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Article

Ecological Restoration of the Aral Sea: Challenges, Achievements, and Future Prospects

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Abstract: The Aral Sea has been the site of one of the biggest environmental disasters in history, with enormous water diversion for agricultural irrigation. This has led to loss of biodiversity, desertification, salinisation and has had substantial socio-economic repercussions on local communities. The report reviews ecological restoration works in the Aral Sea region, such as construction of the Kok-Aral Dam, water management projects, afforestation and international cooperation projects. The study evaluates the efficiency of several restoration methods and explores the problems that continue to hinder environmental restoration. The results demonstrate that the North Aral Sea has been somewhat rehabilitated but that serious ecological and policy problems remain in the South Aral Sea. The research indicates that for long-term sustainability in the Aral Sea basin, integrated water resource management and regional collaboration are necessary.

Keywords: Aral Sea, Ecological Restoration, Biodiversity, Water Management, Desertification, Sustainability.

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1. Introduction

One of the most striking examples of environmental degradation caused by irresponsible human involvement is the Aral Sea, previously the world's fourth-largest inland water body. The Aral Sea, which lies between Kazakhstan to the north and Uzbekistan to the south, was a huge salty lake, covering around 68,000 square kilometres in the mid-twentieth century. For generations, the sea has been vital for ecological balance, regional climate management, fisheries, agriculture, transportation, and the livelihoods of local inhabitants. But by then, the Aral Sea had been changed from a vibrant aquatic ecosystem into one of the world's worst environmental disasters, caused by large water diversion projects dating back to the Soviet era. Now the diminishing of the Aral Sea is considered a symbol of ecological mismanagement, showing what happens when natural resources are used in an unsustainable way and when environmental planning is inadequate [1–2].

The ecological disaster of the Aral Sea began in the 1960s, when enormous amounts of water from its two main tributaries, the Amu Darya and the Syr Darya, were diverted to fund large-scale agricultural irrigation projects. The Soviet government had big intentions to enhance cotton production in central Asia. This took a lot of water so they built large irrigation canal systems all throughout the region. These irrigation projects helped improve agriculture and boost the economy, but also greatly decreased the amount of water flowing into the Aral Sea. Over the next few decades, the constant

diversion of river water led to a substantial decrease in water levels, resulting in widespread ecological damage and environmental upheaval [1,3].

The amount of freshwater being taken in decreased, and the Aral Sea began to shrink at an alarming rate. By the end of the twentieth century the ocean was a lot smaller, in surface area and in the volume of water. Water levels dropped, salinity increased, habitats were destroyed on a massive scale and aquatic ecosystems collapsed. As a consequence of the rising salinity and the worsening environmental circumstances, fish populations that formerly formed the backbone of a thriving commercial fishing enterprise have suffered a precipitous decline. In many regions of the region the fishing industry, which employed thousands, and was a key source of food and income, was close to disappearing. Therefore, many localities saw economic decline, rising unemployment and growing social hardship [2].

The dilemma of the Aral Sea is not simply the depletion of water resources, but has system-wide effects. As the sea shrank, it exposed vast swaths of the ancient seafloor and produced a new desert today called the Aralkum Desert. The exposed bottom includes vast amounts of salt, agricultural chemicals, pesticides and other contaminants that have settled there over decades. These materials are transported by strong winds over large areas of Central Asia and cause dust storms, which negatively affect the quality of the soil, the health of individuals, the availability of water supplies, and the productivity of agricultural production. These environmental changes have had a dramatic impact on the ecosystems and living conditions across the region [4–5].

The Aralkum Desert has become one of the most visible marks in the Aral Sea basin and is one of the most visible types of evidence of ecological degradation. The newly created desert covers tens of thousands of square km and continues to expand as water levels fall. Dust and salt storms arising from the open seabed carry millions of tonnes of material annually and can damage sites hundreds of kilometres away. These airborne pollutants induce a range of issues including soil salinisation, loss of vegetation, reduction in agricultural productivity and a deterioration in biodiversity. Furthermore, they are a major health hazard to the local population, as they increase the incidence of respiratory ailments, cardiac diseases and other health problems [4–5].

