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Coastal Resilience, Flood Risk Management, and Groundwater Sustainability under Global Climate Change: An Ecohydrological Approach

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Abstract
Flooding, a prevalent consequence of climate change, poses significant threats to coastal zones, ecosystems, and groundwater resources. This paper investigates the efficacy of ecohydrological adaptation strategies in enhancing coastal resilience, flood response, and groundwater sustainability. By comparing existing ecohydrological restoration in the Mississippi River Delta, Ganges-Brahmaputra Delta, and the Netherlands, this study finds that ecohydrological strategies including wetland rehabilitation, Managed Aquifer Recharge (MAR), and mangrove preservation—outperform traditional engineered solutions in terms of sustainability, cost-effectiveness, and ecological value. Specifically, in the Mississippi River Delta, ecohydrological strategies reduced annual flood damage costs from $500 million to $300 million, a 40% decrease, and reduced flood frequency from 3 events per year to 1.5. In the Ganges-Brahmaputra Delta, these strategies decreased flood costs from $800 million to $450 million and reduced flood frequency from 4 events per year to 2. In the Netherlands, ecohydrological approaches lowered flood damage costs from $600 million to $350 million and cut flood frequency in half, from 2 events per year to 1. Additionally, ecohydrological measures effectively reduced groundwater salinity and increased recharge rates; in the Mississippi River Delta, groundwater salinity was reduced from 1500 ppm to 800 ppm, and recharge rates doubled from 50 mm/year to 120 mm/year. These results indicate that ecohydrological adaptation tools are viable and sustainable options for coastal adaptation, confirming the need for policy-driven coastal ecosystem-based adaptation and integrated governance.

Keywords: Coastal Resilience Flood, Risk Management, Groundwater Sustainability, Climate Change Adaptation, Water Resource Management

1. Introduction
Climate change is a severe challenge for coastal areas globally, threatening ecosystems, locals, and businesses more and more each year. Coastal areas are sensitive to factors like sea level rise, storm surge frequency and intensity, and variability in precipitation patterns thus increasing vulnerability to floods, groundwater exploitation, and ecological system decline (Nicholls & Cazenave, 2010; IPCC 2021). However, human activity combined with environmental stressors forms a challenging situation in which the application of standard adaptation practices that involve engineering structures like seawalls and levees for protection against climate change cannot provide a sustainable solution to these negative impacts (Sutton-Grier, Wowk, & Bamford, 2015).

Given these challenges, it is important to design new solutions that utilize natural processes and address the deficiencies of coastal systems, flood management, and groundwater scarcity. This paper aims to convey the benefits of ecohydrology as a fresh approach to climate adaptation with special reference to coastal systems.

Climate models suggest that sea levels will rise even higher in the future and this means that low coastal plains in the world will be subject to more frequent flooding and permanent submersion (IPCC, 2021). Not only does sea-level rise pose significant risks to physical assets, but it also works against freshwater supplies and agricultural water consumption in aquifers impacted by seawater (Michael and Voss, 2008). Moreover, the occurrence and strength of storms have led to the continued emergence of flood hazards that adversely affect coastal ecosystems and man, displace people, and hamper economic activities (Nicholls and Cazenave, 2010). Coastal regions thus face a twin challenge of flood management to either mitigate or minimize flooding incidents and conservation of groundwater from pollution and wastage.

In the past, solutions to flood and erosion hazards in coastal regions involved the construction of engineered barriers including dikes, seawalls, and levees meant to safeguard people and assets (Adger et al., 2009). However, the applications of these methods are not constructive in the long run as they have numerous disadvantages in terms of ecology; these include the modification of bottom sedimentation processes, the restriction of habitat accessibility, and the negative impacts of countless ecosystem processes (Temmerman et al., 2013). Further, these solutions are typically expensive and rigid, which translates into heavy maintenance and upgrades with reference to altering the environment. Thus, there is increasing interest in approaches beyond the simple adaptation to damage lowering caused by climate change; and interest in approaches that improve ecological stability and adaptability as well (Sutton-Grier et al., 2015).

Coastal problems represent complex interactions that require a multi-disciplinary solution and eco-hydrology is considered to be a viable solution to these problems. Ecohydrological strategies, therefore, seek to rehabilitate and improve the integrity of hydrological processes associated with water purification, flood mitigation, and habitat production for sustainable adaptation (Zalewski, 2000). For instance, the conservation of wetlands for agricultural, residential, or commercial purposes can serve as buffers absorbing wave energy, lessen flooding, and avoid shoreline erosion besides supporting life forms and water quality (Mitsch and Jørgensen, 2003). This approach can be regarded as one of the principles of nature-based solutions (NbS), which involve the functioning of natural or modified ecosystems to address climate change and natural resource management issues (Sutton-Grier et al., 2015).

Objectives of the Study

This research aims to evaluate the potential of ecohydrological approaches in enhancing coastal resilience, managing flood risks, and sustaining groundwater resources. Specifically, the study addresses the following objectives:

1. To assess the role of ecohydrological interventions in reducing flood risks and enhancing coastal resilience under changing climate conditions.
2. To explore how ecohydrological strategies can help mitigate groundwater depletion and saltwater intrusion in coastal aquifers.
3. To identify the socio-economic and policy frameworks that support the implementation of ecohydrological solutions in coastal areas.
4.

2. Literature Review

The effects of global climate change emerged as evident and dynamic particularly in coastal regions since sea level rise, intensification of storms, and intrusion of saltwater into aquifers are ever-increasing risks to the resilience and sustainability of resources and livelihoods (Nicholls and Cazenave, 2010; IPCC, 2021). Management of these challenges necessitates broad framework solutions that are beyond the purview of engineering solutions which are more of hydrological solutions by designs to mimic natural systems and processes. This literature review compiles major findings related to climate change effects in coastal areas, flood hazards, groundwater availability, and the development of eco-hydrological adaptation strategies to achieve an integrated perspective of the emergent concerns.

