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Habitat Degradation and Restoration in Aquatic Ecosystems: Implications for Fish Populations

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Abstract Aquatic ecosystems provide rich biodiversity and ecological service functions, but also face serious threats of degradation. This study reviews the main habitat types and characteristics of aquatic ecosystems, analyzes the main causes of habitat degradation, such as water conservancy engineering construction, pollution eutrophication, and overfishing, and discusses the impact of habitat degradation on fish population diversity, quantity and life cycle. At the same time, this study reviews a series of aquatic habitat restoration methods such as water conservancy engineering transformation, ecological restoration and ecological management, and discusses the positive role of these recovery measures on the restoration of fish population diversity, resource volume and ecological function. Based on the current research status and future trends, management suggestions such as strengthening comprehensive watershed management, promoting technological innovation and international cooperation were put forward, aiming to provide theoretical support and practical guidance for aquatic ecosystem restoration and fish protection.
Keywords Aquatic ecosystems; Habitat degradation; Ecological restoration; Fish populations; Biodiversity

1 Introduction

Aquatic ecosystems include various water ecological types such as oceans, lakes, rivers, wetlands, etc., and are an important carrier of global biodiversity. Although freshwater bodies account for only 0.8% of the earth's surface, they are home to about 15 000 freshwater fish species (nearly 50% of the global fish species) (Geist and Hawkins, 2016). A large number of studies have shown that the health of aquatic ecosystems is closely related to the survival of fish populations.

In recent years, due to intensified human activities, aquatic habitats have suffered severe damage, and fish populations and diversity are facing a crisis of sharp decline. On the one hand, anthropogenic interference such as pollutant emissions, eutrophication, water conservancy engineering and overfishing has led to a decline in the quality of aquatic habitats, inhibiting the reproduction and growth of fish (Bennett, 2024); on the other hand, the protection and restoration of aquatic habitats are considered to be a key way to maintain and improve the health of fish populations (Theis et al., 2024).

This study aims to systematically sort out the characteristics of different habitat types in aquatic ecosystems, causes of habitat degradation and their impact on fish populations, and review the current commonly used habitat restoration technologies and their positive effects on fish resource recovery. Finally, it proposes future research directions and management suggestions to provide reference for aquatic ecological protection and sustainable use of fish resources.

2 Aquatic Ecosystem Habitat Types and Characteristics

2.1 River ecosystem

River ecosystems (moving water ecosystems) are one of the most active habitats on the earth, and their main features are continuous flow of water, sufficient oxygen, water temperature and water quality are significantly affected by upstream incoming water. The river presents obvious gradients of hydrological, chemical and biological composition from the source to the estuary, forming a rich habitat structure (such as torrents, slow flows, drift belts and beach dam areas, etc.). This complex environmental structure provides fish with diverse living space and food resources (O'Mara et al., 2024). For example, free-flowing natural rivers have nurtured nearly 50% of the world's fish population, and many of them are migratory and require connected habitats in different sections to complete the spawning and foraging processes. River ecosystems usually have strong self-purification capabilities, but are also susceptible to upstream runoff, erosion, and recharge water quality (Wan et al., 2025). Fish often have ecological behaviors of river migration in rivers, and their population structure and distribution are highly sensitive to hydrological changes in the basin and habitat connectivity. Therefore, maintaining the natural flow and connectivity of the river is crucial to maintaining the diversity of river fish.

2.2 Lake and wetland ecosystems

Lake and wetland ecosystems belong to static or semi-static environments, which are characterized by slow water flow, stable vertical structure of water body and large water volume, which are prone to water temperature stratification and nutrient deposition. Lakes are mostly inland water bodies with rich nutrients, with strong occlusion and high ecosystem productivity, but they are also prone to eutrophication and algae blooms. Wetlands (including swamps, estuary swamps, floodplain, etc.) are between land and water, with interlaced ecological characteristics, and are important places for fish reproduction, nurturing and overwintering (Cutler et al., 2024). Lakes and wetlands provide fish with a rich food chain basis (such as phytoplankton and invertebrates) and are key habitats for many freshwater fish. Compared with rivers, lake wetlands often have more complex species communities and ecological corridors, but are also more susceptible to runoff input and internal circulation (Bai et al., 2022). The study found that fish diversity in lakes and wetlands is often restricted by factors such as lake size, connectivity, and nutritional status. For example, large lakes such as Poyang Lake and Dongting Lake in the middle and lower reaches of the Yangtze River in China attract a large number of migratory and settled fish to reproduce every year due to their relatively stable water levels and abundant aquatic plants (Maileht et al., 2024). Protecting lake wetlands requires comprehensive consideration of the overall water quality improvement of lake basins and the restoration of tidal flats and wetland vegetation to support the needs of fish throughout their life cycle.

