

REVIEW

Harnessing Nature's Power: Effective Strategies for Water Ecosystem Recovery and Management

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ABSTRACT

Water ecosystems play an essential role in supporting biodiversity, climate control, and water quality. These ecosystems, however, are under serious degradation by pollution, destruction of their habitats, climate change, and over-extraction. This paper focuses on the most efficient methods of recovery and management of water ecosystems, the advantages of which are the combination of nature-based solutions (NbS) and technological advances. Nature-based projects like wetland restoration, rehabilitation of riparian zones, and reforestation provide cost-effective and sustainable ways of enhancing the health and resilience of the ecosystem. Such strategies not only improve the quality of water and biodiversity, but also reduce the effects of climate change. Additional technological means, such as hydrological and ecological models, technologies of water habitat restoration, and improved water management methods, are used to complement and streamline the process of recovery. Using international case studies in areas like the Kissimmee River (USA), the Loess Plateau (China), and the Thames River (UK), the article shows how successful and difficult it is to use these strategies in different situations. The conclusions demonstrate that an interdisciplinary solution based on a mixture of ecological restoration and technological innovation, as well as interagency governance, is both necessary. With this escalating pressure on water ecosystems, these strategies are a pathway to recovering and long-term sustainability of ecosystems, which will be part of ecological resilience as well as socio-economic resilience.

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ARTICLE INFO

Received: 18 March 2026 | Revised: 21 May 2026 | Accepted: 26 May 2026 | Published Online: 14 July 2026

DOI: <https://doi.org/10.30564/jees.v8i7.13368>

CITATION

Chen, H., Huang, H., Zhong, Y., et al., 2026. Harnessing Nature's Power: Effective Strategies for Water Ecosystem Recovery and Management. *Journal of Environmental & Earth Sciences*. 8(7): 140–159. DOI: <https://doi.org/10.30564/jees.v8i7.13368>

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Keywords: Water Ecosystems; Nature-Based Solutions; Ecosystem Restoration; Technological Innovations; Water Management

1. Introduction

The water ecosystem is important to keep life on Earth. They can offer services that are vital, like fresh water that is used to drink, farm, and to industrialize; they offer a habitat to various species; they control climate conditions and patterns of flooding^[1–3]. Human activities are threatening water ecosystems more than ever before, regardless of their importance of the same. These systems have been greatly degraded by high urbanization, industrialization, agricultural activities, and climate change^[4]. There are various pressures on freshwater bodies such as rivers, lakes, and wetlands, and the marine ecosystem, which include pollution, habitat loss, over-extraction, invasive species, and the disruptive impacts of climate change^[5,6]. This has led to the degradation of biodiversity, ecosystem services, and negative consequences for human health and livelihoods. With the world's water resources straining to the point of breaking, ecosystem recovery and management strategies are more in demand than ever.

Conventionally, the engineering solutions and the top-down management approaches have been used to restore and manage the water ecosystems^[7]. They may include the building of dams, reservoirs, or water treatment plants, mainly aimed at satisfying human requirements in terms of water supply, flood management, and the reduction of pollution^[8]. Although these solutions have been partially successful in controlling water resources, they have failed many times to consider the intertwined and complex nature of ecosystems. Excessive use of technological solutions without the art and science of understanding the complex interplay of the biological, physical, and chemical processes in water systems has often resulted in unsatisfactory consequences, such as the degradation of the ecosystems, biodiversity loss, and even the intensification of water-related issues in certain situations^[9].

Over the past few years, a growing acknowledgment has been made of the fact that nature, per se, can provide rather effective and sustainable solutions to the recovery and management of water ecosystems. Nature-based solutions

(NbS) exploit the natural potential of natural systems to provide people with well-being benefits and enhance the health and integrity of ecosystems. It is a novel strategy that aims at utilizing the ecological mechanisms, rehabilitating natural ecosystems, and preserving or increasing biodiversity to obtain the desired results in managing water. Replicating or reinstating the natural operation of ecosystems, NbS can deliver a range of advantages, which are water quality enhancement, biodiversity enhancement, minimization of flood risks, and encouragement of carbon sequestration, all coupled with long-term sustainability. In contrast to the old-fashioned engineered methods, NbS emphasizes the processes in the ecosystem rather than interventions and provides a more comprehensive, economically sustainable, and environmentally friendly solution to water resources management^[10,11].

The article under review is innovative in the sense that it brings together the latest and innovative ideas of water ecosystem restoration with an emphasis on utilizing the power of nature^[12]. This review advances beyond existing literature in three specific ways. First, while previous reviews have examined acid mine drainage, tailings stability, or revegetation as discrete problems, we explicitly frame abandoned mines as coupled socio-ecological-geological systems where landform instability, contaminant flux, ecological succession, and governance capacity interact as feedback-driven processes. Second, unlike closure-focused syntheses that treat institutional factors as external implementation issues, we integrate governance continuity, monitoring durability, and stewardship finance as inherent performance variables that co-determine long-term outcomes. Third, we directly confront the timescale mismatch that most reviews overlook: engineered interventions operate over decades, whereas geochemical weathering, groundwater rebound, and ecological succession operate over centuries. By synthesizing these cross-disciplinary interactions, this review provides a novel systems-based framework for long-term stewardship that is neither purely technical nor purely ecological, but explicitly hybrid and adaptive.

In addition, the review is interdisciplinary and is based on ecology, hydrology, policy, and technology to provide

more of an integrated approach to the management of water. Through the analysis of diverse innovative solutions, including wetland restoration, riparian buffer zones, reforestation, and the introduction of new technologies, including ecological modeling and remote sensing, we will be able to underline the enormous opportunities of the synthesis of natural processes and human ingenuity^[13]. Another aspect focused on in the review is the significance of case studies and success stories, which not only provide a perspective on how these strategies can be put into practice but also have a lot of lessons to impart on how to overcome the challenges and scale solutions^[14].

The freshness of this article is also in the emphasis of the perspective of the transformative change that can be achieved through ecosystem-based approaches in the context of increasing uncertainties about the environment. As the effects of global warming continue to increase speedily, water ecosystems are exposed to increased droughts, floods, and other extreme weather events^[15]. This offers a rare chance to policymakers, scientists, and practitioners to reconsider prevalent management paradigms and transition away to more resilient and adaptive systems. By mentioning the strength of nature and presenting the successful methods of recovery and management, this review will urge future studies and will shape decisions in the most important field of water ecosystem sustainability^[16].

To conclude, the article is a timely and comprehensive review of the best strategies that can be used to recover and manage water ecosystems. It underlines the worth of solutions based on nature, the combination of innovative technologies, and the global case study lessons^[17]. Contributing to the growing body of knowledge required in addressing the complex challenges of water resource management in an age of environmental change, this review adds to the existing knowledge on how nature can be used to rehabilitate water ecosystems.