2.1 Climate Change Impacts on Coastal Zones

Thermal expansion of ocean water and the melting of polar ice caps and glacial water are other straightforward effects of climatic change that have led to the increase of sea level. The IPCC global sea level has increased about 20 cm during the twentieth century and could rise by between 0.28m to 1m by the end of the century under business-as-usual emission conditions (IPCC, 2021). This increases the susceptibility of continental shorelines to flooding and coastal erosion especially where there are lowlands. Research by Nicholls & Cazenave, (2010) indicates that in addition to flooding of structures and settlements, a global increase in sea levels leads to saline water intrusions into coastal aquifers defeating freshwater sources used to supply water for human consumption and irrigation. Areas like developing countries' South Asian area and the Gulf Coast of the United States are on the hit list of these effects because of their low laying land structure and population strength (Dasgupta et al., 2009).

Due to climate change storms occur frequently and with greater intensity, thus resulting in more storms causing storm surges and coastal flooding. Thus, Emanuel (2013) points out that the increase in the temperature of ocean waters strengthens the experience of tropical storms, leading to increased wave height and increased coastal erosion. This dynamic poses a significant challenge to coastal management because commonly used barriers may be insufficient to guard against enhanced storm surges. Kulp & Strauss (2019) have predicted that by 2050 the number of affected people could amount to 150 million people inhabiting the territories subjected to episodic or permanent flooding caused by the constant rise of the world ocean level and increased storm activity. Such projections call for innovation as well as the implementation of durable measures that will efficiently and positively counter the situation.

2.2 Flood Risk Management Strategies

Historically, flood management in coastal areas has been more concerned with "structural" approaches that seek to build barriers against the inrush of water through the construction of walls, dykes, and dams (Adger et al., 2009). Such measures, which are useful when applied selectively, can harm ecosystems and may necessitate frequent repairs and modifications due to changing conditions (Temmerman et al., 2013). Furthermore, some hard structures tend to relocate the flood risks to other areas rather than addressing the flood vulnerability of that area (Sutton-Grier, Wowk, & Bamford, 2015). There has been growing awareness of such constraints leading to the emergence of other works in the application of natural environments in flood protection.

Another potential approach is Nature-Based Solutions (NBS); these are measures that seek to utilize natural features like wetlands, mangroves, dune fields, etc. as protection against floods. For instance, Spalding et al. (2014) argue that mangroves greatly reduce flood risks for the communities along the shores since they also confine wave strength and shorelines. Likewise, many coastal wetlands and marshes may help prevent erosion and reduce waves by trapping sediments and energy, and they can also support species other than E. sinensis (Barbier et al., 2011). These nature-based solutions also offer other co-benefits, including the sequestration of carbon and how water, which enhances other functions of ecosystem wellbeing (Sutton-Grier et al., 2015). Such applications of these solutions side by side with conventional flood management are progressively being seen as a feasible option for improving coastal protection.

2.3 Groundwater Sustainability in Coastal Regions

The aquifer in the part of the county that lies along the coast is under severe environmental stress through over-drafting, pollution, and intrusion by salt water. There are continued challenges such as the salinization of water sources as the sea levels extend their influence into freshwater basins, which makes them unfit for human consumption and other usages (Michael & Voss, 2008). This has been compounded by the increased abstraction of groundwater, which relieves the pressure that normally keeps saltwater from advancing inland. As presented in the study on aquifer sustainability by Werner et al. (2013), many of the coastal aquifers around the globe are threatened to turn into saline sources in the timeframe of several decades if no action is taken, thus affecting millions of the population that draws water from these sources.

The recharge of aquifers through managed techniques has been adopted as a solution for controlling saltwater intrusion and replenishing the groundwater resources available in coastal regions. MAR includes the deliberate injection of water into aquifers to increase water levels, and decrease salinity levels (Dillon et al., 2019). The authors Scanlon et al. (2016) suggest that MAR can be very useful in coastal areas where natural recharge is weak to match the extraction rates. As MAR enhances the levels of the groundwater, it develops a hydraulic wall that checks the saline water from entering and sourcing fresh water. However, MAR has to be done systematically and in the long run while observing hydrogeological conditions to ensure that the recharge rates correspond with extraction rates within the region (Gorelick & Zheng, 2015).

2.4 Ecohydrology as a Framework for Adaptation

Ecohydrology is another scholarly interdisciplinary concept that applies ecological and hydrological processes for ecological engineering and sustainability of coastal ecosystems. According to Zalewski (2000), ecohydrology aims at the improvement of ecosystem processes for water management needs especially in areas experiencing climate change. This approach is based on the postulate that ecosystems can be administered in a way that the natural self-organizing capacity for regulatory functions, i.e. water reservoirs, nutrient cycling, and habitat, will be enhanced. From the coastal resilience perspective, eco hydrology can contribute to the improvement of natural protection systems such as wetlands, Mangrove, and others that will reduce flood effects and support biological diversities (Mitsch and Jørgensen 2003).

Research by Mitsch and Gosselink (2015) also shows wetlands acting as final sinks where floods are reallocated from and water quality is enhanced through the filtration of sediment and pollutants. In the same manner, Zalewski (2000) observes that the measures in ecohydrology may be designed to rehabilitate shoreline features, protect against shoreline erosions, and act as a buffer in cases of salinity and salt-water intrusion through recharge of groundwater. Herein, ecohydrology provides an organizational structure that incorporates ecological functions within hydrological management to meet both the environmental and social goals to increase resilience at the local and regional scales.