2.3 Marine and coastal ecosystems

Marine ecosystems include offshore, far sea, coral reefs and mangroves and are the largest aquatic habitat system in the world. Compared with freshwater systems, the ocean has a wider spatial scale and physical environmental heterogeneity, such as constant salinity but drastic temperature changes with latitude, and the current transport of matter (Griffin et al., 2025). Coastal ecosystems such as coral reefs, algae reefs and mangroves provide complex reef structures and juvenile habitats for numerous marine fish, supporting rich species diversity (Ghimayen et al., 2024). Marine habitats are usually relatively productive, with marine fish populations having high mobility and large-scale migration behavior. Due to human development of marine resources, marine ecosystems are also facing threats such as overfishing, marine pollution and climate change. In general, the habitat characteristics of marine ecosystems are vast areas, large depths, and abundant species, but due to marine biology and physics laws (such as light depth and nutrient distribution), fish have clear niche stratification and seasonal distribution laws in different sea areas.

3 Main Causes of Habitat Degradation

3.1 Water conservancy project construction and habitat breaking

Water conservancy projects such as dams, reservoirs, and waterway improvement built by humans have changed the natural hydrological dynamics of the original rivers, causing habitat fragmentation and significant changes in the physical environment. The dam storage has slowed down the river flow rate, a large amount of sediment and nutrients deposited in the upstream reservoir area, and the sand content and nutrient input of the water in the downstream river section have sharply decreased, destroying the basement conditions and floating food chain required for fish to lay eggs (Dudgeon, 2024). After the basin connectivity is cut off, migratory fish have difficulty returning to the spawning area through obstacles, and their life cycle is seriously disrupted. Statistics found that dams and other river channels are important reasons for the sharp decline in the number of migratory freshwater fish (Figure 1). In addition, river channel interception, channelization and flood control dams have destroyed the upstream and downstream connections of rivers and floodplain ecology, suppressed the recovery capacity of flood alluvial plains, and caused many fish that rely on seasonal floods to lose their key habitat (Arthington, 2018). In short, while meeting the needs of water supply, power generation and shipping, water conservancy projects have caused serious physical damage and isolation effects to fish habitats, greatly aggravating the degradation of aquatic habitats.

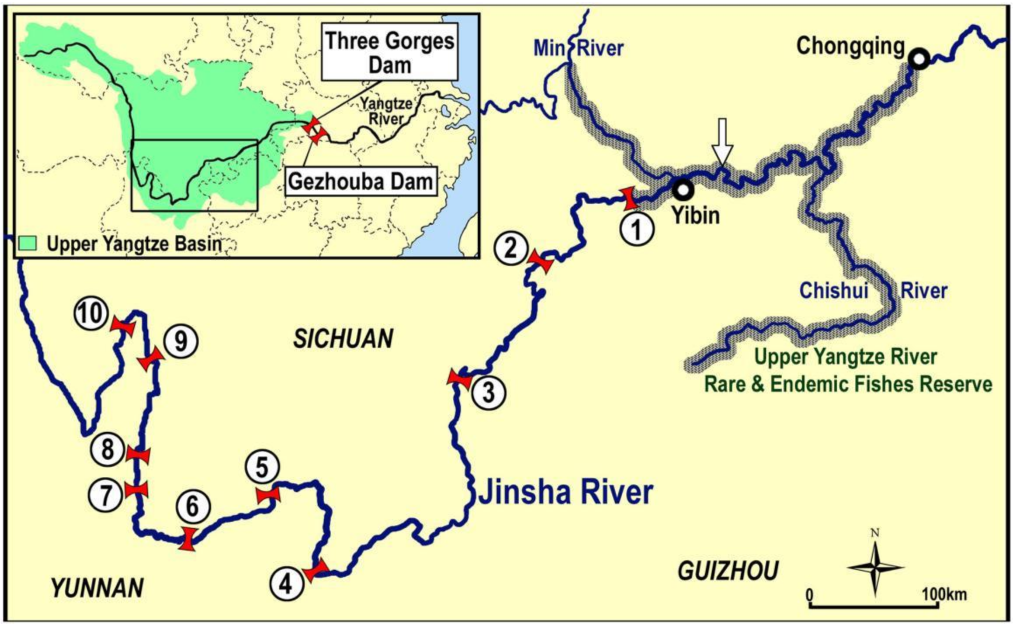

Figure 1 The Jinsha (upper Yangtze) River in China shows the location of 10 dams above the Three Gorges Dam and Gezhouba Dam (Adopted from Dudgeon, 2024)

