total phosphorus, and biochemical oxygen demand were analyzed. The sediment was tested for the presence of organic matter, nitrogen, phosphorus, and sediment size fractions. Physical habitat condition was determined using substrate quality, habitat complexity, aquatic vegetation, shallow water areas, shoreline condition, and hydrological connection.

Restoration Interventions

The restoration measures that were undertaken depended on the type of degradation stresses as determined from the baseline assessment. Native aquatic vegetation was introduced in areas that would suit them, so that there could be sediment stabilization, increased habitat complexity, and increased nutrient retention. Sediment deposition was controlled in areas where it was required, and degraded shallow-water and hydrologic habitat were restored. The riparian vegetation and vegetated buffer zones were created where needed to reduce surface runoff and external nutrient supply.

Biological and Biodiversity Assessment

Aquatic vegetation was evaluated through species richness, percent cover, plant density, and biomass. The macroinvertebrates were assessed through richness, abundance, Shannon diversity index, evenness, and the ratio of pollution-sensitive and tolerant organisms. The microbial community was also assessed by determining the species diversity and the nutrient cycling and organic matter decomposition functional groups.

Ecosystem Function and Resilience Assessment

Functioning of the ecosystem was measured by nutrient storage, organic matter degradation, productivity of the habitats, and indicators of functional diversity. Resilience of the ecosystem was measured through resistance to stresses in the environment and capability for recovering the ecology after disturbances. A composite resilience index was calculated based on indicators of stability of water quality, biodiversity, habitat complexity, vegetation recovery, and biological community stability:

$$RI = \sum_{i=1}^{n} w_i Z_i \quad (1)$$

Equation (1) where $RI$is the resilience index, $Z_i$is the standardized value of each indicator, and $w_i$is its weighting coefficient.

Monitoring and Statistical Analysis

Monitoring after restoration was done using the same sampling points and analyses that were used during baseline sampling. The changes in the environmental and biological parameters were compared at baseline, post-restoration, and reference conditions. Percentage recovery was calculated based on:

$$Recovery(\%) = \frac{X_{post} - X_{baseline}}{X_{reference} - X_{baseline}} \times 100 \quad (2)$$

Equation (2) where X_{post}, $X_{baseline}$, and $X_{reference}$represent post-restoration, baseline, and reference values, respectively. Statistical analysis was carried out using either analysis of variance or non-parametric tests. The use of multivariate analyses was employed to assess changes in community structure, with significance tested at P<0.05.

IV. Results

Overall Ecological Recovery

The restorations led to a significant improvement in the overall ecological status of the degraded aquatic habitat. The ecological status score rose from 42.6 ± 6.8 pre-restoration to 71.8 ± 7.4 post-restoration, and was getting close to the reference level of 82.4 ± 5.9. There were also significant increases in habitat complexity, vegetation cover, and biodiversity.

Table 1: Overall ecological response to aquatic habitat restoration

Indicator	Baseline	Post-restoration	Reference
Ecological Condition Index	42.6 ± 6.8	71.8 ± 7.4	82.4 ± 5.9
Habitat Complexity Score	38.7 ± 7.2	69.5 ± 6.8	79.2 ± 5.6
Vegetation Cover (%)	21.4 ± 6.3	56.8 ± 8.1	68.7 ± 7.4
Biodiversity Index	2.31 ± 0.38	3.47 ± 0.41	3.82 ± 0.35
Resilience Index	0.43 ± 0.08	0.72 ± 0.07	0.81 ± 0.06

The ecological reactions after the process of restoration are presented in table 1 below. The high levels of habitat complexity, vegetation cover, biodiversity, and resilience point to the general recovery of the ecosystem. The post-restoration values were comparable to those from reference sites, showing that the restoration approach was effective in terms of structure and ecology.