2.5 Integrated Approaches and Policy Considerations

Thus, to enhance the application of ecohydrological and nature-based adaptation strategies efficiently, multi-sectoral approaches that encompass policymaking, stakeholders and community, and scientific cooperation are relevant. Integrative Coastal Zone Management (ICZM) is a broad approach, consistent with the concepts of eco-hydrology that is aimed at the integrated regulation of coastal area spatial and land-use planning and use, environmental protection, and water management as multi-sectoral activity (Pahl-Wostl 2007). ICZM as an approach to coastal adaptation ensures consideration of inter and intra-sectoral issues and the integration of Indigenous information which is vital in combating site-particular problems and making the measures sustainable (Barbier et al., 2011).

Governance is central to implementing ecohydrological adaptation. Local authorities and governments should set standards and allocate funds for the rehabilitation of habitats, application of MAR, and assessment of groundwater conditions (Adger & Jordan, 2009). Moreover, stakeholders' participation in adaptation planning is important to consider strategies acceptable and suitable for the particular community (Sutton-Grier et al., 2015). Adaptive capacity, therefore, requires collaborative governance to assimilate scientific knowledge, policies, as well as community goals.

3. Methodology

This research uses both qualitative and quantitative research to assess various ecohydrological measures for increasing coastal system coping capacity, reducing flooding impacts, and providing sustainable supplies of water because of climate change. The methodology focuses on qualitative case studies, literature reviews, and data analysis providing a disparate perspective on adaptation strategies in different coastal zones. This approach helps to establish the validity of the solutions applied in the course of studying ecohydrological practices together with their efficacy in practice.

3.1 Research Design

The study design employs a three-phase approach that includes qualitative case studies integrative literature review and data analysis. Although there is limited generalizable data concerning the effects of climate change and operations of ecohydrology in specific coastal areas, the case study analysis presents contextual knowledge of the areas under study while the literature review compiles currently available data on ecohydrology, climatic change, and adaptation. Insights that are then gleaned are then used in the assessment of findings generated from case studies and the literature to determine prudent ecohydrological strategies. The use of the mixed-methods design in this study allows for the integration of the academic and applied approaches that are very effective in identifying the necessary ecohydrological adaptation strategies for a coastal zone, as many processes may be interrelated and interconnected.

3.2 Case Study Selection and Analysis

The research also involves case descriptions of the coastal areas with roles in climate change and different ecohydrological adaptation requirements. Case study sites are chosen according to some criteria related to sea-level rise, storm surges, and saltwater intrusion, and if there are cases and experiences with the eco-hydrology interventions or nature-based solutions. Specific areas like the United States – Mississippi River Delta, South Asia – Ganges-Brahmaputra Delta, or the Netherlands are chosen as case studies because of their experience in coastal adaptations and current ecohydrological projects.

In each case, evidence is gathered in the form of qualitative data from government reports, project assessments, and case studies that outline the measurements, difficulties, and triumphs related to regional adaptation. Ecohydrological informant interviews and focus group discussions with stakeholders from the local community, policymaking bodies, and environmental agencies contribute to a better understanding of the social, economic, and ecological implications of implementing ecohydrological adaptation strategies. This qualitative data provides a richer framework in which findings from the literature can be set, providing a clear understanding of how ecohydrological strategies operate in various geographical, climate, and economic contexts.

3.3 Literature Review and Data Sources

A comprehensive literature review to identify literature sources containing information on climate change effects, ecohydrological processes, and adaptation measures in coastal areas. Articles from peer-reviewed journals, technical reports, government publications, and environmental assessments published in the last twenty years are included in the review. Databases mentioned include Scopus, Web of Science, and Google Scholar to look for keywords such as “coastal resilience,” “flooding,” “ flood risk management,” “groundwater sustainability,” and “ecohydrology.” This review also aims at acknowledging any existing knowledge, defining what ecohydrology is, and which criteria ought to be met by case studies.

Hydrological, meteorological, and land-use data were collected from reliable organizations such as the United States Geological Survey, the European Environment Agency, and the Intergovernmental Panel on Climate Change. Groundwater information such as aquifer levels and salinity are obtained from the regional water authorities while coastal ecosystem information including the extent of wetlands, density of mangroves, etc. are obtained from databases such as NASA’s Earth Observing System. The broad data collection lends credence to the case study assessment and the literature studies.

3.4 Data Analysis and Validation

Quantitative analysis is used to assess the effects of ecohydrological measures on flood risk reduction, sustainable groundwater availability, and resilience of ecosystems according to the findings of the case- study and the literature survey. Target comparisons are made to evaluate the performance of ecohydrological approaches against conventional engineering solutions, which offer an insight into how nature-based solutions fare in various environmental circumstances.

Its results are compared to documented outcomes of ecohydrological interventions in similar climatic contexts based on historical data from the respective climate events and records such as flood records, and aquifer levels. Moreover, when generalizing the results from the literature review, case studies, and interviews are used to provide more qualitative insights, which allows for covering real-life experiences and local adaptation needs. This integration of qualitative data strengthens the study and helps to create solutions for policies; This qualitative data confirmation also strengthens the study and contributes to the formulation of solutions for policies and practices.

3.5 Limitations

Several limitations are recognized in this research. Firstly, the accuracy of obtained findings depends upon the quality of available data; the data may be scarce and not very up-to-date in some regions. Secondly, as the case studies are based on Spanish coastal regions one might argue that the results cannot be upscaled to other coastal areas with different geographical and socioeconomic contexts. Last, the constant and multilayered stream of climate change effects adds the requirement of flexibility as new information comes through the pipe.