3.2 Pollutant enrichment and water quality deterioration

Industrial and agricultural pollution is one of the main chemical causes of aquatic habitat degradation. Agricultural non-point source pollutants (fertilizers, pesticides, etc.) and domestic sewage enter the water through runoff, causing eutrophication and harmful algae blooms, consume a large amount of oxygen in the water, and produces bad environment nitrogen and phosphorus enrichment caused by fish death (Kumari, 2022). Industrial pollution (heavy metals, organic pollutants) and urban domestic sewage lead to increased toxicity of water, which can damage the immunity and reproductive system of fish, change the levels of sex hormones, and inhibit fish health even at low concentrations. Pollutants discharged on land have intensified the circulation of nutrients at the bottom of the water body, weakening the stability of the bottom-water habitat. Under the pressure of pollution, the number of aquatic plants and benthic invertebrates has decreased, the food chain structure has been disrupted (Brain and Prosser, 2022), and the resources on which fish rely on are reduced. At the same time, the increase in water temperature and changes in precipitation patterns caused by climate change are also changing the physical and chemical conditions of the water body, exacerbating the negative impact of water quality deterioration.

3.3 Overfishing and other human factors

Overfishing puts indirect pressure on habitat by directly reducing the number of fish individuals. Continuous high-intensity fishing has led to a younger age structure and a smaller size of fish populations, destroying the replenishment and reproduction process of natural populations. According to a report by the World Fish Migration Foundation, overfishing accounts for about one-third of the threat to freshwater migratory fish. In addition, invasive alien species and biological invasions will also compete with local fish for habitat and food, changing ecological balance. Rapid changes in land use (such as urbanization, riparian development, wetland landfill) reduce the available habitat space for fish. Climate change makes water temperature and flow fluctuate more violently, leading to a mismatch of timing of migration and reproduction, further weakening the ability of fish population recovery (Girkar et al., 2017). Habitat degradation is the result of a combination of multiple factors. Human engineering activities, pollution emissions, overuse of resources and climate drive have jointly accelerated the deterioration of fish habitat in aquatic ecosystems.

4 Effects of Habitat Degradation on Fish Populations

4.1 Fish diversity and distribution range decline

Habitat degradation has led to a significant decline in fish species diversity. A large number of studies and monitoring results show that global fish populations have shown a widespread decline due to the long-term deterioration of the aquatic environment (Jan et al., 2023). For example, a global assessment showed that between 1970 and 2020, the population of migratory freshwater fish fell by an average of 81%, and the number of many once prosperous species decreased dramatically or even endangered. River breakage and habitat isolation have reduced the distribution range of many fish species, not only the population has decreased, but also the number of cases of regional extinctions has increased (Grokhovska and Konontsev, 2020). Statistics found that due to dams and other river barriers, more than half of the assessed freshwater fish populations are at risk of extinction within certain geographical ranges, and on average, each species may lose about 3.3% of their habitat range. Degradation also leads to simplification of the food web structure and loss of ecological niches. The original rich fish ecosystem succession often degenerates into simple systems dominated by a few dominant species.

4.2 Reduced fish population and resources

As habitat quality declines, the number of individual fish and overall resource volumes have significantly decreased. A large number of cases show that fish catches and biomass are declining in contaminated or modified water bodies. Habitat deterioration often leads to a decrease in fish survival rate, a decrease in the survival rate of juvenile fish, and difficulty in population renewal. In highly polluted or vegetative waters, the survival environment of fish eggs and juvenile fish is destroyed, weakening the fish's replenishment capacity; the cut-off of rivers blocks the migration route of migratory species, resulting in failed reproduction. The study pointed out that among the multiple cases reported by the World Fish Migration Foundation, river fish populations have dropped dramatically over the past fifty years, with few parent fish left in many basins to breed populations. The decline in fish resources will also affect local fishermen's livelihoods, and fishing catches continue to decline in many areas, further leading to additional human pressure on water resources and the destruction of ecosystem services (Crane et al., 2020).