This review followed a systematic literature search using Web of Science, Scopus, and Google Scholar (2000–2025). The search string combined: (“abandoned mine” OR “orphan mine” OR “legacy mine*”) AND (“long-term stewardship” OR “post-closure” OR “adaptive management” OR “acid mine drainage” OR “ecological restoration” OR “mine closure”). Inclusion criteria required: (1) focus on abandoned/orphaned (not active) mines, (2) temporal per-

spective ≥ 10 years post-closure, (3) relevance to coupled physical-chemical-biological-social processes. Exclusion criteria removed: active mine operations, single-event acute disasters without legacy context, and purely engineering designs without environmental or temporal dimensions. From 847 initially identified records, 148 sources were selected after title/abstract screening ($n = 847 \rightarrow 312$), full-text eligibility assessment ($n = 312 \rightarrow 178$), and quality evaluation based on methodological rigor and contribution to systems-based frameworks ($n = 178 \rightarrow 148$). Gray literature from international mine closure conferences (2006–2025) and citation chaining added 23 additional sources. No language restrictions applied, though non-English sources with available translations were included only if they provided unique regional case data.

2. Understanding Water Ecosystem Degradation

Water systems, including rivers, lakes, wetlands, and coastal areas, are complex systems that accommodate numerous ecological, hydrological, and socio-economic processes^[18]. Such systems are important sources of the ecosystem, such as water filtration, biodiversity preservation, control of floods, and climate regulation. Nevertheless, the watersheds in the world are experiencing unprecedented rates of degradation, which is largely caused by human actions. This part will explore the major contributors to the degradation of water ecosystems, the reasons, effects, and outcomes of the deterioration of these important ecosystems.

2.1. Drivers of Water Ecosystem Degradation

The decline of the water ecosystems can be said to be due to an elaborate span of anthropogenic causes that disrupt the already fragile balance of the water ecosystems. They are pollution, habitat destruction, excessive use of water resources, and the introduction of invasive species^[19]. The drivers all work together to intensify the process of degradation and make it a vicious cycle that jeopardizes the health and sustainability of water ecosystems. The information contained in **Table 1** gives a broad perspective of the key causes of the decline of water ecosystems and their effects, which will serve as background to the next strategies for restor-

ing the ecosystem. **Figure 1** below depicts the sequence of ecosystem degradation by showing the effect of various drivers on water ecosystem deterioration; drivers include pollution, habitat destruction, and over-extraction.

Table 1. Drivers of Water Ecosystem Degradation and Their Impacts.

Driver	Description	Impacts on Ecosystem
Pollution	Contamination from industrial discharge, agricultural runoff, and untreated sewage	Eutrophication, decreased water quality, loss of biodiversity, habitat destruction
Habitat Destruction	Urbanization, land reclamation, dam construction	Loss of natural habitat, reduced species diversity, altered hydrological processes
Over-extraction	Excessive withdrawal of water for agricultural, industrial, and domestic use	Disruption of water flow, drying of ecosystems, decreased biodiversity
Invasive Species	Introduction of non-native species through trade, travel, and human activities	Outcompeting native species, altering food webs, spreading disease
Climate Change	Changes in temperature, precipitation patterns, and extreme weather events	Altered hydrological cycles, increased water scarcity, flooding, ecosystem instability

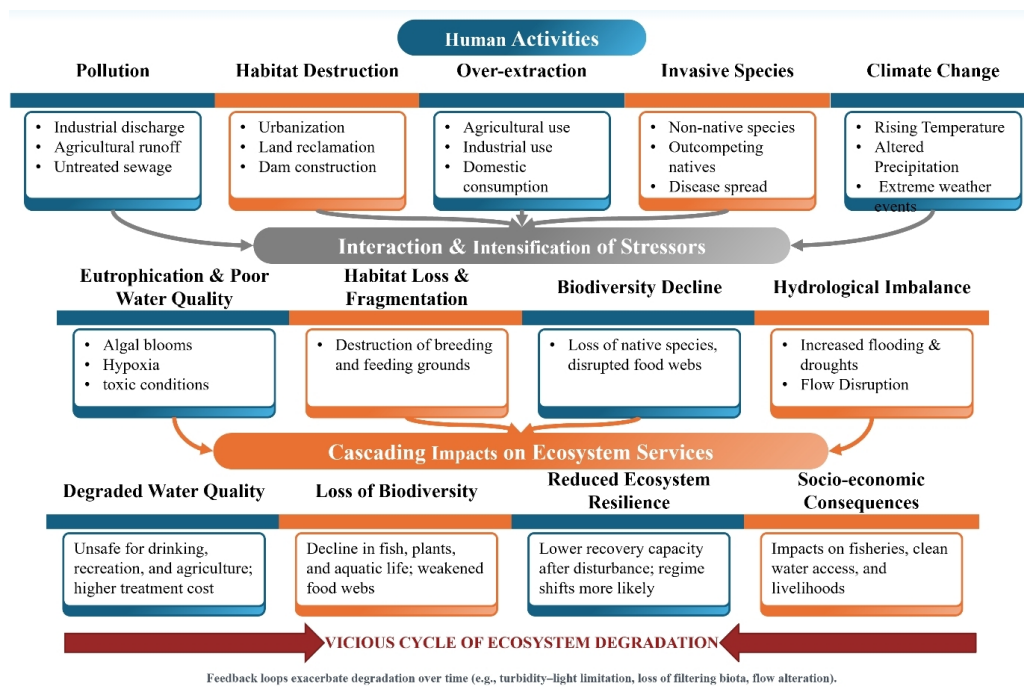


Figure 1. Schematic illustrating the process of water ecosystem degradation and its cascading impacts on ecosystem services.

Pollution, whether point or non-point sources, is one of the biggest sources of water ecosystem degradation. Industrial effluents, agricultural effluents, and untreated sewage have also deposited extensive amounts of contaminants (including nutrients (e.g., nitrogen and phosphorus), heavy metals, pesticides, pharmaceuticals, etc.) into water bodies^[20]. Nutrient pollution is also known as eutrophication, which results in excessive growth of algae that lowers oxygen content in the water and forms dead zones where a majority of aquatic organisms cannot survive^[21]. The mass pollution of freshwater and marine environments not only destabilizes the natural nutrient cycles but also makes water management more difficult.

Besides pollution, human actions that cause a transformation of the natural habitats are a major threat to water ecosystems^[22]. The process of urbanization, agriculture, and the development of infrastructure has led to the destruction and fragmentation of important habitats, including wetlands, riparian zones, and floodplains. Wetlands are the most at risk, especially due to drainage and the conversion of land to other uses that are involved in water purification, flood management and carbon sequestration. River meandering and urban run-off on the river banks and coastlines, with deforestation and urban sprawl, increase erosion and sedimentation, hence causing deterioration of water quality and habitat loss of aquatic organisms.

The degradation of the ecosystems is also due to over-exploitation of water resources to carry out human activities especially in areas that experience water shortages. Overuse of water for irrigation, industrial, and urban water decreases the natural flow of the rivers, lakes and wetlands leading to disturbances in the ecosystems and their normal functioning^[23]. Hydroelectric power generation or irrigation through damming of rivers and diversion of water further changes the natural flow regimes with negative effects on aquatic species that use seasonal or unobstructed water flow to move, spawn, and feed^[24].