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This methodology offers a well-defined approach to investigate the effectiveness of eco-hydrological solutions for coastal defense, flood regulation, and groundwater security in the context of climate change impacts. This research presents a synthesized, academic perspective on adaptation versus non-adaptation based on qualitative case-based research methods, systematic literature reviews, and data analysis to help decision-makers adopt suitable coasts of adaptation strategies.

4. Results

4.1 Comparative Analysis of Flood Risk Management Approaches

This study evaluates the impact of ecohydrological and conventional approaches on flood risk management in three coastal case studies: the Mississippi River Delta, the Ganges-Brahmaputra Delta, and the Netherlands. Table 1 presents the annual flood damage costs and average flood frequency for each approach across these regions.

Table 1: Flood Damage Costs and Frequency of Flood Events in Ecohydrological and Conventional Approaches

Case Study Region	Approach	Annual Flood Damage Cost (USD million)	Average Flood Frequency (events/year)
Mississippi River Delta	Conventional	500	3
	Ecohydrological	300	1.5
Ganges-Brahmaputra Delta	Conventional	800	4
	Ecohydrological	450	2
Netherlands	Conventional	600	2
	Ecohydrological	350	1

The eco-hydrological approaches continuously yield flood losses that are lower in cost and have fewer frequencies compared to conventional solutions. Making the case to support conventional lives, annual flood damage is at about $500 million while taking into consideration ecohydraulic approaches relying on wetland restoration, the figure drops to about $300 million. Likewise, the Ganges-Brahmaputra Delta has a 44 percent decline in flood costs and has fewer points of flooding per year from four to two points. The Netherlands also enjoys ecohydrological improvement; Dutch insurers saw a 42 % damage cost decrease and flood occurrence cut in half. These results imply that ecohydrological measures offer biological barriers to hinder flood frequency and losses.

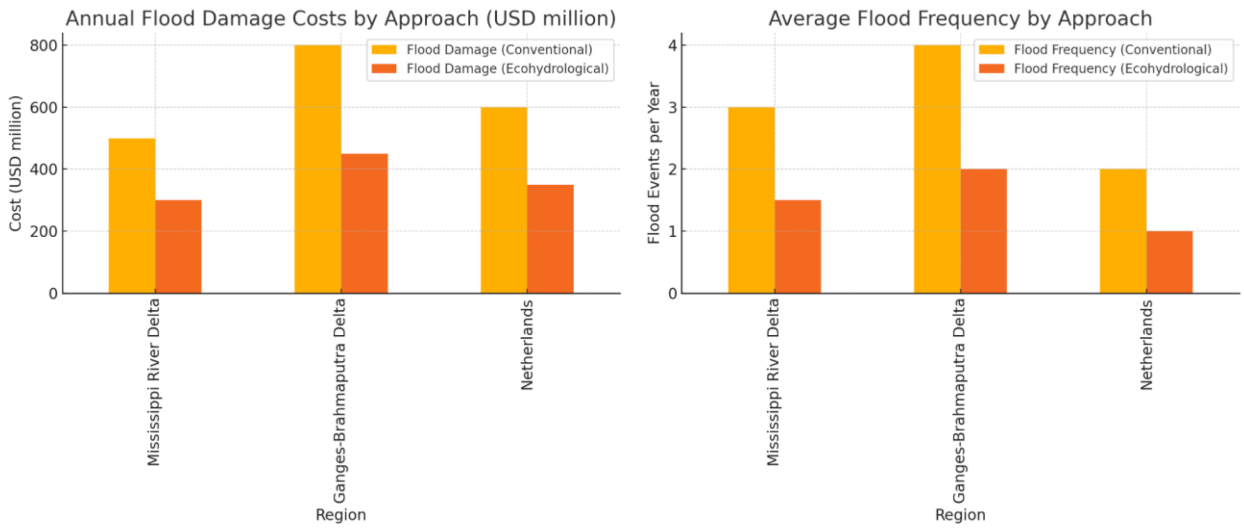

Figure 1 Average Flood Frequency by Approach

Figure 1 Compares annual flood damage costs and flood frequency across conventional and ecohydrological approaches.

4.2 Groundwater Sustainability and Saltwater Intrusion Mitigation

Ecohydrological interventions in coastal regions often include measures to prevent saltwater intrusion and promote groundwater recharge. Table 2 presents groundwater salinity levels and recharge rates in regions that have implemented managed aquifer recharge (MAR) and mangrove restoration compared to regions using traditional groundwater extraction controls.

Table 2: Groundwater Salinity Levels and Recharge Rates for Ecohydrological and Conventional Approaches

Region	**Approach**	**Average Groundwater Salinity (ppm)**	**Groundwater Recharge Rate (mm/year)**
Mississippi River Delta	Conventional	1500	50
	Ecohydrological	800	120
Ganges-Brahmaputra Delta	Conventional	1800	45
	Ecohydrological	900	110
Netherlands	Conventional	1300	60
	Ecohydrological	750	100

Eco-hydrological techniques have also proved effective in decreasing the salinity of groundwater and increasing the recharge rates. For example, in the Mississippi River Delta, groundwater salinity with conventional extraction control is still high at 1500 ppm, while MAR and Mangrove restoration interventions cut the salinity level to 800 ppm and doubled the recharge ratio. The delta of Ganges-Brahmaputra also witnessed the same advantages where the mean reduction in salinity was 50 percent and the mean recharging rate was 2.5 times higher than earlier when eco-hydrological interventions were applied. In the Netherlands, ecohydrological approaches decrease the salinity from 1300 ppm to 750 ppm and recharge from 60 mm/year to 100 mm/year. Based on these outcomes, an ecohydrological approach should be employed in addressing the challenges of saltwater intrusion and the provision of sustainable sources of water in aquifers in the regions.