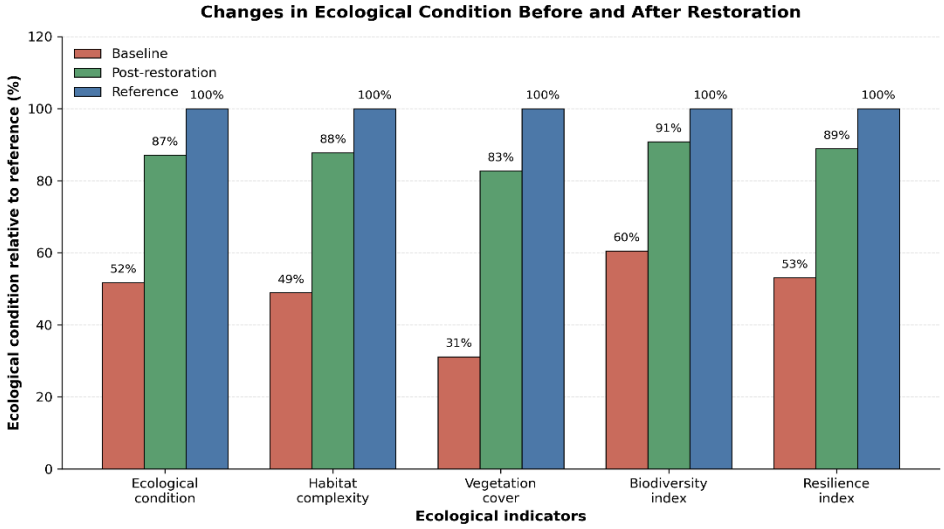


Figure 2: Changes in Ecological Condition Before and After Restoration

Figure 2 illustrates comparisons between pre-restoration, post-restoration, and reference states for ecological condition, habitat complexity, aquatic vegetation, biodiversity, and ecosystem resilience. Values are depicted in comparison with the reference state, which is equivalent to 100%. This allows for comparison of indicators in different units.

Improvement in Water and Sediment Quality

The water quality was significantly enhanced through the restoration process. There were increases in levels of dissolved oxygen from 4.2 ± 0.8 to 6.8 ± 0.9 mg/L and decreases in turbidity from 28.6 ± 7.4 to

13.2 ± 4.1 NTU. Decreases in nitrate, phosphate, total nitrogen, and total phosphorus also occurred. Organic matter in sediments declined from 9.4 ± 1.8% to 6.1 ± 1.3% together with sediment nitrogen and phosphorus content.

Table 2: Changes in Water and Sediment Quality Following Restoration

Parameter	Baseline	Post-restoration	Reference
Dissolved Oxygen (mg/L)	4.2 ± 0.8	6.8 ± 0.9	7.4 ± 0.7
Turbidity (NTU)	28.6 ± 7.4	13.2 ± 4.1	8.7 ± 2.8
Nitrate (mg/L)	4.8 ± 1.1	2.6 ± 0.7	1.9 ± 0.5
Phosphate (mg/L)	0.42 ± 0.11	0.19 ± 0.06	0.12 ± 0.04
Total nitrogen (mg/L)	6.74 ± 1.26	4.03 ± 0.88	3.21 ± 0.64
Total phosphorus (mg/L)	0.81 ± 0.18	0.39 ± 0.11	0.27 ± 0.08
Sediment organic matter (%)	9.4 ± 1.8	6.1 ± 1.3	5.3 ± 1.1

Table 2 demonstrates the improvement in environmental quality after the restoration process. An increase in the concentration of dissolved oxygen and a decrease in turbidity and nutrient concentrations show that the environmental stress has been lowered. The reduction in the concentration of sediment organic matter and nutrients also shows that the benthic environment has been improved.

Aquatic Vegetation and Habitat Recovery

Vegetation cover showed a significant increase after the restoration was implemented, increasing from 21.4 ± 6.3% to 56.8 ± 8.1%. The number of plant species in the community also increased, rising from 7.2 ± 1.8 to 13.6 ± 2.4 species. An increase in plant biomass and density was also observed.