4.3 Fish behavior and ecological functions are disturbed

Changes in habitat structure interfere with the life history process and ecological behavior of fish. For example, the migration and spawning behavior of fish are highly dependent on river connectivity and specific hydrological conditions. Once the river channel is blocked by the dam, the fish cannot complete the migration back to the spawning area, thus destroying the entire life cycle. In addition, water quality changes can also affect fish migration timing, foraging and social behavior (Napit, 2024); high temperature and low oxygen conditions may force fish to adjust their distribution depth or migrate to areas with better water quality. Habitat degradation also alters the interactions of fish with other species, such as benthic fish in eutrophied lakes that may trigger swamp cycles, aggravate water turbidity, interfere with plant growth, and thus affect other fish species (Einarsson, 2016). Overall, habitat degradation has a comprehensive adverse impact on fish population structure, population dynamics and ecological functions by destroying the habitat conditions and life cycle environment on which fish rely on.

5 Aquatic Habitat Restoration Methods

5.1 Engineering ecological restoration

In response to habitat damage caused by water conservancy projects, engineering ecological restoration methods focus on restoring water connectivity and physical structures, such as demolishing unnecessary dams, building fish paths or cascade aqueducts. Demolition of aging dams can quickly restore river continuity and improve the traffic rate of migratory fish; if completely removing the dam is not feasible, building an eco-friendly fish path is a common alternative method to enable fish to bypass obstacles and continue to migrate. River channel transformation (such as filling channels, restoring bends) can reconstruct a variety of riverbed morphology and water flow environments, increasing fish hiding places and foraging sites (Hayes et al., 2023). In lakes and wetlands, dredging of polluted sediments and rebuilding the bottom terrain is also an important means to restore water cleanliness and benthic biological habitats. Many cases show that the general improvement in fish diversity and abundance of rivers and lakes after engineering intervention is a direct and significant improvement measure (Bennett, 2024).

5.2 Ecological engineering and biological restoration

Ecological engineering restoration focuses on the use of natural processes to restore ecological functions, such as wetland reconstruction, vegetation restoration and artificial reef construction. Restoring wetlands and mangroves can provide fish with natural spawning and childbirth places, while improving water quality through vegetation purification (Whiterod et al., 2021). Artificial reefs (such as dropping trunks, stones or artificial structures) can simulate natural reef environments, provide fish with habitat and food opportunities, and increase local biomass. Researchers also often regulate the food network by combining the control of fish population (such as moderate clearing of nets to reduce the amount of fish at the bottom) and proliferation and release (artificial breeding of fish and release of fish) to restore the ecosystem to a stable state. In recent years, microhabitat restoration technology based on the principles of fish ecology has made progress, such as designing spatial structures according to the needs of fish migration and egg spawning, and optimizing hydrological conditions in combination with flow regulation (Wang, 2025). These ecological restoration methods are often combined with engineering methods to comprehensively improve habitat quality and have a more lasting effect.

5.3 Comprehensive management and legal protection

Scientific and reasonable laws, regulations and management measures are the guarantee for the restoration of aquatic habitats. Many countries have formulated strict fishery fishing bans and water quality standards. For example, China's implementation of a ten-year fishing ban in the Yangtze River Basin has provided a policy-level protection period for the recovery of fishery resources. Through the basin master plan, the water resources management department will limit new pollution emissions, strengthen basin monitoring and cross-regional coordination, and achieve pollution control and ecological restoration from source to end. In addition, the establishment of public education and ecological compensation mechanisms can also improve the protection awareness of the whole society (Zhao et al., 2015). The internationally advocated watershed management concept of "from source to estuary" and measures such as comprehensive water resource management can effectively prevent the negative effects caused by disorderly local repair measures. Comprehensive strategies combining engineering technology, ecological methods and legal management are an effective way to restore aquatic habitats and maintain the health of fish populations.

6 The Positive Impact of Recovery on Fish Populations

6.1 Improvement of fish species diversity and population density

Habitat restoration significantly improves the number and diversity of fish populations. Taking the ten-year fishing ban in the Yangtze River as an example, within only more than four years of fishing ban, the monitoring species of indigenous fish in the Yangtze River Basin increased from 308 before the fishing ban to 344, with 36 new species added. This trend shows that fish populations have strong resilience without overfishing interference (Hardison et al., 2023). Similarly, after the river barrier was removed, the migratory channels of fish along the coast were reopened, and the number of backswimming fish species increased significantly (Figure 2). For example, the WWF reported that after the demolition of old dams in Maine, the United States, the number of local migratory fish sub-adult fish jumped from thousands to millions. In lake wetland restoration projects, wetland area expansion and water quality improvement are often accompanied by rapid rebound in fish populations, indicating that the restoration of benthic food webs and habitat structures provides the basis for fish reproduction (Figure 3) (Mahoney et al., 2021).