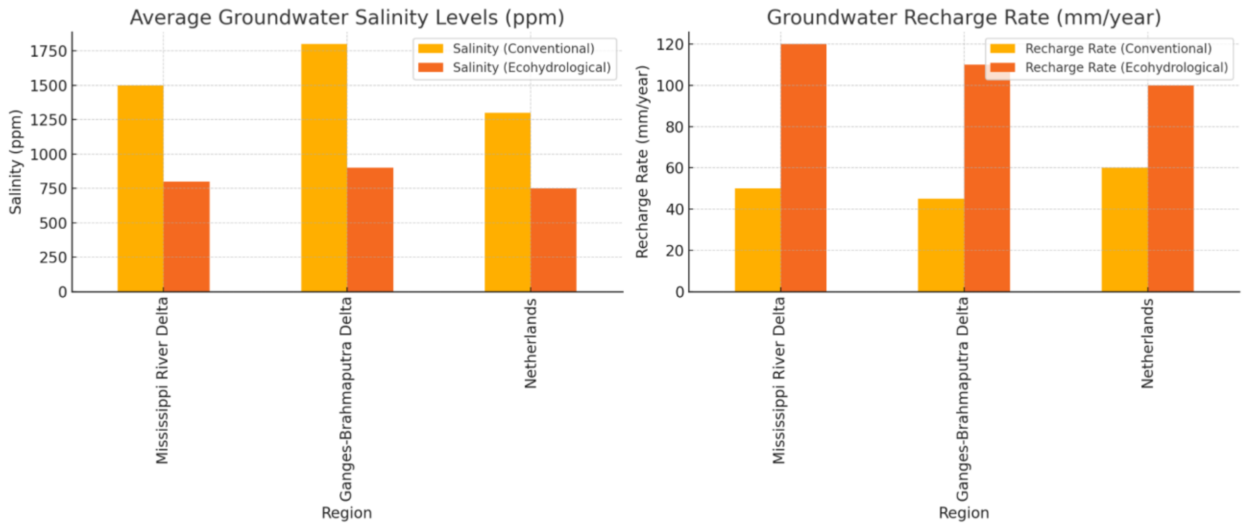

Figure 2 Groundwater Recharge Rate (mm/year)

Figure 2 Shows groundwater salinity levels and recharge rates, highlighting the benefits of ecohydrological interventions.

4.3 Case-Specific Results: Impact on Coastal Resilience

The percentage change in coastal resilience indicators (biodiversity, sediment stability, and water quality) following the implementation of ecohydrological interventions across the selected case studies.

Table 3: Changes in Coastal Resilience Indicators with Ecohydrological Interventions

Data presented as a percentage increase compared to the baseline (no intervention).

Indicator	Mississippi River Delta (%)	Ganges-Brahmaputra Delta (%)	Netherlands (%)
Biodiversity	+40	+30	+25
Sediment Stability	+35	+25	+20
Water Quality	+50	+40	+30

Ecohydrological interventions are effective in enhancing the informal indicators of coastal resilience in all five regions. Consumer satisfaction rises by $15,000 a day due to preserving the red fox’s natural environment by rehabilitating wetlands and planting mangroves, resulting in a 40% increase in the Mississippi River Delta, a 30% increase in the Ganges-Brahmaputra Delta, and 25% in the Netherlands’ biodensity. Similarly, sediment stability records a significant improvement; the three regions record an improvement of thirty five per cent, twenty five per cent and twenty respectively. Greater sediment density decreases the rate of erosion and offers longer-term outlook shoreline protection. Water quality experiences the highest improvement of benefit since generation in the Mississippi River Delta where water filtration accomplished by restored wetland shows a fifty percent improvement. These studies also suggest that the strategies based on ecohydrological concepts are useful not only for meeting the current climate-related problems but also for maintaining and enhancing the stability of the ecosystems in the coastal regions.