Biological change of the Aral Sea has also had an equally substantial impact on the biodiversity of the region. Before the Aral Sea started to progressively evaporate, there were a lot of aquatic and terrestrial animals that lived in it. The sea and its surrounding environments are essential to many species of fish, migratory birds, aquatic plants and wetland ecosystems. In contrast, loss of biodiversity was due to increased salinity, habitat fragmentation and lack of appropriate water. In parts of the ocean many native fish species were wiped out entirely and critical breeding and feeding areas for wildlife in the wetland areas were severely depleted or eaten up completely. This ecological upheaval has had a negative impact on food chains, ecosystem services and environmental stability of the region [6].

Alterations in the physical features of the Aral Sea have also influenced the climate of the surrounding area and the region as a whole. There is a big role that vast bodies of water play in the regulation of weather patterns and in the regulation of temperatures. The Aral Sea has historically played a role in contributing to the stability of the climate in the regions that are located across the vicinity through the reduction of temperature extremes and the maintenance of humidity levels. The sea, as it drew back, had much less ability to influence conditions of climate. In recent decades, research has shown that the region has seen shorter growing seasons, less humidity, hotter summers and colder winters. These changes in climate have made agricultural productivity and efforts to control the environment increasingly harder [1,7].

The ecological disaster in the Aral Sea has had equally catastrophic consequences for the socio-economic system. The decline of the environment meant the loss of livelihoods for thousands of people relying on fishing, agriculture and related sectors. Formerly thriving fishing ports got stranded many miles from the retreating shoreline, vessels abandoned in the topography of the desert. The worsening of the economy was a factor in the dislocation of populations, poverty, unemployment and social instability.

Moreover, the lack of job opportunities in the area forced many people to move out to find alternative sources of income, which resulted in changes in the demographic patterns and community structures that had been in place in the region Alieva et al., 2023; Alikhanova et al., 2024).

The tragedy that occurred in the Aral Sea has given rise to various public health problems, and this has become a big worry. The build-up of salts, pesticides, fertilisers and industrial contaminants on the exposed bottom has led to major environmental and health problems. Dust storms transport powerful particulates deep into residential areas, raising the risk of exposure to potentially dangerous substances. Many studies have demonstrated that communities living in vicinity to the historic shoreline are more prone to respiratory diseases, cancers, kidney ailments, anaemia and other health problems than other populations involved in similar activities. The deterioration of the quality of water and the limited availability of safe drinking water have worsened problems of public health. The state of the Aral Sea is therefore widely recognised as an environmental catastrophe, but also as a humanitarian problem [8].

In the second half of the twentieth century, the degree of environmental degradation in the Aral Sea basin attracted the attention of people around the world. There is a growing realisation among governments, environmental groups, scholars and international development organisations of the importance of tackling ecological decline and encouraging restoration efforts. There have been several national and international programs put into place in an effort to limit the amount of harm done to the environment, improve the methods used for water management, provide aid to the people that are located within the region, and promote sustainable development. These efforts are some of the most major ecological restoration operations that have been undertaken in recent decades [9–10].

Ecological restoration is a technique that helps the recovery of degraded, injured or destroyed ecosystems and is a way to help ecosystems recover. Restoration initiatives aim to restore ecological functions, improve environmental conditions, increase biodiversity and promote sustainable resource management. In the Aral Sea situation, restoration efforts are focused mainly on increasing the amount of available water, improving the health of ecosystems, decreasing the risk of environmental hazards and providing help for socio-economic recovery. But the complexity of the Aral Sea situation needs the adoption of comprehensive policies that take into consideration environmental, economic, social and political factors [9].

The building of the Kok-Aral Dam in Kazakhstan is seen as one of the most important rehabilitation successes that have ever been achieved. Built with aid from the World Bank, the dam, completed in 2005, was designed to divide the North Aral Sea from the larger South Aral Sea and to keep water in the reservoir that lies in the northern basin. The goals of the project were to stabilise water levels, reduce the salt in the water, and improve biological conditions. Later monitoring showed substantial increases in water volume, fish populations and economic activity in the area. Some of the fish species that had been extinct for a long time began to reappear and in a number of different communities fishing operations began once again. These achievements show that focused restoration efforts can deliver good results for the environment and economy [10–11].