Lastly, invasive species have contributed to the deterioration of water ecosystems to a great extent^[25]. Human activities, especially global trade, have brought with them the introduction of non-native species, which in turn causes the shift in native species as well as the changes in the food webs. The invasive species may outcompete the native species by consuming resources, interfering with the ecological processes, and introduce new diseases to the already fragile ecosystem. Poor water quality and hydrological changes normally contribute to the spread of invasive species, which in turn leads to a feedback mechanism that promotes the degradation process of the ecosystem.

2.2. Impacts on Ecosystem Services

The deterioration of the water ecosystem has a far-reaching and significant impact on both the environment and society^[26]. Effects of poor water ecosystems do not just limit themselves to the loss of biodiversity, but in addition to this, they also lead to erosion of basic ecosystem services that are indispensable to humans. These services encompass purification of water, flood control, carbon sequestration, and the provision of food and livelihood.

Water purification is one of the most important ecosystem services that water ecosystems offer^[27]. Wetlands, the riparian and floodplains are the natural filters that make use of physical, chemical, and biological processes to remove pollutants in water. These ecosystems entrap sediments, assimilate nutrients and decompose organic contaminants and hence enhancing the quality of water. Nevertheless, the destruction or degradation of these ecosystems reduces their capacity to filter pollutants, and this causes a decline in the quality of water. Subsequently, this may lead to higher costs

of water treatment, reduced access to potable water, and more health hazards to the population living on such water sources.

Another important service of healthy water ecosystems is flood regulation, especially wetlands and floodplains^[28]. These ecosystems serve as natural cushions absorbing the surplus water during the many rainy seasons and slowly releasing it over time. This lowers the chances of downstream flooding and it minimizes the effects of storm surge. This has however been augmented by the destruction of wetlands and floodplains coupled with urbanization of flood prone areas which has further exacerbated the occurrence and intensity of floods in most areas. This not only causes the loss of life and property, but also derails the local economies and increases the vulnerability of communities residing in flood-prone areas.

Water ecosystems are also impacted negatively, which also has important implications for biodiversity^[29]. The freshwater ecosystems constitute a very tiny portion of the surface of the earth, but harbor a disproportionate portion of biodiversity on the globe. The result of this destruction of these ecosystems, together with pollution, loss of habitat, and the spread of invasive species, has caused many aquatic species to be on the decline, including fish, amphibians, and invertebrates. This degradation of biodiversity impairs the sustainability of the ecosystems and diminishes their capacity to offer important services to the environment, like food and carbon sequestration. Any cause of the decline in fish stocks, such as the loss of fish, has dire effects on global food security, especially in parts of the world that depend on fish as a main source of food.

In addition to that, the deterioration of water ecosystems impacts human livelihoods, especially communities that rely on the ecosystems to carry out agricultural, fishing, tourist, and other economic activities^[30]. The communities located along the coastlines and freshwater habitats are especially susceptible to ecosystem services loss, because their survival directly depends on the well-being of the waters in which they are located. Societies in most regions of the globe that primarily depend on fishing as a source of their food and livelihood are experiencing reduced harvests due to over-fishing, pollution, and the destruction of habitats. This has contributed to poverty, food shortages, and social instability in certain areas.

2.3. Socio-Economic Consequences

Besides the environmental effects, water ecosystem degradation has major socio-economic implications as well. Poorer communities and those that are already marginalized tend to be the worst hit by these effects, as water is already a limited commodity in these areas. With the degradation of the water ecosystem, clean water and other important resources become scarce, causing more people to compete over resources, leading to political instability and social conflicts^[31].

Among the obvious socio-economic effects of the degradation of water ecosystems, it is possible to note the rise in the cost of water purification^[32]. With the degradation of water quality as a result of pollution and depletion of natural filtration services, governments and municipalities must incur increased expenses in water treatment systems. This may be especially cumbersome in low-income neighborhoods, where money is already tight, and access to clean water is already a challenge. In others, water degradation has caused water crises and has enhanced the struggle to access water, especially in areas where water is a luxury.

The other important socio-economic effect is the agricultural effect^[33]. The loss of wetlands and floodplains and excessive extraction of water to irrigate the land have led to soil erosion and depletion of fresh water in most agricultural areas. Where irrigation is widely used to support crop production, depletion of water resources can lead to low agricultural output, low food security, and higher poverty. Particularly so in the regions already experiencing the effects of climate change, where droughts and erratic weather conditions contribute to scarce water supplies.

The natural beauty and biodiversity of water ecosystems can easily be degraded, threatening the tourism industry, which, in many instances, depends on these ecosystems^[34]. Coral reefs, wetlands, and other water habitats damaged may result in loss of tourism revenue, especially in areas where ecotourism forms a major sector of the economy. Decreased biodiversity and decreased water quality may lead to a decrease in the number of visitors, which subsequently impacts

local businesses and communities reliant on tourism.

Water ecosystem degradation is a complex phenomenon with ecological, socio-economic, and cultural impacts that extend deep and far. The major causes of this degradation are pollution, destruction of habitats, over-extraction, and invasion of species, all of which have added complexity to the plight of water ecosystems around the world^[19]. Ecosystem degradation is not solely ecological but also substantially socio-economic, influencing access to clean water and food security, as well as livelihoods, especially in susceptible communities. The solution to these challenges would be a multi-faceted, multi-dimensional approach to water management that involves both technology and nature-based solutions. With an idea of the main causes of water ecosystem degradation and the far-reaching effects, we could better contextualize approaches to ecosystem recovery and management that would restore balance to these indispensable systems.

3. Nature-Based Solutions for Water Ecosystem Recovery

With the degradation of water ecosystems increasingly visible, there has been an increasing acknowledgement of the desirability of sustainable and resilient methods of their restoration and management. Conventional engineering remedies, although effective in some situations, are not always successful in overhauling the causes of ecosystem degradation, and they can have unforeseen outcomes. On the contrary, nature-based solutions use the energy of natural processes to heal and better the condition of water ecosystems through environmental and socio-economic advantages^[35]. The following section will discuss the different nature-based approaches to the recovery of water ecosystems, specifically the wetlands, riparian zones, and reforestation. Various approaches to ecosystem recovery are described, including the advantages and difficulties concerning each, to help the readers grasp the peculiarities of NbS. **Table 2** compares them.

Table 2. Comparison of Nature-Based Solutions for Water Ecosystem Recovery.

Solution	Ecosystem Functions	Restoration Techniques	Benefits	Challenges
Wetland Restoration	Water filtration, flood regulation, biodiversity support	Reintroduce natural hydrology, remove invasive species, replant native vegetation	Improved water quality, enhanced biodiversity, flood mitigation	Requires large-scale effort, ongoing pollution

Table 2. Cont.