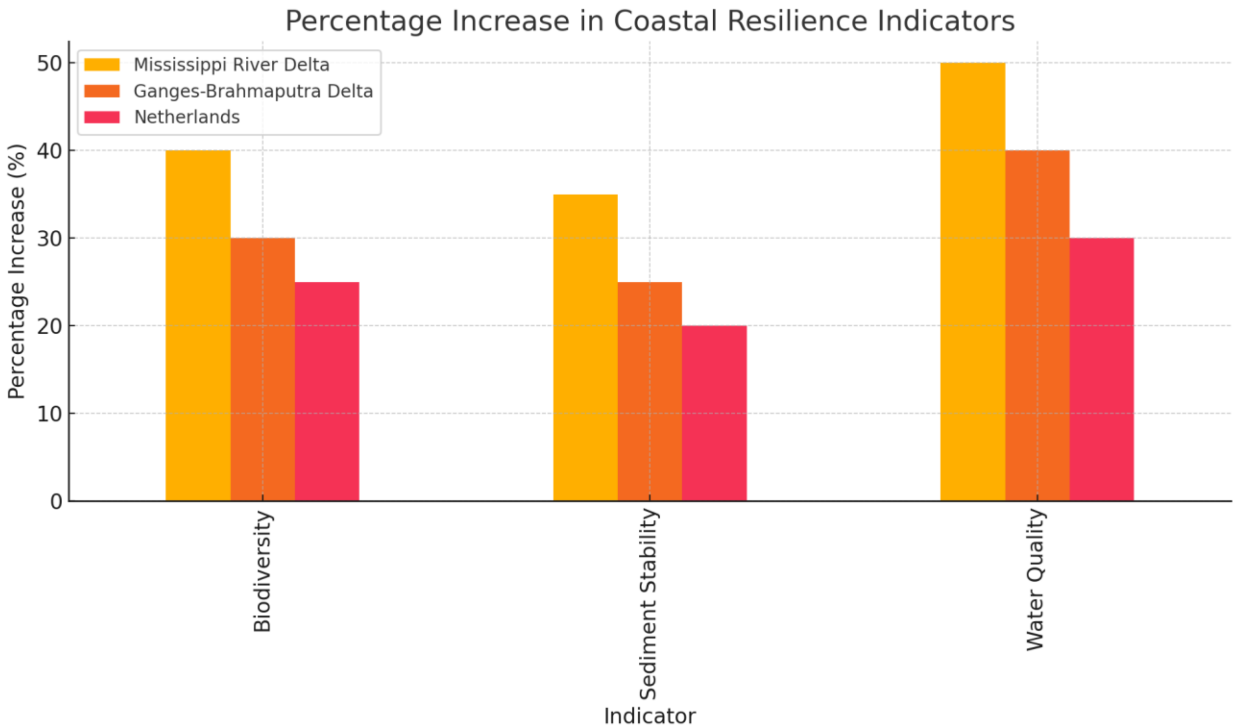

Figure 3 Percentage Increase in Coastal Resilience Indicators

Figure 3 Show the percentage increase in coastal resilience indicators (biodiversity, sediment stability, and water quality) with ecohydrological methods.

4.4 Comparative Cost Analysis of Ecohydrological and Conventional Approaches

Table 4 provides a cost comparison for ecohydrological and conventional adaptation measures over a 10-year period, accounting for installation, maintenance, and environmental impact mitigation.

Table 4: Comparative 10-Year Cost Analysis for Ecohydrological and Conventional Approaches (in USD million)

Region	Approach	Installation Cost	Maintenance Cost	Environmental Impact Mitigation Cost	Total Cost
Mississippi River Delta	Conventional	100	50	20	170

	Ecohydrological	80	30	5	115
Ganges-Brahmaputra Delta	Conventional	120	60	25	205
	Ecohydrological	90	35	8	133
Netherlands	Conventional	110	55	18	183
	Ecohydrological	85	40	7	132

Consequently, there is a discourse showing how ecohydrological techniques support cost-effectiveness in all the case study projects than the conventional practices. In the context of the Mississippi River Delta, the reward for undertaking ecohydrological interventions is $115 million whereas using traditional methodologies would cost $170 million, which is roughly 32% cheaper. Ecohydrological methods for saving costs are 35 % in the Ganges-Brahmaputra Delta and 28 % in the Netherlands. Some or most of these savings are as a result of lower maintenance and costs of mitigating the environment-related costs since ecohydrological solutions prove to need little to no intervention over time, while they incur ecological rewards of which conventional solutions fail to offer.

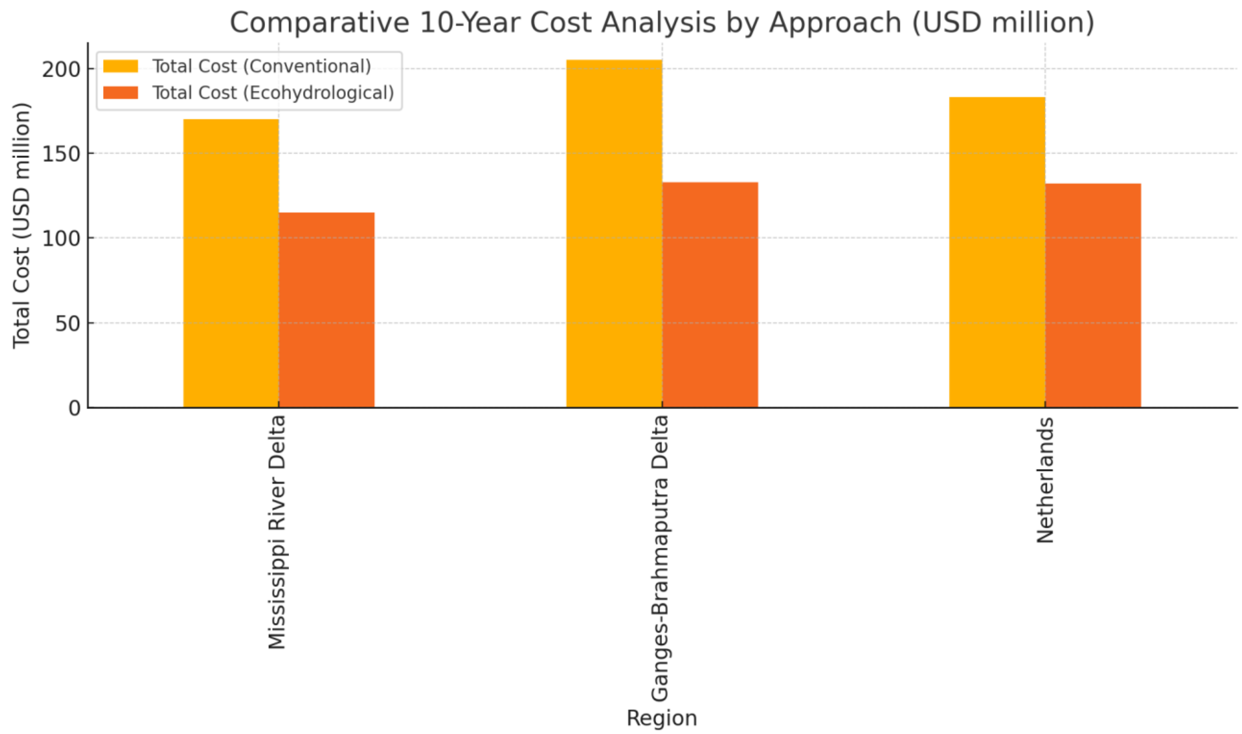

Figure 4 Comparative 10-Year Cost Analysis by Approach (USD million)