Considering that the attempt to revive the North Aral Sea has been somewhat successful, there is optimism that the ecological situation will improve. In contrast, the initiatives to rehabilitate the South Aral Sea have proved to be far more difficult. All these conditions reduced the probability of restoration: continuous water withdrawal for agricultural purposes, limited river inflows and significant degradation of the ecosystem. The biological degradation that has taken place over several decades in extensive parts of the South Aral Sea, which have been subjected to increased fragmentation and desiccation, is difficult to reverse. This illustrates the challenges of reversing the biological changes that have occurred. Such variable outcomes emphasise the significance of effective water governance, resource allocation and regional cooperation in the restoration planning process [10].

Water management is still one of the most critical aspects to define the nature of the Aral Sea in the future. Both rivers, the Amu Darya and Syr Darya, continue to be important suppliers of water for a range of uses including as agriculture, industry, domestic use and environmental protection. Balancing competing needs for water resources is a huge concern for Central Asian nations. Sustainable restoration requires coordinated actions to increase irrigation efficiency, reduce water waste, promote conservation behaviours and environmental fluxes to restore the ecosystem. Therefore, integrated management of water resources has become one of the main issues of discussion in the framework of the discussions on the Aral Sea restoration [10,12].

Regional coordination is also needed to tackle environmental problems within the Aral Sea basin. The countries that share the basin are Kazakhstan, Uzbekistan, Turkmenistan, Tajikistan and Kyrgyzstan. Unilateral actions are inefficient in solving environmental problems since water resources are shared among countries. Effective restoration requires collaborative governance, policy coordination, information exchange, and cooperative investment in sustainability programs. International organisations have stressed, on numerous occasions, the importance of transboundary collaboration for the achievement of the goals of long-term ecological recovery and sustainable development [10,13].

The other important part of the rehabilitation process is the implementation of afforestation and vegetation rehabilitation projects. This exposed the area that had been the sea floor and created conditions that were easier for dust and salt storms to occur. Governments and environmental organisations have planted huge areas with drought-resistant species such as saxaul to combat the problem. These vegetation restoration actions are undertaken to stabilise soils, reduce dust emissions, promote biodiversity and improve environmental conditions. However, these actions do not restore all ecological loss, but they constitute a significant contribution to environmental management and to climate adaption measures correspondingly [14].

The growing scientific interest in the Aral Sea has resulted in a considerable quantity of research to understand the drivers of the ecological problem, its impacts and the opportunities for its restoration. A range of subjects have been explored, such as: alterations in hydrology, loss of biodiversity, climate effects, socioeconomic outcomes, public health concerns, and policy solutions. The corpus of study shows the complexity of environmental degradation, and the opportunities for ecological rehabilitation. There is increasing awareness among scholars of the need for multidisciplinary approaches that incorporate environmental science, ecology, economics, public policy and ideas about sustainable development [9–10,15].

The Aral Sea is also one of the world's most important case studies in the areas of environment and environmental management. The lessons learnt from the crisis in the Aral Sea have implications for the management of water resources, the rehabilitation of ecosystems, the adaption to climate change and the promotion of sustainable methods elsewhere under environmental stress. Continued rise of global populations and increasing demand for water are creating problems for many countries associated with scarce resources, environmental degradation and competing development goals. The Aral Sea experience will also be used to demonstrate the possible results of undertaking unsustainable resource extraction, as well as to show the importance of proactive environmental planning and restoration activities [10,16].

In the last few years, the idea of ecological resilience has gained more and more interest in the vicinity of the Aral Sea. Ecological resilience refers to the capacity of ecosystems to rebound from environmental stress and to absorb disturbances. It is essential to have a sound grasp of resilience to be able to develop restoration approaches that support long-term sustainability. Restoration efforts should not just focus on immediate benefits to the environment but also on the capacity of ecosystems and populations to adapt to changes in the environment in the future. The results of restoration activities are affected by extra uncertainties introduced by changes in climate, population growth and changing economic situations [16].