Solution	Ecosystem Functions	Restoration Techniques	Benefits	Challenges
Riparian Zone Restoration	Erosion control, water purification, habitat provision	Replant native trees, shrubs, grasses, and stabilize riverbanks	Enhanced ecosystem services, improved habitat connectivity	Land-use conflicts, maintenance challenges
Reforestation in Watersheds	Soil stabilization, water retention, carbon sequestration	Plant native trees, prevent deforestation, restore riparian buffers	Reduced erosion, improved water flow regulation, enhanced biodiversity	Land availability, climate change impacts
Mangrove Restoration	Coastal protection, carbon sequestration, biodiversity support	Replant mangrove species, restore tidal flow, protect coastal zones	Erosion control, fish habitat restoration, carbon storage	Vulnerability to rising sea levels, human encroachment

3.1. Restoration of Wetlands and Riparian Zones

Wetlands and riparian zones are very important in ensuring the well-being of the water ecosystems because they carry out very essential duties such as purifying water, controlling floods, and sustaining biodiversity^[36]. A conceptual framework on how various solutions based on nature work in water ecosystems as part of recovery and resilience is pre-

sented in **Figure 2**. Wetlands, marshes, swamps, and bogs are natural buffers that remove pollutants in water, contain sediments, and absorb surplus nutrients. They also support the habitat of a large number of aquatic and terrestrial species such as migratory birds, amphibians, and fish. The riparian areas or the lands on both sides of the rivers and streams, are also vital in controlling the water quality, erosion, and stabilization of water flow as well.

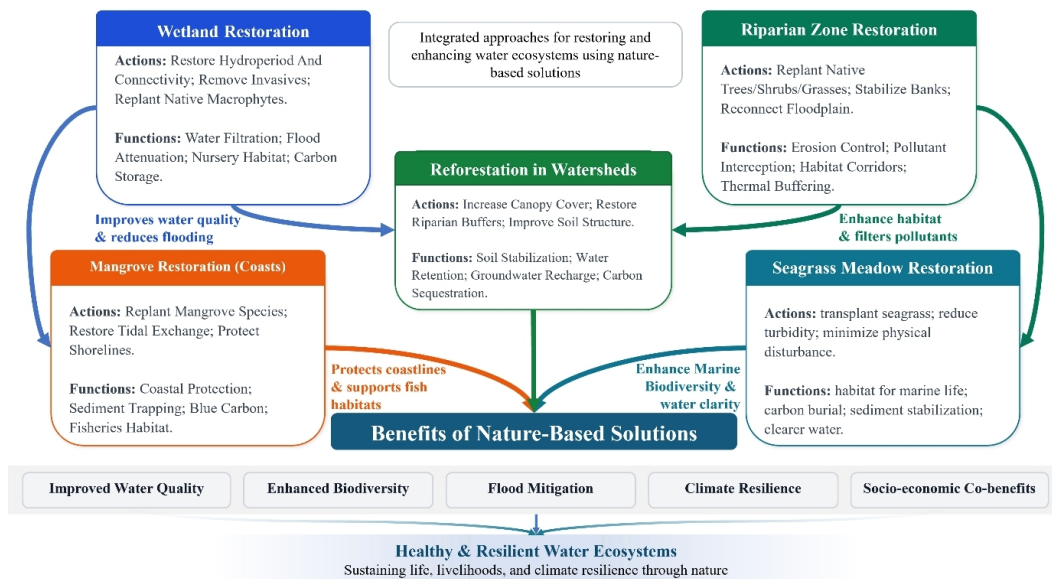


Figure 2. Conceptual framework illustrating the role of different nature-based solutions in water ecosystem recovery and the benefits they provide.

One of the elements of nature-based approaches to water ecosystem recovery is the restoration of the degraded wetlands and riparian areas. The restoration of wetlands entails reinstating the hydrological systems of wetlands by re-establishing natural water flow over them, reintroducing native vegetation, and re-establishing the connection between wetlands and their neighboring ecosystems^[37]. This is usually achieved through the removal of invasive species, natural plant reintroductions, and reestablishment of natural

hydrological regimes. As an illustration, in regions where wetlands have been drained due to agricultural or urban development, the reinstatement of hydrological relationships and re-planting of native vegetation could go a long way to enhance the ecosystem capacity to filter water, flood control, and biodiversity.

On the same note, riparian zone restoration will assist in reducing the degradation of water quality, avoiding soil erosion, and increasing biodiversity^[38]. Riparian restoration

contributes to stabilizing soils, decreasing sedimentation, and purifying runoff by replenishing native trees, shrubs, and grasses on the banks of rivers. Reconnecting the habitats would also be enhanced by restoring these regions, enabling the species to be more mobile in the terrestrial and aquatic habitats. Riparian restoration has even been known to be able to undo erosion effects and also enhance water quality by decreasing the quantity of nutrient-rich runoff into water bodies.

Recovery of wetlands and riparian areas has been found to offer great environmental and human benefits. As an example, wetlands are natural sponges that capture surplus nutrients and pollution in agricultural run-offs to prevent expensive water purification systems^[39]. They are also important in carbon sequestration, which is useful in reducing climate change. Moreover, riparian zone restoration has the ability to augment ecosystem services, including flood control, water mitigation, and habitat, to make water ecosystems more resilient to future disruptions.

3.2. Reforestation and Natural Vegetation for Watershed Management

Natural vegetation and forests are critical in ensuring the stability and health of the water ecosystem^[40]. Specifically, forests in watersheds are part of the water quality, water flow, and sedimentation regulation. Forests are used as natural filters where they trap sediments, control nutrient cycling, and contribute to the hydrological integrity of river systems. Deforestation and land-use change, on the other hand, have contributed to the degradation of numerous watersheds, which has resulted in soil erosion, sedimentation, and water quality degradation.

One of the nature-based solutions to the restoration of the ecosystems of watersheds is known as reforestation, which is the process of planting trees in the regions that have been either deforested or degraded^[41]. Reforestation will stabilize the soils, minimize runoffs, and prevent erosion because it has a canopy cover that slows the flow of water in the landscape. The roots of trees and plants aid in the formation of soil particles that are held together by the roots, hence the soil and sedimentation do not erode into the rivers and lakes that are close to the trees and plants. Moreover, the recovery of riparian forests on river and stream banks provides useful habitat for both aquatic and terrestrial species, and increases

biodiversity and connectivity among ecosystems.

Reforestation is also important in water control and the quality of the water. Through recovering the forest cover, the natural mechanisms of water infiltration, groundwater recharge, as well as water evapotranspiration, are reinstated and result in a more stable water flow regime^[42]. This will aid in mitigating the occurrence as well as intensity of floods and droughts since forests provide natural buffers that can store water during the seasons of heavy rainfall and release it slowly during dry periods. In addition, reforestation may enhance the removal of pollutants by agricultural runoff that may lead to increased levels of nutrients, pesticides, and other pollutants getting into the water bodies.

Besides reforestation, natural vegetation in watersheds can be restored to increase the ability of water ecosystems to withstand climate change^[43]. With the rising rate of climate change leading to more extreme weather occurrences like floods, drought, etc., already degraded ecosystems tend to be less adaptable to such changes. Through the re-establishment of natural vegetation like grasslands, wetlands, and forests, the resilience of water ecosystems can be strengthened to help mitigate the effects of climate change and safeguard the vital water resources.