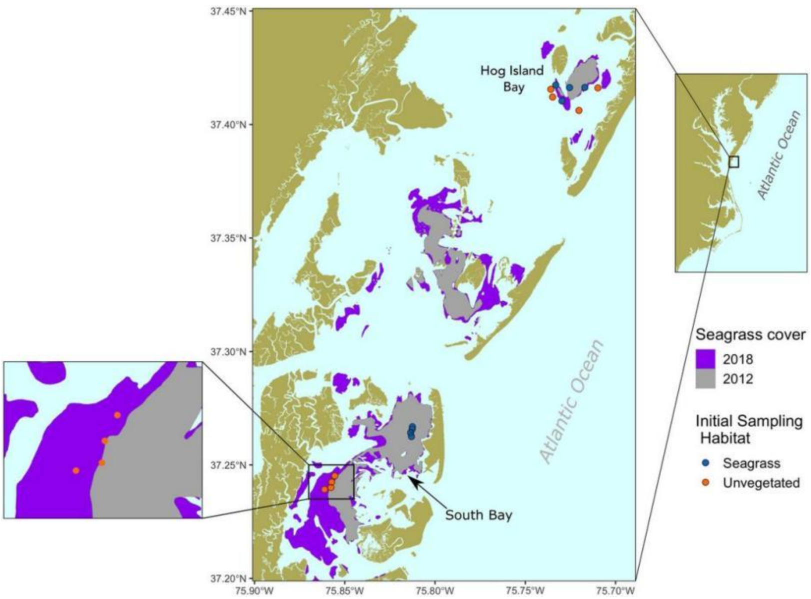

Figure 2 Fish sampling sites in Hog Island and South Bay seagrass meadows in the Virginia Coast Reserve (VCR) along the Atlantic coast of Virginia (USA) (gray, extent of seagrass in 2012; purple, extent of seagrass in 2018; points, sampling sites; colored points, presence [blue] and absence [orange] of seagrass at sampling sites when fish surveys began in 2012). Some sites that were initially unvegetated became vegetated during the study period (e.g., bottom left inset) (Adopted from Hardison et al., 2023)

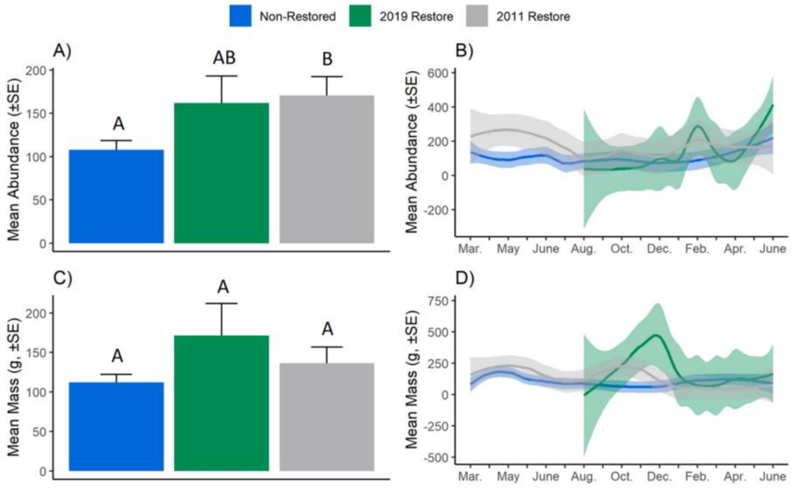

Figure 3 Mean (±standard error) (A) abundance of all fishes and mobile decapods by site type; (B) abundance of all fishes and mobile decapods per sampling event for each treatment type over time (shading = 95% CI); (C) biomass of all fishes and mobile decapods by site type; and (D) biomass of all fishes and mobile decapods per sampling event for each treatment type over time (shading = 95% CI). Letters represent significant differences among treatment types, as determined by Tukey HSD post hoc tests ($p < 0.05$) (Adopted from Mahoney et al., 2021)