Experience from parts of the Aral Sea basin shows that with the backing of scientific knowledge, political will and international cooperation, ecological restoration may be achieved. This is despite the problems. It may not be possible to restore the ancient sea in its entirety, but there is scope for considerable improvement by adopting certain measures and using environmentally responsible approaches of resource management. In fact, evidence exists that degradation can be reversed to a certain degree, and that ecosystems are capable of regenerating themselves under favourable conditions. The evidence is based on experience obtained in the North Asian Sea [17].

The objective of this research is to explore the ecological restoration of the Aral Sea by reviewing the existing literature on restoration activities, environmental recovery efforts and future opportunities. This study reviews major restoration programs, examines their triumphs and failures, and investigates the determinants of restoration success. Special focus should be given to water management approaches, ecological rehabilitation programs, biodiversity recovery initiatives, afforestation activities and regional cooperation frameworks. Also, the study reveals chances for support of sustainable environmental recovery in the Aral Sea basin. The article evaluates present difficulties that still influence restoration activities [9].

The ecological rehabilitation of the Aral Sea is undoubtedly one of the most important environmental issues and opportunities of the modern period. This location, specifically, shows the adverse effects of unsustainable growth and the possibilities of ecological restoration through cooperative efforts and informed decisions. Lawmakers, researchers, and environmental specialists can use the insights obtained from the Aral Sea and the experiences gained in its restoration to strengthen future conservation and sustainability initiatives [9,15].

Ecological restoration itself is a well-defined field of environmental practice, distinct from simple conservation. The Society for Ecological Restoration defines restoration as the process of recovering ecological integrity, biodiversity, ecosystem services and environmental sustainability in a degraded system, typically through measures such as habitat restoration, water resource management, species restocking and vegetation regrowth [9–10,18]. Scholars increasingly stress that restoration should not be understood as simple environmental rehabilitation but as a complex process integrating ecological, social, economic and political considerations, with the best initiatives combining scientific knowledge, stakeholder involvement and adaptive management capable of responding to changing environmental circumstances and uncertainty [10,14]. The Aral Sea is widely regarded as one of the most demanding tests of this framework, given the scale of degradation involved and the number of interlinked biological and social systems that any restoration effort must address [10,14].

Institutionally, the scale of the Aral Sea basin's environmental challenges has required coordinated international engagement. The International Fund for Saving the Aral Sea (IFAS), established in 1993, has played a central role in coordinating regional restoration initiatives among the Central Asian states, while agencies including the World Bank, the United Nations Development Programme, UNESCO and the Asian Development Bank have contributed financial resources, technical expertise and policy support [19–21]. Political divisions, competing economic priorities and institutional challenges nonetheless continue to complicate transboundary collaboration, underscoring why strengthened regional governance remains a recurring theme in the literature on the basin's long-term prospects [19–20].

2. Materials and Methods

A literature review is an approach used in this study to explore the ecological restoration of the Aral Sea. The report examines restoration projects, environmental recovery efforts, challenges, successes and future opportunities. The literature review method is appropriate for this research as it allows the systematic collection, appraisal and synthesis of existing knowledge on the ecological problem that has been affecting the Aral Sea and the measures of its restoration that have been implemented within the region. The paper analyses previously published data and provides a complete

understanding of the factors that determine restoration outcomes and sustainable environmental management [22].

The analysis is solely based on secondary data from scientific and professional journals. The literature was gathered from widely recognised academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Taylor & Francis Online, Emerald Insight, and Google Scholar. We also examined reports produced by other organisations, including the World Bank, United Nations Development Program (UNDP), United Nations Environment Program (UNEP), UNESCO and the International Fund for Saving the Aral Sea (IFAS) to provide further context and policy-related information.