3.3. Mangrove and Seagrass Restoration in Coastal Ecosystems

Mangroves, seagrasses, and salt marshes are also important ecosystems that reduce shoreline erosion, improve water quality, and increase biodiversity in the coastal areas^[43,44]. Mangroves are natural barriers that occur in tropical and subtropical coastal regions and help to decrease erosion of the coast, absorb storm surge, and provide a home to many marine species. The seagrasses that grow in the coastal waters also serve an important role, stabilizing the sediments, filtering water, and providing food and shelter to the marine organisms.

The recovery of mangrove forests and seagrass beds is an effective nature-based intervention to safeguard the coastal waters^[45]. Mangrove restoration is usually done by planting mangrove seedlings in places that have had their mangrove ecosystems degraded or destroyed by development along the coastline, aquaculture, or agriculture. Mangrove rehabilitation has been known to greatly minimize the erosion of the coastline, safeguard the coastal people against storm

surges, and furnish valuable breeding and feeding grounds to fish and other sea creatures. Moreover, mangroves are excellent carbon captures, thus they can be applied to reduce climate change effects.

On the same note, restoration of seagrass can offer a lot of advantages to the coastal ecosystems. Seagrasses are quite effective at holding the sediments, deterring erosion, and improving the water clarity by filtering off suspended substances^[46]. Restoring seagrass beds means planting seagrass species in degraded or lost areas, in many cases with the involvement of local communities and stakeholders. Seagrass recovery is not only useful in improving the water quality and stabilizing coastal sediments, but also in improving biodiversity since it offers homes to young fish, shellfish, and other marine life.

The recovery of the mangroves and seagrasses is especially relevant in the context of the rising sea levels and the intensification of storms due to climate change. They act as a natural buffer to the coastal floods and offer essential habitat to the organisms that are essential in marine and human food webs^[47]. Through investing in restoring mangroves and seagrasses, coastal communities are able to make their communities more resilient to climate change and also experience the environmental, economic, and social benefits of these useful ecosystems.

3.4. Challenges and Limitations of Nature-Based Solutions

Nature-based solutions are indeed beneficial to the recovery of the water ecosystem, but they have their flaws and drawbacks. The large-scale implementation and long-term commitment are one of the most crucial challenges^[48]. The restoration projects are time-consuming projects that are financially and manpower consuming, and the success of such projects may take years or even decades to be realized fully. Moreover, the success of NbS may be affected by numerous factors, among which are the extent of the restoration process, the surroundings, and the existence of other sources of stress, such as pollution or invasive species.

The other weakness of NbS is that it is difficult to control and promote the recovery of water ecosystems. The process of ecosystem restoration is usually non-static and unpredictable, and the results can be conditioned by some interacting factors. As an illustration, the use of restoration

work in a given area would be compromised by perpetual pollution or climate-change effects in the host area. Thus, NbS should be incorporated into the framework of other management strategies to ensure long-term success of water ecosystem restoration, including pollution control, sustainable land use, and adaptive governance^[49].

Green systems, nature-based solutions, are a promising and sustainable way of recovery and management of water ecosystems. Recovering wetlands, riparian areas, forests and mangroves, and seagrasses will help us increase the resiliency of water bodies, water quality, and alleviate climate change effects^[50]. Nevertheless, implementation of NbS is a complex undertaking that needs proper planning, commitments in the long-term, and a combination of these solutions with the overall water management plans. The nature-based approaches, despite the challenges, are considered to possess potential benefits, including, but not limited to, biodiversity rebuilding, flood alleviation, and carbon sequestration, which makes them an important part of global efforts to safeguard the water ecosystems and restore them.

4. Technological and Innovative Approaches for Ecosystem Management

Although nature-based solutions have demonstrated great potential in the restoration and management of water ecosystems, the growing demand of climate change, urbanization, and industrialization is compelling the need to add to technology and innovative solutions. These approaches are supplementary to the conventional ecological restoration activities and also provide innovative approaches to enhancing the performance, scale, and flexibility of the water ecosystem management methods^[51]. The paper discusses how the new technologies, such as hydrological and ecological modeling, habitat rehabilitation technologies, and sustainable water management practices, can be used to complement the recovery of the ecosystem and long-term sustainability.

4.1. Hydrological and Ecological Modeling for Predictive Management

Hydrological and ecological models are potent tools that offer knowledge on how a water ecosystem operates

and functions. The models enable scientists and managers to model the behavior of the aquatic system in various environmental conditions and management situations^[52]. Through data-driven methods, hydrological and ecological models are able to forecast the reaction of ecosystems to alterations in land use, water quality, climate, and restoration interventions, thereby facilitating improved decision-making in water resource management.

The hydrological models model the flow, distribution, and quality of water in a watershed. Such models are used in predicting streamflow, groundwater recharge, flood risks, and water availability, which are important in water management^[53]. They come in handy mostly in areas where water shortage, pollution, or flooding are common. Hydrological models can also be used to determine the susceptible areas and to make policies to reduce the effects of water stress or water over-exploitation by simulating various scenarios, e.g., changing land cover, human activities, or rainfall patterns.

The ecological models, in their turn, pay attention to the interactions between biotic and non-biotic elements of the ecosystem^[54]. These models enable the researcher to model the impacts of various management strategies, including habitat restoration, species reintroduction, or control of pollution, on the ecosystem. Ecological models are useful in predicting the results of restoration activities that can be used in designing interventions that ensure maximum biodiversity and ecosystem functionality. Indicatively, it is possible to

forecast the impact that alterations in the condition of water quality or flow regimes will have on aquatic species by using it to determine key thresholds that could result in irreparable ecosystem collapse.

Hydrological and ecological models, when combined, can offer a more comprehensive view of the outcome of water ecosystems with respect to many environmental and management stressors^[55]. This predictive ability is essential in responding to the uncertainty of climate change, whereby ecosystems are deemed to experience variable water supply, extreme temperatures, and altered patterns of precipitation. Through modeling tools added to the ecosystem management, the decision-makers are able to come up with more specific, active, and flexible techniques that improve the resilience of water ecosystems.

4.2. Aquatic Habitat Restoration Technologies

Besides the more traditional ecological restoration techniques, a spectrum of new technologies has become accessible to help restore aquatic habitats in a more efficient and effective manner. The technologies include bioengineering options, including artificial reefs and artificial wetlands, and high technology approaches to soil and sediment stabilization and fish habitat development^[56]. The role that technology can play in managing water ecosystems, whether in monitoring or restoration activities, is visually illustrated in **Figure 3**.