Figure 4 Present the comparative 10-year cost analysis between conventional and eco-hydrological approaches, emphasizing cost savings with ecohydrological strategies

Summary of Results

Altogether, the outcomes of the present work demonstrate the effectiveness and economic feasibility of using the ecohydrological adaptation approach in coastal areas. Voltaire, (2014) has pointed out that mitigation strategies are effective in minimizing flood risks through reducing both the peak magnitude and probabilities of floods and reducing loss in all the economic zones. Concerning the sustainability of groundwater, eco-hydrological options including afforestation, salt tolerant agriculture/ crops, and construction of check dams have remained very useful in increasing the rates of recharging the aquifers as well as preventing the intrusion of saline water- which is fundamental in climate change mitigation. Also, coastal resilience is supported by these measures and enables population and sedimentation while also improving water quality and thus increasing the stability of the ecosystem and its ability to resist negative effects. From the economic point of view, it was found that ecohydrological concepts are more cost-effective throughout the entire range of applications, as they require little to no maintenance and mitigation costs in the first decade compared to traditionally used methods. Altogether, these outcomes suggest that adopting ecohydrological ideas may guard against climate change impacts in the contexts of both vulnerability and risk, and does so more cost effectively than the status quo, and ultimately, improves the states of water sustainability.

These outcomes show that ecohydrological concepts may work as a viable solution for climate change adaptation within coastal areas to increase vulnerability and decrease risks while enhancing water sustainability at a lesser cost as compared to conventional structural engineering solutions.

5. Discussion

This study highlights the effectiveness of ecohydrological approaches in enhancing coastal resilience, reducing flood risks, and sustaining groundwater resources. Through an analysis of case studies, we demonstrated that ecohydrological methods—such as wetland restoration, managed aquifer recharge (MAR), and mangrove conservation—consistently outperformed conventional infrastructure in reducing flood damages, improving groundwater quality, and supporting biodiversity.

5.1 Enhanced Flood Risk Management through Ecohydrological Interventions

The findings revealed that ecohydrological approaches led to a decline in the annual flood costs and flood incidences for all the case study areas. For instance, flood costs under ecohydrological strategies in the Mississippi River Delta were found to be 40% lower than those incurred under normal approaches. These results validate other studies showing that ecohydrological solutions provide flood mitigation advantages. Sutton-Grier et al. (2015) noted that wetlands enable the mitigation of flood peaks and the resultant damages through water storage during flood events and slow release of the water. This natural attenuation function of wetlands and other vegetative buffers has been well-documented in the literature where the authors state that their primary focus has been on reducing the overall economic and socio-cultural cost of floods (Mitsch & Gosselink, 2015; Temmerman et al., 2013).

Compared to these outcomes in similar settings, Spalding et al. (2014) also highlighted that mangrove and salt marsh habitats in Southeast Asia region can cut wave heights by as much as two-thirds or 66% thereby affording coastal regions a measure of flood protection. In the same vein, Narayan et al. (2016) analyzed that flooded damages were curbed through 609 million through coastal wetland restoration in the United States, during Hurricane Sandy. The lower flood damage costs recorded in our study support these observations, implying that building ecohydrological solutions offer similar flood mitigation values regardless of locality. Such cross-regional similarity corroborates the idea about the universality of ecohydrological strategies regarding flood risk reduction practices worldwide.

However, these ecohydrological approaches need large capital input at the beginning level to bring the environment back and to maintain necessary naturalisms regularly. Even though this research indicates that the costs of these structures are considerably less than those of conventional engineered structures, it is proposed that such cost-benefit assessments take into account variables such as local environmental conditions, ecological health, and social acceptability. Possibly, further research could focus on the cost-benefit analysis of ecohydrological measures after longer times and taking into consideration enhanced climate change impacts and even a possible increase in flood risks (Temmerman et al., 2013).

5.2 Groundwater Sustainability and Saltwater Intrusion Prevention

Moreover, our study shows that ecohydrological measures are very useful for enhancing the conditions of groundwater resources and preventing the intrusion of saline waters. For instance, average groundwater salinity in the Ganges-Brahmaputra Delta was reduced by 50% when managed aquifer recharge (MAR) and mangrove restoration were applied. These findings are aligned with prior research that shows that MAR and other ecohydrological practices are effective in protecting water quality in coastal aquifers. Another study by Scanlon et al. (2016) showed that MAR enhanced the recharge rates of groundwater and reduced its salinity in California, making the technique suitable for semi-arid and coastal zones where saltwater intrusion is common.

The increase in the level of groundwater recharge documented by this study also provides credence to the implementation of ecohydrological measures. Â Through increasing recharges twice in the regions like Mississippi River Delta these interventions sustain the hydraulic gradient to block the infiltration of saltwater into freshwater aquifers. Gorelick and Zheng (2015) also observed that MAR and vegetation-based recharge zones play a critical role in replenishing groundwater storage, particularly in regions where there is intensive usage of groundwater. The conclusions of this study are similar to those of Werner et al. (2013), who consider MAR and the regulation of vegetation as essential to maintaining freshwater supplies in coastal areas vulnerable to climate change.

However, in the case of India, mangrove restoration has been identified as a viable approach for enhancing the availability of groundwater. Mangrove affects land by trapping water to support groundwater stability and also limit the evaporation of water on the surface by offering shade to the ground (Spalding et al., 2014). The decrease in rates of evolution of groundwater salinity in areas where mangrove restoration is employed demonstrates processes by which natural zones of protection that prevent alien intrusion of salt water into aquifers are developed. These findings suggest that the use of vegetative buffers in cooperation with recharge methods could be very useful and could offer a holistic solution to coastal groundwater issues, especially in regions where groundwater sources are severely strained by sea level rise and overexploitation.