Table 3: Aquatic Vegetation and Physical Habitat Recovery

Indicator	Baseline	Post-restoration	Reference
Vegetation cover (%)	21.4 ± 6.3	56.8 ± 8.1	68.7 ± 7.4
Plant species richness	7.2 ± 1.8	13.6 ± 2.4	16.1 ± 2.1
Plant density (individuals/m²)	18.7 ± 4.9	41.3 ± 7.2	48.6 ± 6.8
Biomass (g/m²)	184 ± 42	390 ± 67	448 ± 61
Habitat complexity score	38.7 ± 7.2	69.5 ± 6.8	79.2 ± 5.6

Recovery of the vegetative cover, species richness, density, and biomass, in addition to habitat complexity, is indicated in table 3. These results clearly show that the establishment of the native vegetation and heterogeneous habitat characteristics, which can support a wide variety of aquatic organisms, were achieved through this restoration project.

Biological Community Recovery

Ecological recovery of macroinvertebrates and microbes was evident. The richness of macroinvertebrates increased from 24.3 ± 4.6 to 38.7 ± 5.2, while Shannon diversity increased from 2.41 ± 0.32 to 3.36 ± 0.37. The pollution-sensitive taxa increased, while the pollution-tolerant taxa decreased. An increase in richness and diversity of the microbes and an increase in the functional groups of nutrient cycling was observed.

Table 4: Biological Responses to Restoration

Biological indicator	Baseline	Post-Restoration	Reference
Macroinvertebrate Richness	24.3 ± 4.6	38.7 ± 5.2	43.8 ± 4.7
Macroinvertebrate Shannon Diversity	2.41 ± 0.32	3.36 ± 0.37	3.61 ± 0.31
Sensitive Taxa (%)	14.8 ± 4.1	28.4 ± 5.3	34.7 ± 4.8
Tolerant Taxa (%)	47.6 ± 7.2	29.8 ± 5.4	22.1 ± 4.6
Microbial Richness	1,846 ± 214	2,485 ± 267	2,731 ± 251
Microbial Shannon Diversity	3.12 ± 0.28	3.91 ± 0.31	4.12 ± 0.27

Biological recovery for macroinvertebrates and microbes is provided in table 4. Increasing richness and diversity, coupled with increasing abundance of sensitive species, suggests that the habitat quality is improving. The decrease in the number of tolerant species and increased diversity of microbes implies that the restoration process relieved stress and improved ecological conditions.

Ecosystem Functioning and Resilience

Ecosystem functioning and resilience were enhanced through the process of restoration. Nutrient retention rose from 38.4 ± 6.7% to 54.8 ± 7.2%, while the ecosystem functioning index rose from 0.46 ± 0.07 to 0.69 ± 0.08. The composite index of resilience rose from 0.43 ± 0.08 to 0.72 ± 0.07, indicating a marked increase in resilience.

Table 5: Ecosystem Functioning and Resilience Following Restoration

Indicator	Baseline	Post-Restoration	Reference
Nutrient Retention (%)	38.4 ± 6.7	54.8 ± 7.2	61.7 ± 6.4
Organic Matter Processing Index	0.47 ± 0.08	0.64 ± 0.09	0.71 ± 0.07
Functional Diversity	1.82 ± 0.24	2.49 ± 0.27	2.73 ± 0.25
Ecosystem Functioning Score	0.46 ± 0.07	0.69 ± 0.08	0.78 ± 0.06
Resistance Index	0.41 ± 0.07	0.69 ± 0.06	0.77 ± 0.05
Recovery Rate Index	0.46 ± 0.09	0.75 ± 0.08	0.84 ± 0.07
Composite Resilience Index	0.43 ± 0.08	0.72 ± 0.07	0.81 ± 0.06

Table 5 shows the positive impacts of restoration on ecosystem functioning and resilience. There was an improvement in nutrient retention, functional diversity, resistance, and recovery capacity. The overall resilience value was close to the reference condition, suggesting that restoration improved the capacity of the ecosystem to resist stress and recover from disturbances.