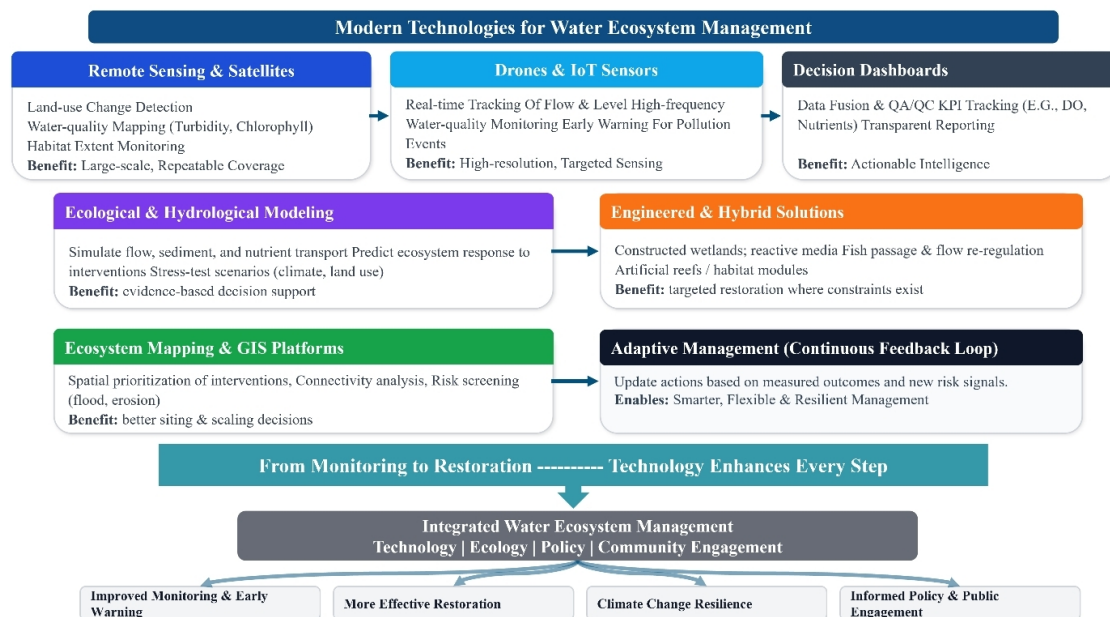


Figure 3. Diagram showing the role of various technological tools in enhancing water ecosystem management and restoration.

Artificial reefs may be considered one of the most famous applications of the technology of aquatic habitats restoration^[57]. Constructed using a variety of materials like concrete, steel, or even recycled materials, these structures are created to resemble the complicated habitat structures found in the natural reefs. Artificial reefs are also important habitats to marine life, increasing biodiversity, and can increase fish population, particularly in regions where coral reefs or other natural habitats have been destroyed due to pollution, overfishing, or climate change. The man-made structures also aid in curbing the coastal erosion since the energy of the waves is used up and the shoreline is protected against storm surges and rising sea levels. Hydrodynamic models can be used to design and locate artificial reefs in optimal locations where they can be most effective in providing habitats and protection to the coastline.

Another new technology that is applied in the restoration of the aquatic ecosystems is engineered wetlands^[58]. These are planned wetlands that are engineered to emulate both water treatment and habitat-rich (like natural) wetlands. They come in handy, especially when it comes to treating polluted water, because they sieve out any surplus nutrients, sediments, and contaminants to increase the quality of water. The artificial wetlands can be incorporated in both urban and industrial environments to treat stormwater run-off, wastewater, and agricultural run-off before their release into the natural water bodies. Engineered wetlands replicate the ecological functions of natural wetlands through vegetation, microbial processes, and soil filtration, and the provision of good habitat to wildlife. In a few instances, engineered

wetlands may even be used in conjunction with other forms of restoration, e.g., restoration of riparian zones to produce more multi-functional ecosystems.

Technologies that address sediment stabilization as well as erosion control are also significant in the restoration of aquatic habitats. The high rate of riverbank and shoreline erosion may lead to the destruction of habitat, sedimentation, and water quality. In order to solve this problem, various measures, including the impact of biodegradable erosion control mats, geotextile fabrics, and planting vegetation, are employed in order to stabilize the soil and prevent further erosion^[59]. In other instances, bioengineering interventions can be used to recover the natural vegetation, which is crucial in the maintenance of a healthy aquatic environment, and this can be done by planting native grasses, shrubs, and trees along the shorelines.

The other new technology in the restoration of aquatic habitats is the application of remote sensing and drones in monitoring and assessing the conditions of the habitats^[60]. The drones fitted with high-resolution cameras and sensors are able to provide detailed images of the aquatic ecosystems, enabling scientists to measure the water quality, vegetation growth and population of wildlife in real-time. The technology presents a non-invasive, yet affordable method of data collection in difficult-to-access or remote locations and offers very useful information about the health of the ecosystem and the success of the restoration process. **Table 3** is a summary of some of the technological tools that have been applied in managing water ecosystems, including how they are used, advantages, and weaknesses.

Table 3. Technological Tools and Their Role in Ecosystem Management.

Technology	Primary Application	Benefits	Limitations
Hydrological Modeling	Simulate water flow, quality, and availability	Predictive insights into water management scenarios	Relies on accurate data, complexity of ecosystems
Ecological Modeling	Predict ecosystem responses to management strategies	Optimizes restoration efforts, identifies critical thresholds	Limited by data availability and model complexity
Artificial Reefs	Marine habitat restoration	Enhances biodiversity, protects coastal areas	High cost of installation, potential ecological risks
Engineered Wetlands	Water filtration and pollution removal	Provides natural water treatment, habitat creation	May require ongoing maintenance and monitoring
Remote Sensing (Drones)	Monitor aquatic ecosystems in real-time	Non-invasive, cost-effective, captures high-resolution data	Limited by access to technology and data processing capabilities

4.3. Sustainable Water Management Practices

Sustainability in water management activities is vital in ensuring the sustainability of the water ecosystems par-

ticularly in areas that have a high rate of water stress^[61].

These practices are designed to reconcile the human water needs and the ecological functions that should be preserved, as well as the long-term availability of clean water. The

world is adopting several innovative practices to encourage sustainable water usage and alleviate the adverse effects of over-extraction, pollution and climate change.

The adoption of integrated water resources management (IWRM) is one of the major sustainable water management practices^[62,63]. IWRM is a management style that aims at coordinating and sustaining the management of the water resources to consider the social, economic, and environmental requirements of all stakeholders. It is a process that includes a combination of different water uses like agriculture, industry, and domestic consumption, with conservation of the environment; this includes protection of habitat, control of pollution, and restoration of an ecosystem. IWRM promotes the engagement of stakeholders, the adoption of adaptive management, and the analysis of ecosystem services. This comprehensive strategy assists in ensuring that the utilization of water resources is efficient, equitable, and sustainable, as well as safeguarding the well-being of the water ecosystem.

The other sustainable water management tool is encouraging the use of water-efficient agricultural methods, including precision irrigation and rainwater harvesting^[64]. These methods will help minimize the use of water in agriculture, the greatest consumer of fresh water around the world. Precision irrigation is an irrigation approach that applies technology, including soil moisture sensors and weather information, to spray water more effectively and only when necessary, which minimizes the environmental impact of irrigation. Rainwater harvesting, as an alternative, refers to the process of collecting and storing rainwater and using it to irrigate, serve household or industrial needs, instead of using fresh water sources, thereby relieving the issue of straining local water ecosystems.