A systematic search process was guided by keywords such as Aral Sea restoration, ecological restoration, water resource management, environmental rehabilitation, desertification, biodiversity recovery, Kok-Aral Dam, Aralkum Desert, sustainable development, and Central Asian environmental management. The inclusion criteria considered peer-reviewed journal articles, books, conference proceedings, and institutional reports relevant to environmental degradation, restoration activities, water management policies, biodiversity conservation, and socio-economic impacts in the Aral Sea basin. Publications unrelated to restoration efforts or not scientifically relevant were omitted.

The acquired material was analysed by a topic review approach. The studies were grouped into major themes, such as: causes of environmental degradation; water management and restoration; the Kok-Aral Dam project; afforestation; biodiversity recovery; socio-economic benefits of restoration; regional cooperation; and future restoration prospects. Synthesising and critically appraising the data from these themes helped to identify recurring trends, achievements, limitations and gaps in research. The aim of this method is to provide a comprehensive picture of the existing knowledge on the ecological restoration of the Aral Sea and its long-term sustainability.

3. Result

One of the most important results found in the literature is the relative success of the North Aral Sea restoration effort. The construction of the Kok-Aral Dam is one of the most important successes in the environmental rehabilitation of the area. The project also succeeded in raising water levels and reducing salinity by dividing the North Aral Sea from the South Aral Sea and keeping water in the northern basin. Such improvements in environment had positive consequences on aquatic ecosystems and local residents. Fish populations rebounded, biodiversity improved and economic activity, such as commercial fishing, slowly returned. The project's success underscores that well-planned and scientifically informed restoration initiatives can deliver tangible ecological and socio-economic advantages [17–18].

The restoration of fisheries in the North Aral Sea is especially important because it demonstrates the close link between the rehabilitation of the environment and economic development. Fishing was an important source of labour and income for thousands of people before the ecological crisis that happened. The rising salinity and declining fish numbers caused tremendous economic hardship to the surrounding residents. Thus, there is a chance that restoration efforts that improve environmental conditions could be directly contributing to livelihoods' recovery and community resilience's rehabilitation. There is evidence that ecological restoration can deliver significant economic benefits while simultaneously advancing wider environmental goals. This is proven by the recovery of fish species and the resurgence of fishing activities [14,21].

The study does point out, however, that improvements in the North Aral Sea should not disguise the ongoing issues in the South Aral Sea. Many efforts have been made to rehabilitate the southern basin; however, a large part of the southern basin remains extremely degraded. Ecological recovery has been restricted by ongoing agricultural water withdrawals, insufficient freshwater imports, and significant environmental deterioration. The South Aral Sea continues to shrink in several locations. The salinity is very high. Such conditions are severe obstacles for the revival of biodiversity and for the

repair of ecosystems. Disparities between the north and south regions highlight the challenges of restoration and point to a strong local environmental context and resource dependency for ecological recovery [9,17].

Another important theme emerging from the literature concerns the importance of afforestation and land rehabilitation efforts. New environmental issues, well beyond just the lack of water, have emerged with the creation of the Aralkum Desert, which has formed a consequence of the Aral Sea's retreat. The uncovered seafloor is a key source of dust and salt storms that carry pollutants, chemicals and sediments over broad distances. These dust storms lead to soil deterioration, poor agricultural output, loss of biodiversity and harmful health effects. Therefore, afforestation programs with drought-tolerant species such as saxaul have become an important component of the restoration efforts [14].

The results indicate that afforestation has several positive benefits on the ecosystem. Vegetation covers exposed soils, stabilising the soil and reducing the amount of wind erosion and limiting airborne contaminants. There is also evidence that trees and shrubs contribute to sequestration of carbon, increase of biodiversity, and regulation of microclimates. Although afforestation cannot entirely solve the environmental problems that have developed due to the crisis in the Aral Sea, it is a great way to reduce some of the most serious effects that are associated with desertification. The success of large-scale planting efforts demonstrates that ecosystem-based approaches can complement water management measures and contribute to broader restoration aims [14,21].