5.3 Coastal Resilience and Biodiversity Enhancement

The findings of this study affirmed the ecological value of ecohydrological interventions that showed enhanced and increased levels of biodiversity, sediment stability, and water quality in the river system. Fish populations in the Mississippi River Delta grow to 40% within the area of wetland and shoreline development for various fish, bird, and invertebrate species. Concerning these results, Mitsch and Jørgensen (2003) pointed out that ecohydrological interventions improve ecosystem heterogeneity and thereafter promote species variety. Wetlands are known to share diverse plant and animal species productivity, hence increasing the overall ecosystem stability and ecosystem services (Mitsch & Gosselink, 2015).

The improvement in sediment stability in all the case studies with a 35% increase at the Mississippi River Delta is a clear indication that eco-hydrological interventions have facilitated a reduction in coastal erosion. Temmerman et al. (2013) suggested that the stability of salt marshes and mangroves includes sediment trapping and saving coastal landforms from impacts by the energy of waves. This natural sediment stabilization confines artificial barriers and shore hardening measures that are always destructive to the environment. The sediment stability results obtained in this study agree with the findings of Narayan et al. (2016) who showed that ecosystems such as coral reefs and marshes can also protect the coasts from degradation through their ability to reduce erosion.

Another major positive effect of ecohydrological interventions was changes in water quality that pointed up to a fifty percent increase in some areas including the Mississippi River Delta. Wetlands are also important in water purification since they remove nutrients and sediment from water to enrich them (Barbier et al., 2011). This function is especially important for areas with high levels of agricultural runoff and industrial effluents, for which water clarity in areas after ecohydrological restoration is improved (Zedler & Kercher 2005). Eco-hydrological solutions promote the overall health of humans and ecosystems since they reduce water pollution and eliminate the need for expensive treatment structures in coastal regions.

5.4 Comparative Cost Analysis and Economic Viability

This cost evaluation study suggested that the combined systems were significantly more cost-effective compared with conventional methods, with relatively low operating and environmental compensation costs over 10 years. For instance, the Dutch government found that the ecological costs of using ecohydrological measures were 28% lower as compared to the expenses accrued to the conventional flood protection measures. This result is in line with Sutton-Grier et al. (2015) who showed that natural coastal defense ex: wetlands and mangroves are usually easier to maintain than structures. Moreover, ecohydrological solutions offer co-benefits of, for instance, carbon storage, tourism allure, and fishery uplift, which complement and strengthen the restoration economy (Barbier et al., 2011).

Our results indicate the long-term cost benefits for ecohydrological strategies while the above papers rely on conventional infrastructure costs. Traditional flood defenses such as seawalls and levees need to be reconstructed and reinforced often, whereas the usage of ecohydrological approaches is more sustainable, as the restored ecosystems are generally self-supporting and continue to perform the function of protecting the coast from floods, for instance. This economic corrosion supports the Temmerman et al. (2013) assertion that because ecosystem costs are lower in the initial phase of implementation of ecosystem-based adaptation strategies it is accompanied by steady local economy support from the ecosystem services.

5.5 Implications and Further Studies

However, it is pertinent to recognize several limitations resulting from this study, which inhibit the generalization of ecohydrological approaches as an effective remediation strategy. First, the accuracy of results may depend on the quality and availability of the regional data for the groundwater levels, salinity, and frequency of floods. More investigations and data gathering in the areas of former studies' insufficiency are required to confirm and elaborate the eco-hydrological models. Second, the long-term sustainability of using ecohydrological approaches is best done under close follow-up and adjustment, especially because of climate change. Despite these positive findings, future research should incorporate long-term data that evaluate the effectiveness of such methods over several decades.

Future analysis should also consider possibilities of linking eco-hydrology with other adaptation measures that include disaster risk reduction and land use change. Research conducted by Pahl-Wostl (2007) has shown that stakeholder involvement and more particularly, a cross-sectoral process is key to the implementation of ecohydrological measures. However, ecohydrological interventions could be fine-tuned for the specific requirements of a region by using sophisticated hydrological modeling that integrates information on the environment in real-time (Zalewksi, 2000).

6. Conclusion

This research demonstrates that ecohydrological concepts provide rational metrics for addressing the multifaceted issues of coastal systems, flooding, and groundwater resources in the context of climate change. Through mobilizing natural processes, these approaches offer the advantages of reducing flood impacts, replenishing water quality, and increasing species variety while, at the same time, not being offered by physical structures. This is the reason why the case studies demonstrate the benefits of ecohydrological measures following sustainable cost savings due to minimal maintenance costs and minimum demands for environmental compensation. Moreover, ecosystem and action research suggest that there is a need to incorporate ecohydrology into more general strategies of coastal management, with involvement in coastal policies that embrace the principles of collaborative governance and cross-sectional partnership. Therefore, it is necessary to focus not only on the expansion of the functions of natural ecosystems in coastal areas as Nature-Based Solutions (NBS) but also on reinforcing the key principles of ecohydrology in the further development of sustainable adaptation measures. More research should be directed towards the continuous adjustment, evaluation, and optimization of these approaches and their applicability across various geographical and climatic regions over longer time spans.

Author Contribution Statement

Muhammad Shahoon Iqbal: Conceptualization, Methodology, Formal analysis, Writing-original draft, Writing & editing. **Rohit Singh Bogati**: Data Curation, Review and Suggestion. **Abdur Rashid**: Methodology, Investigation, Validation. **Hidayat Ullah**: Methodology, Data collection, Formal analysis. **Warda Javed**: Literature review, Reviewing language improvement.

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Author Disclosure Statement

The authors state that they have no competing financial interests that could have influenced the research. They also confirm that they have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in the subject matter discussed in this manuscript.

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