Sustainable stormwater management practices are becoming more significant in urban areas. The green roofs, permeable pavements, and urban wetlands are techniques that can be used to control the stormwater runoff and ease the drainage system, as well as improve the water quality^[65]. Not only do these green infrastructure solutions allow the management of water in a more sustainable way, but they also offer some additional benefits, such as the ability to reduce the urban heat island effect, improve biodiversity, and beautify urban landscapes.

4.4. The Role of Technology in Enhancing Adaptive Management

Adaptive management is a crucial practice in managing the water ecosystem where there is uncertainty, which is increasingly being brought about by climate change^[66]. In this style, the main emphasis is placed on flexibility, constant learning, and adaptability of management strategies according to the new information and new circumstances. Adaptive management requires the application of emerging technologies that will transform water ecosystem operations to incorporate real-time monitoring, data analytics, and decision support systems.

Real-time monitoring systems are systems that involve the use of sensors to monitor the water quality, flow, temperature, and other environmental factors to allow managers to monitor the well-being of the ecosystem and act promptly in times of unforeseen threats^[67]. Combining this data with predictive models, the decision support systems can give the managers the tools to make informed decisions and to modify their strategies with the changes in the conditions. These technologies make it possible to create a more dynamic and responsive management of water ecosystems, so that the interventions do not lose their relevance and efficiency in the conditions of changing environmental and social conditions.

Innovative and technological solutions provide priceless resources to the improvement of water ecosystem recovery and management^[68]. Hydrological and ecological modeling, restoration technology in habitats, and sustainable water management practices allow all to make better decisions, to efficiently apply this to the restoration, and to have more resilient ecosystems. The technologies can be used together with solutions based on nature and offer a holistic approach to the issues of water ecosystems that are currently being experienced. In an attempt to manage the uncertainties of climate change and growing human demands on water resources, a combination of technology and traditional ecological approaches will be central to the attainment of sustainable, adaptive, and effective water ecosystem management.

5. Case Studies and Success Stories

The success of water ecosystem recovery and management strategies is best explained through actual scenarios.

Case studies provide a good idea of how various strategies have been implemented in various locations and ecosystems, and what has worked well and what has not worked. Not only do such stories present actual evidence of how beneficial nature solutions and technological advances can be, but they also demonstrate how complicated the implementation of these strategies in various environmental and socio-economic settings can be. In this segment, we have a few prominent case studies of water ecosystem restoration and management, where both conventional and new methods have been effectively used.

5.1. The Restoration of the Kissimmee River, USA

The rehabilitation of the Kissimmee River in Florida, USA, is one of the best-studied cases of a successful restoration of a water ecosystem^[69]. The river had been grossly transformed in the 1960s when the U.S Army Corps of Engineers built a canal to drain the river so as to regulate the flooding in the area. Diversion of the river resulted in loss of wetlands, water quality, and a reduction in fish population. Nutrient pollution in the river system in the form of agricultural runoff and residential structures along its banks further strained the river ecosystem.

The Kissimmee River was also restored in the 1990s as part of the bigger Comprehensive Everglades Restoration Plan (CERP), a multi-agency project to restore the Everglades ecosystem^[70]. The purpose of the project was to re-establish the natural meandering river flow, to recreate wetlands, and to improve water quality. By the first years of the 2000s, the work had commenced to take away the canal and restore the river to its historic floodplain. This was a large-scale restoration project that involved the application of nature-based solutions to restore hydrological functionality and ecosystem services.

The recovery of the Kissimmee River has paid off. Wetland habitats have increased, water quality has been enhanced, and fish populations such as the endangered snail kite have started to recuperate^[71]. The success of large-scale river and wetland restoration in enhancing the general well-being of a watershed was also exhibited by the restoration project. Nevertheless, there are hurdles to overcome, especially in controlling the continuous pollution of nutrients due to the neighboring agricultural farms. The Kissimmee River

restoration, however, was one of the most successful river restoration projects in the United States, which can serve as an example to the rest of the world.

5.2. The Reforestation of the Loess Plateau, China

One of the biggest and most successful reforestation and land restoration projects is the Loess Plateau in the north-central part of China^[72]. The region experienced severe soil erosion and desertification as a result of unsustainable agricultural activities over the centuries, such as deforestation, over-grazing, and high-intensity farming. The deprivation of vegetation cover and degradation of the plateau watersheds led to the deterioration of the water quality, less agricultural output, and floods.

The Chinese government developed an extensive reforestation campaign in the 1990s as a Tiananmen government initiative to respond to this crisis under the name of the program Grain for Green^[73]. This was aimed at recovering vegetation cover, stabilising soils, and enhancing water retention in the area. The project entailed the use of millions of trees, the introduction of sustainable land management, through terracing and crop rotation, to minimize soil erosion and enhance water conservation.

The outcomes of the reforestation processes have been spectacular^[74]. The vegetation cover has been enhanced, soil erosion has been minimized, and there is an improvement in the water retention in the watershed. These developments have helped restore local ecosystems, such as the rehabilitation of riparian habitats along rivers and streams. In addition, socio-economic gains have been realized by the local communities as a result of the reclamation of the Loess Plateau. Better crop yields have been realized by the farmers, as well as better access to clean water due to the improvement in water quality. This is a success story to show how reforestation and ecosystem-based land management can lead to the restoration of degraded water ecosystems and sustainable development.

Nonetheless, other problems that have been encountered in the project of the Loess Plateau are the long-term sustainability of re-established ecosystems and how to handle the strain of population increase and climate change^[75]. Nevertheless, it can be said that the Loess Plateau continues to be a powerful testament to what can be achieved through

large-scale ecological restoration, as a means of strengthening the environment in both environmental and economic respects.

5.3. The Rehabilitation of the Thames River, UK

Another such water ecosystem that has experienced considerable recovery following the concerted efforts to revive the ecosystem is the Thames River in the United Kingdom^[76]. There was a time when the river was highly polluted by industrial processes, the release of sewage, and agricultural effluent. By the 1950s, the river was so polluted that it was declared dead, with very little or no aquatic life. Nevertheless, continuous policy modifications, technological advances, and solutions that are founded on nature have led to a spectacular recovery of the Thames over the decades.

A set of laws and regulations was put in place in the 1960s and 1970s to regulate industrial pollution and enhance the treatment of sewage^[77]. In 1973, the establishment of the Thames Water Authority was aimed at improving the use of the infrastructure in wastewater treatment and lowering the emission of pollutants into the river. Simultaneously, nature-oriented solutions were also introduced to urban planning,

including the restoration of riparian areas and the establishment of green lands along the river. These also contributed to the water quality improvement, but offered valuable wildlife habitats.