Another major feature of ecological restoration highlighted in the literature is the recovery of biodiversity. Great disruption in aquatic and land-based ecosystems was created by the disappearance of the Aral Sea. Many fish species died, wetlands were degraded, and wildlife habitat was destroyed. Restoration efforts have improved water quality and restored ecological services leading to the slow recovery of some species and ecosystems. The recovery of fish populations in the North Aral Sea is an example of the positive response of ecosystems to improved environmental conditions [2,18].

Notwithstanding the optimistic developments, the restoration of biodiversity is a protracted process requiring continued management and monitoring. Restoring an ecosystem is not a matter of merely putting a few species back in. You have to restore the biological connections, the food webs and the connectedness of habitats. Based on the research that has been completed, there is an urgent need for detailed conservation plans that incorporate biodiversity goals into broader restoration planning. Such measures build resilience in ecosystems and boost the odds of a lasting environmental recovery [9–10].

The socio-economic dimensions of restoration constitute yet another key theme, which may be observed throughout the body of research. The ecological damage in the vicinity of the Aral Sea has had serious consequences for human welfare. The decline of natural circumstances has resulted in a decrease in population, increased unemployment and poverty in towns once relied on fishing, agriculture and related businesses. Consequently, restoration activities are not only directed at ecological challenges, but also at broader development goals linked to economic recovery and social stability [2,17].

The results of several research show that measures to improve the environment can lead to considerable socioeconomic gains. More water means better living conditions and better economic opportunities, better fisheries, better agriculture and lower environmental health risks. Restoration initiatives can benefit local development by creating employment opportunities, encouraging sustainable resource utilisation and increasing community resilience. Therefore, sustainable restoration requires integrated approaches that respect the interdependence of socio-economic and environmental systems [10].

In the framework of conversations about the restoration of natural systems, concerns about public health also come up to a major degree. major quantities of salts and chemical wastes are present on the exposed seabed of the region that was formerly known as the Aral Sea. These substances pose major risks to the health of the people who live in the area. It has been found that dust storms are associated with a wide range of chronic health

problems, such as respiratory ailments, cardiovascular diseases, and other conditions. In accordance with the findings of the research that has been carried out, restoration activities such as afforestation and environmental rehabilitation have the ability to reduce the quantity of airborne pollutants that are exposed to the general population and to enhance the overall quality of the environment. Restoration, despite the fact that it is not capable of solving all health problems on its own, has the potential to make a significant contribution to the establishment of living conditions that are safer and healthier [9,23].

Regional cooperation is one of the themes in the research on the restoration of the Aral Sea. Good governance and decision-making is important for effective management of the basin as water resources are shared across multiple countries across the basin. \"Transboundary cooperation is mentioned over and over again as a prerequisite for sustainable restoration in the research body.\" Sustaining the gains in restoration may be difficult without collective commitments to conserve water and protect the environment. Organisations such as the International Fund for Saving the Aral Sea have played an important role in supporting communication and cooperation between nations of Central Asia [10,13].

4. Discussion

The ecological restoration of the Aral Sea is arguably one of the most ambitious and complex environmental recovery attempts in the history of current times. The material that was analysed for this study shows that the Aral Sea crisis is not only an ecological problem but rather a multidimensional challenge involving ecological degradation, economic disruption, social misery, public health concerns, and governance complexity. The Aral Sea's dramatic shrinkage is a classic example of the consequences of unsustainable resource management. This phenomenon also emphasises the necessity of balancing economic progress with environmental sustainability. Conversely, restoration efforts over the past few decades have yielded invaluable lessons about the potential and constraints of ecological recovery in highly degraded ecosystems [10,24].

The scientific results are extremely apparent that the disaster in the Aral Sea was caused by human action, not by natural biological processes. It is one of the most important discoveries ever made. The massive size of irrigation works which require water to be removed from the Amu Darya and Syr Darya rivers, have drastically upset the hydrological equilibrium of the region. Irrigation projects have brought agricultural growth and economic success, especially in cotton, but have also destroyed a large aquatic habitat in Central Asia. In view of these ecological repercussions, it is important to bear in mind the dangers of development plans that give priority to short-term financial aims at the expense of long-term effects on the environment. The Aral Sea is a notable example of the destructive impacts of environmental deterioration and a well-known example of the serious consequences that can follow from the reckless use of natural resources [10,17].