Overall Restoration Effectiveness

Recovery percent for all the major ecological indices improved significantly. In the case of habitat complexity, there was 82.9% recovery, whereas 82.4% recovery was observed for dissolved oxygen and 79.3% for macroinvertebrate diversity. The resilience index showed 73.7% recovery, whereas 76.2% ecological recovery was observed relative to reference conditions.

Table 6: Percentage Recovery of Major Ecological Indicators

Indicator	Recovery (%)
Dissolved Oxygen	82.4
Turbidity	76.8
Nutrient Condition	71.5
Aquatic Vegetation	74.6
Macroinvertebrate Diversity	79.3
Microbial Diversity	72.1
Habitat Complexity	82.9
Ecosystem Functioning	70.8
Resilience Index	73.7
Overall Recovery	**76.2**

Table 6 shows the relative level of recovery attained for all ecological parameters. Most parameters exhibited good recovery, especially habitat complexity and dissolved oxygen. The total recovery level of 76.2% suggests that the restoration approach has successfully transformed the damaged aquatic ecosystems into ones resembling the conditions of the reference ecosystem.

V. Discussion

The results reveal that the ecosystem recovery was significantly improved as a result of the proposed restoration techniques, with total ecological recovery of 76.2% compared to the reference state. The highest ecological recovery of 82.9% was observed for habitat complexity, while dissolved oxygen achieved recovery of 82.4% and macroinvertebrate diversity of 79.3%, with a resilience index of 73.7%. This suggests that restoration has positively affected the structure and function of the ecosystem. It can also be concluded from the increases of dissolved oxygen from 4.2 to 6.8 mg/L and vegetation cover from 21.4% to 56.8%. This means that a combination of the establishment of native vegetation, sediment control, habitat restoration, and nutrient loading reduction is more efficient for the restoration of aquatic environments compared to restoration based on one of these components. The increased number of macroinvertebrate species from 24.3 to 38.7 species and the increased resilience of aquatic organisms from 0.43 to 0.72 mean the recovery of biological communities and their increased resistance and recoverability. This is important because restoration can have positive effects on water quality, biodiversity, ecosystem functioning, and resilience.

At the same time, the obtained results cannot provide information about the sustainability of these processes in the long run or during climatic perturbations. In addition, it remains unclear how the efficiency of restoration changes for different aquatic ecosystems under various conditions of ecosystem disturbance. Therefore, further research should include multi-year monitoring of the studied areas, investigation of the impact of extreme climatic events on restored ecosystems, comparison of restoration practices, and evaluation of socio-economic issues of restoration.

VI. Conclusion

The degradation of aquatic habitats poses a risk to biodiversity, functioning of ecosystems, water quality, and resilience of aquatic ecosystems. This research has tackled this issue by assessing an integrated restoration project of degraded aquatic habitats with the combination of native aquatic vegetation establishment, sediment management, habitat rehabilitation, hydrological connectivity restoration, and nutrient load reduction. The results show that the resilience-focused restoration effort significantly enhanced the ecological condition of the degraded habitats. The increase in the ecological condition index was observed from 42.6 ± 6.8 to 71.8 ± 7.4, and in the resilience index – from 0.43 ± 0.08 to 0.72 ± 0.07. Vegetation cover was raised from 21.4% to 56.8%, and macroinvertebrate richness increased from 24.3 to 38.7 species. Water quality also improved, as dissolved oxygen concentration increased from 4.2 to 6.8 mg/L and turbidity decreased from 28.6 to 13.2 NTU. Generally, there is a recovery of 76.2% of the overall ecological condition, 82.9% for habitat complexity, and 82.4% for dissolved oxygen. The key takeaway is that there is a need for a shift from individual actions to adaptive and resilience-based management. It is suggested to use long-term monitoring and climate-smart restoration approaches to maintain ecological rehabilitation efforts and enhance restoration success.

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