By the 2000s, the river Thames had a large variety of aquatic life, such as salmon, not seen in the river for over 100 years^[78]. The success of the restoration was indicated by the return of fish to the river as well as the quality of the water. The Thames is considered to be one of the most successful urban river restoration projects to date, all over the world. It has emerged as a recreational, tourism, and biodiversity center and is still being used by other cities that want to reclaim poor urban rivers.

With all such achievements, there are still issues that are associated with controlling the mounting pressure of urbanization, climate change, and population growth along the Thames. Continued attempts at harmonizing the interests of the river ecosystem with the needs of the local communities are necessary to guarantee the health and sustainability of this vital waterway in the long term. **Table 4** contains the summary of case studies, gives an overview of the real-world applications and outcomes, and assists in placing the lessons learned during the different successful cases of restoring the environment.

Table 4. Summary of Successful Case Studies in Water Ecosystem Restoration.

Case Study	Location	Restoration Strategy	Outcomes	Challenges Faced
Kissimmee River Restoration	Florida, USA	Reconnection of river to floodplain, wetland restoration	Improved water quality, habitat recovery, fish population rebound	Agricultural runoff, ongoing nutrient pollution
Loess Plateau Reforestation	China	Large-scale reforestation, soil erosion control	Reduced soil erosion, improved water retention, enhanced biodiversity	Sustainability of forest cover, land-use pressures
Thames River Restoration	United Kingdom	Pollution control, riparian zone restoration	Return of species like salmon, improved water quality	Urbanization pressures, managing pollution runoff
Ebro Delta Rehabilitation	Spain	Wetland restoration, hydrological flow restoration	Improved water quality, recovery of eel populations	Sea level rise, water scarcity, agricultural impacts

5.4. The Successful Restoration of the Ebro Delta, Spain

One of the most important Mediterranean wetlands with important ecosystem services is the Ebro Delta in northeastern Spain, which plays a vital role in water filtration, flood control, and biodiversity provision^[79]. But the delta over the years has faced huge challenges, such as land reclamation to cultivate agriculture, diversion of water to irrigate lands, and the polluting agricultural run-off and industrial activities. All these, together with the increase in sea level and climate

change, have caused the deterioration of the ecosystems of the delta and especially the wetlands and marshes.

The Spanish government and other stakeholders in the Ebro Delta have responded to these challenges by adopting several restoration strategies in the Delta^[80]. These are the reintroduction of natural hydrological flows in the wetlands, the restoration of vegetated coastal areas, and the establishment of artificial wetlands to replicate the natural activities in the delta. Moreover, the sustainability of agricultural practices has been encouraged to minimize the number of

pollutants that get into the ecosystem.

The rehabilitation of the Ebro Delta has brought about water quality improvement, growth of wetlands, and reintroduction of the species that had been displaced, like the endangered Ebro Delta eel^[81]. The local communities have also benefited from these endeavors because the delta has been used to sustain major agricultural activities, especially rice farming. Nature-based solutions that have been properly incorporated into the agricultural systems have assisted in ensuring the sustainability of the economy and ecosystems of the region in the long-term.

Regardless of the efforts that have been undertaken to restore the Ebro Delta, the current obstacles are how to control the impact of climate change, especially the dangers of the escalating sea level and the salinity^[82]. Restoration of the Ebro Delta remains a prime example of how to address the requirements of agriculture, biodiversity, and climate resiliency in a fast-evolving world.

5.5. Lessons Learned and Challenges

The case studies below show that a mix of nature-based solutions, technological solutions, and effective governance regimes is needed to effectively recover and manage water ecosystems^[49]. The major lessons of these examples are the necessity to follow long-term commitment, coordinate the work of stakeholders, and introduce scientific research into the process of decision-making.

But there is still difficulty in generalizing these successes and extending them to other settings. The presence of persistent pollution, climate change, and alteration of land-use remains a threat to endangering the health of water ecosystems in most parts of the world^[22]. Additionally, the intricacies of managing water ecosystems that may cut across various jurisdictions and involve various stakeholders demand adaptable management approaches and steady monitoring of the ecosystem to ascertain the success of restorative programs.

Case studies will also be conducted worldwide to give us some insight into the possibility of restoring and managing water ecosystems using a mix of both nature-based solutions and technological advances. These instances demonstrate that effective recovery of water ecosystems can be achieved when there is an appropriate mix of policies, allies, and management approaches. Even though these are still challenges, the success stories of the Kissimmee River, the Loess Plateau,

the Thames River, and the Ebro Delta offer hope and direction in future efforts to restore and preserve the water ecosystems of the world. With the mounting pressures on water ecosystems, the case studies are used as guides to the incorporation of sustainable, flexible, and cooperative management of the water ecosystems.

6. Conclusion

The bottom line to sustaining the well-being of our planet's natural systems and ensuring access to important resources is to restore and sustainably manage water ecosystems. Water ecosystems offer very important services which are used to sustain biodiversity, climate, and availability of clean water, and which are vital in achieving ecological and socio-economic stability. Nevertheless, human pressures, climate change, and pollution are increasingly placing pressure on these ecosystems, and their ability to provide these important services is declining.

This article has identified numerous successful strategies to recover and manage water ecosystems, both through nature-based solutions and non-standard technological solutions. Restoration of wetlands, riparian zones, and forested watersheds is a nature-based solutions that provide effective, cost-effective, and sustainable ways of improving water quality, improving biodiversity, and mitigating the effects of climate change. In parallel, hydrological and ecological modeling and other technological innovations to improve the effectiveness of such work and its scalability are presented using the tools of aquatic habitat restoration technologies and advanced water management practices.

The case studies used in this review, the Kissimmee River in the United States, and the Loess Plateau in China, illustrate the transformative possibilities of these strategies provided they are implemented at the appropriate scale and in the appropriate contexts. The problems persist, especially relating to scaling up restoration activities, controlling current threats like pollution and invasive species, and adjusting to the unpredictabilities of climate change, but these instances provide useful insights on how to combine nature- and technology-based solutions in order to manage water ecosystems sustainably.

When we consider the future, it is obvious that the recovery and management of water ecosystems must be as-

sociated with an integrated and interdisciplinary approach that will incorporate scientific, policy-based, and active sectoral cooperation. For governments, communities, scientists, and businesses, there is a need to unite in order to develop adaptive management strategies that can address existing and emerging challenges. These strategies are now needed as ever, with the effects of climate change, water over-exploitation, and loss of biodiversity threatening the resilience of our water ecosystems ever more.

Finally, restoring water ecosystems is not only an important ecological issue, but a route to sustainable development. Healthy water ecosystems help to achieve food security, economic well-being, climate resilience, and human health, and therefore their recovery and protection are at the core of the United Nations Sustainable Development Goals (SDGs). We can collaborate with the power of nature and the development of new technologies to create a future where not only will the water ecosystems be restored, but also preserved by generations to come. This integrated, cooperative solution will mean that the water ecosystems will remain to sustain life on Earth, delivering the necessary services on which all life relies.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or generated in this study. As this is a review, it is based on data and information from previously published sources, which are cited in the reference list.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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