6.2 Improvement of biodiversity and ecological functions

With the recovery of fish populations, the overall biodiversity and ecological functions of aquatic ecosystems have also been improved. Healthy fish can restore the multi-level transmission effect of the ecological chain and regulate downstream resources such as algae and invertebrates. During the restoration of important wetlands such as Poyang Lake, the recovery of fish resources has promoted the regression of waterfowl and other biological species, forming an ecological pattern of symbiosis of multiple species. China's Yangtze River Research found that the fishing ban has increased the population of top predators such as the Yangtze River porpoise. The prosperity of this symbolic species means that the basic productivity and food chain of the entire ecosystem are connected. In addition, the recovery of fish has also improved the purification function of river wetland water bodies. Fish feeding behavior can promote the recycling of organic and nutrients, help maintain clear water quality (such as the water quality of Poyang Lake is clear and visible every year). Therefore, habitat restoration and fish restoration have a positive feedback relationship, which jointly enhances the stability and resilience of aquatic ecosystems (Pfirrmann and Seitz, 2019).

6.3 Economic and social and cultural benefits

The restoration of aquatic habitats and fish resources also brings significant economic and social benefits. Fish are not only an important source of protein for residents of many regions, but also the foundation of the fishery economy. According to statistics, at least 2.5 billion people around the world rely on fishing catches in water as their main source of food. Habitat restoration replenishes fishery resources, thereby increasing catches and fishermen's income. For example, after the implementation of fishing ban in the Yangtze River Basin, the number of fishing catches in the lake area increased significantly, and the livelihoods of tens of thousands of fishermen were guaranteed. Healthy fishery resources can also drive the development of tourism and leisure fisheries and inject new vitality into the local economy (Gilby et al., 2019). Culturally, fish have socio-cultural value in many places, and restoring the diversity of fish species will help protect fishery cultural heritage and traditional production methods. In summary, by restoring aquatic habitats, a win-win situation between ecological and economic benefits can be achieved.

7 Future Outlook and Management Suggestions

7.1 Strengthen comprehensive river basin management

In the future, we should strengthen the coordinated management of water resources management and ecological protection based on river basins. It is necessary to establish a cross-departmental and cross-regional collaborative mechanism to promote pollution prevention and ecological restoration from the source to the estuary to avoid secondary problems caused by one-sided governance. Ecological goals for stratified classification should be formulated, such as protecting free-flowing river sections and key wetlands, while taking into account the needs of agricultural water use and urban development. Strengthen hydrological and biological monitoring to provide data support for scientific assessment of ecological changes (Jia et al., 2023). International experience shows that protecting free-flowing rivers, restoring key habitats, and strictly controlling water quality are key measures to restore the diversity of freshwater fish. Therefore, China should also accelerate the improvement of the legal and regulatory system, promote the construction of water ecological civilization, and achieve coordination and unity between economic development and ecological protection.

7.2 Promote the application of scientific and technological innovation and ecological restoration technology

Innovative technologies play an important role in water ecological protection and fish restoration. It is recommended to promote environmental DNA (eDNA) monitoring technology and satellite remote sensing technology to improve the monitoring efficiency of aquatic biodiversity and habitat status, and provide a basis for the evaluation of restoration effect. At the same time, the research and development of ecological restoration methods should be strengthened, such as fish path optimization design, artificial wetland reconstruction, and in-situ pollutant removal. In the future, simulation research should be carried out to predict the impact of repair measures on hydrological conditions and fish, and to scientifically guide specific projects. Actively introduce natural-based solutions (NbS), such as ecological corridors and shore vegetation belt restoration, to better integrate engineering construction with ecological effects (Wang et al., 2019). Strengthening monitoring and early warning, resource management and restoration implementation through scientific and technological innovation will improve the effectiveness and sustainability of aquatic ecological protection.

7.3 Enhance international cooperation and public participation

Aquatic habitat conservation and fish population recovery are global challenges that require international cooperation and public participation. Exchanges with neighboring countries in joint management of water resources and biodiversity protection should be strengthened, international experience should be learned from, and cross-border river and marine ecological governance capabilities should be improved. Increase publicity and education efforts, improve the public's awareness of the importance of water ecological protection, and guide social forces to participate in wetland protection, river dredging and artificial reef construction. It is encouraged to formulate an ecological compensation mechanism to allow protection behavior to receive corresponding economic support, thereby improving the feasibility of ecological protection. In addition, we should combine the background of climate change to promote the formation of long-term ecological restoration plans to ensure the sustainability of fish resource recovery on a larger spatial and temporal scale.

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Conflict of Interest Disclosure
The authors confirm that the study was conducted without any commercial or financial relationships and could be interpreted as a potential conflict of interest.

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