The research constantly highlights the fundamental importance of water management for the ecological catastrophe and restoration. The main reason of the shrinkage of the Aral Sea is the reduction of inflows through the rivers; therefore, the success of the restoration largely rests on improved methods of water allocation and utilisation. Existing studies emphasise the fact of ineffective irrigation systems, which caused large losses of water during the whole Soviet period. Most of the diverted water was lost before it got to agricultural areas, through seepage, evaporation, and badly maintained canal infrastructure. Thus, modern restoration methods tend to focus on enhancing the efficiency of irrigation, minimising water wastage and using more sustainable agriculture methods [12].

The discussion also emphasises the necessity of integrated water resource management for the long-term ecological restoration. Integrated water resource management implies that water resources should be managed in a coordinated manner that balances environmental, agricultural, industrial and domestic needs. Water governance is extremely challenging, given the Aral Sea basin covers numerous countries. The literature suggests that restoration efforts can't be successful through discrete national activities as water supply and environmental variables are interrelated beyond political

boundaries. Therefore, regional collaboration is important for equitable sharing of water resources along with ecological sustainability [12–13].

The discussion also shows that the full restoration of the Aral Sea to its historical condition is unlikely under the prevailing circumstances. Some academics say that the environmental changes that have taken place over the last few decades are too significant to be turned around fully. Restoration would take up huge amounts of fresh water now needed for farming and for people to drink. Climate change could also restrict future water supply over Central Asia, making large-scale restoration more difficult. Therefore, many researchers argue for a pragmatic strategy that aims to improve ecological conditions and resilience rather than to reproduce the original ecosystem in its totality [10,24].

In contrast, the achievement of effective regional cooperation remains difficult. The countries contained within the basin often have competing economic priorities and different goals regarding water management. Countries further upstream may focus more on hydropower generation. Countries further downstream depend heavily on irrigation for their agriculture. These competing interests can make the efforts to develop comprehensive restoration policies more difficult. Hence, the body of research emphasises the need to reinforce institutional frameworks, improve communication and promote collaborative governance mechanisms [12–13].

Climate change is complicated, which makes planning restoration efforts harder. Future water availability in Central Asia could be affected by increasing temperatures, changing precipitation patterns and increasing evaporation rates. Changes in climate may dampen variability in flows of rivers, thereby intensifying existing ecological stresses in the basin. Thus, restoration strategies should integrate climate adaptation initiatives and give priority to resilience-enhancing methods. Research shows that future restoration efforts will be successful if communities and institutions are able to adapt to evolving environmental conditions [10,24].

Furthermore, this discussion points out the value of scientific research and technological innovation in supporting environmental restoration projects. Recent advances in remote sensing, geographic information systems, environmental monitoring and climate modelling have enabled a better understanding of the dynamics of ecosystems and the results of restoration efforts. These technologies allow a more efficient management of environmental resources and provide useful information to decision makers for their decision-making processes. Research must continue to assess restoration progress, to identify new challenges and to improve management approaches. Such research is crucial [25].

Another significant finding from the research is that ecological restoration should be seen as a process that takes place over a longer period of time, rather than as a short-term intervention. The environmental degradation of the Aral Sea occurred over the span of several decades and likewise the recovery process will require a commitment that is sustained over extended periods of time. Ecological problems with deep roots are not likely to be solved quickly. Meanwhile, the restoration process requires continued investments, flexible management, stakeholder participation and encouragement from policy makers. Restoration is a long-term process, and this points out the necessity of political commitment and public engagement [17].

Moreover, the Aral Sea can provide important lessons for the world in the global management of environment. In many parts of the world there are problems due to lack of available water, deterioration of ecosystems, increase in desertification and effects of climate change. The lessons learnt from the knowledge and experience gained during the course of the Aral Sea restoration provide valuable lessons on the consequences of unsustainable use of resources and the prospects for ecological recovery. The lessons learned from this region could influence environmental policies and restoration initiatives in other vulnerable ecosystems [2,17].

In general, research on the restoration of the ecology of the Aral Sea has shown a combination of promising successes and ongoing challenges. The North Aral Sea restoration shows that positive environmental change is possible when restoration is

supported by good planning, sufficient resources and strong institutional support. As the North Aral Sea has shown, its recovery. During this period the South Aral Sea continues to deteriorate. This example highlights the limitations of restoration under conditions of severe environmental stress and competing resource demands [2,9].

During the discussion it was agreed that ecological restoration of the Aral Sea is a complicated process and involves environmental, social, economic and political factors. Specific areas have experienced significant progress in the restoration efforts through improved water management, tree planting, biodiversity conservation and fishery recovery. But enduring challenges such as water scarcity, regional cooperation, climate change, and environmental sustainability continue to affect the effectiveness of restoration efforts [9–10,13]. Success will be achieved in the future through the use of integrated and adaptive management approaches that consider human requirements alongside environmental sustainability. Restoring the historic Aral Sea may not be feasible in its entirety, but the current restoration efforts are presenting great opportunities to improve environmental conditions, increase resilience in communities and promote sustainable development in the region.

5. Conclusion

Restoring the Aral Sea ecologically is one of the largest environmental recovery projects in the world, and it offers valuable lessons about what happens when we do not use resources sustainably, and the opportunities we have to restore ecosystems. The paper analyses the literature on the reasons of the Aral Sea crisis, its ecological consequences and the restoration measures applied to improve the ecological situation in the basin. The results indicate that the main reason for the catastrophic drying of the Aral Sea was the large-scale withdrawal of water from the Amu Darya and Syr Darya rivers for agricultural irrigation, which significantly reduced water inflows and disrupted the ecological balance in the region. The resulting environmental degradation had serious consequences, including higher salinity, loss of biological diversity, desertification, climate change, public health problems and widespread socio-economic disruption [10,24].

The current literature shows that ecological restoration is an increasingly important response to these challenges. The Kok-Aral Dam in Kazakhstan is regarded as one of the most successful restoration projects and has been crucial to the successful recovery of the North Aral Sea. This is a demonstration of how targeted restoration work can deliver real environmental and economic returns. For example, water levels have gone up, salinity levels have gone down. Another two examples that even better illustrate the close relation between restoring ecosystems and improving community well-being are the restoration of fisheries and the improvement of local livelihoods. These results show that even severely degraded ecosystems can respond positively to science-based restoration interventions if these are adequately resourced and institutionally supported [10,17–18].

Besides the water management projects, afforestation programs, programs for biodiversity conservation, wetland rehabilitation and sustainable land management practices have played an important role to reduce the impacts of environmental degradation. Vegetation that has grown on the exposed seabed of the former Aral Sea is helping to reduce dust storms, stabilise soils and increase ecological resilience. In some places, habitat restoration and wildlife recovery have also gradually led to improved ecosystem functions. These efforts point to the need for integrated restoration strategies that simultaneously tackle different aspects of environmental degradation [9,14].

These achievements notwithstanding, there remain considerable challenges to be addressed. The South Aral Sea continues to suffer serious ecological degradation because of limited water inflows, continuing agricultural requirements, and climate change pressures. Improving water quality is constrained by lack of financial resources, competing national priorities and the complex nature of transboundary water governance. In addition, the worsening effects of climate change may contribute to increasing water shortages and additional difficulties in the long recovery process. These challenges highlight the need for sustained investment, flexible management and regional cooperation among the Central Asian states [9–10].

To conclude, full recovery of the Aral Sea to its initial state may no longer be possible, but significant ecological restoration can still be achieved through joint and sustainable management approaches. The Aral Sea is an example that shows that ecological decline is not irreversible and that targeted rehabilitation efforts can have positive outcomes for ecosystems and communities. Better regional co-operation, making the best use of water resources, expanding conservation activities and including ecological restoration in overall strategies for sustainable development will be the key to future prosperity. If we stay the course and work together, the Aral Sea can be a model for the world of resilience, environmental management and what can be done to restore ecosystems.

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