

Wetlands and Climate Change Resilience, an Enhancing Ecosystem Services for a Sustainable Future: A Review

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Abstract: Wetlands are crucial in enhancing climate change resilience due to their unique ecological functions and services. These unique networks are vital in carbon sinks in their soils, plants, and peat layers, mitigating climate change by sequestering carbon dioxide from the atmosphere. Wetlands are susceptible to weather events with increasing temperatures, changed precipitation patterns, and risky weather events that affect their stability and function. The degradation of wetlands due to human activities, such as drainage for agriculture, urbanization, and peat extraction, exacerbates these vulnerabilities. Conversely, the conservation and restoration of wetlands offer significant potential for climate mitigation by enhancing carbon storage and reducing emissions. This review examines the intricate contributions of wetlands to climate adaptation and mitigation, analyzing various studies and models that highlight their importance. Wetlands play a dual role in climate variations as vital ecosystems that can help vulnerable environments that need protection to prevent the release of stored greenhouse gases. They are essential to combat climate change through carbon sequestration. We explore the mechanisms through which wetlands regulate hydrological cycles and carbon sequestration and provide barriers against extreme weather events. Furthermore, the review identifies gaps in current research and suggests future directions for maximizing the persistence potential of wetlands regardless of accelerating climate change. This review paper explores the strength of wetlands, focusing on their ecological importance, impacts of climate change, vital resilience mechanisms, and human adaptation strategies. The paper synthesizes current research findings and provides future research and policy recommendations.

Keywords: wetlands; climate change; carbon cycle; wetland restoration; climate change resilience; human Adaptation strategy

1. Introduction

Wetlands are unique ecosystems that serve more than one function, providing a variety of ecological functions critical for environmental health and human well-being. Wetlands, which encompass marshes, swamps, bogs, and fens, are the most effective ecosystems. They offer many ecological offerings critical to environmental balance and human well-being. In weather extremes, wetlands have gained interest for their capacity to enhance resilience via environmental processes. This creation unit the degree of knowledge of the essential position of wetlands in weather alternate resilience via outlining their key functions, the threats they face from weather alternate, and the significance of keeping and restoring those ecosystems. Wetlands are essential ecosystems that offer several ecological benefits, like water purification, flood management, and carbon sequestration (Karmakar, S. et al., 2024). However, they may be incredibly at risk of weather alternatives. This paper evaluates the influences of weather alternatives on wetlands, their resilience mechanisms, and techniques to enhance their resilience. This review is beneficial for environmental researchers and academics for their future work. The policymakers and planners are tasked with building up their consecutive policy development strategies. The local communities and non-governmental organizations have benefited, giving support for the protection and



restoration of the wetland ecosystem. Climate scientists and urban planners have a guideline to build sustainable mitigatory development programs.

2. Wetland Ecology: Definition and Classification

The wetlands are a wide environmental area that explains regions in which land and water cooperate, distinguished by the water's existence at diverse occurrences and positions, creating a unique and wet environment. A variety of environments, including marshes, swamps, mudflats, estuaries, lakes, marsh forests, mangroves, and many aquatic ecosystems, are referred to as wetlands. These areas are usually rich in ecological variety, supplying wealthy surroundings that support several flora, fauna, and surrounding services. Here are diverse strategies for categorizing wetlands; these special classifications aid in the higher safety and control of those priceless environments to confirm they keep offering surrounding services, flood control, water refinement, flora and fauna habitats, and sources associated with socio-economic events. The significance of wetlands creates them an important location for maintainable environmental management (Mitsch, W. J. et al., 2015; Wang, Y. (Ed.), 2020; Lu, M., et al., 2024).

Classification of Wetlands into 5 categories, which may include (1) Based on water type, they are in three types- Freshwater wetlands are categorized by the occurrence of non-saline water and are typically found inland, away from coastal areas, which include lakes, rivers, streams, ponds. Saltwater wetlands are found in littoral areas where they are affected by saline water, usually from the ocean. The salinity levels can vary depending on the tidal effects and freshwater contribution from rivers. Encircling coastal salt marshes, estuarine wetlands, and littoral lakes are stimulated through waves and saline water (Mitsch, W. J. et al., 2015). Brackish wetlands are transitional zones between freshwater and saltwater wetlands, typically found in estuarine environments where freshwater from rivers mixes with seawater. These wetlands consist of salt pans and coastal salt-tolerant vegetation (<https://forest.jharkhand.gov.in/>).

(2) Based on water periodicity, there are three types: Perennial wetlands have a constant presence of water throughout the year, regardless of seasonal changes. These wetlands are often fed by permanent sources such as springs, rivers, or consistent rainfall (Keddy, 2010). Seasonal wetlands are characterized by water presence only during certain times of the year, typically during the rainy season or when snow melts. The water levels can alter significantly throughout the year. These wetlands may include seasonal ponds and marshes. Intermittent wetlands are wetlands that are periodically flooded without following a specific seasonal pattern. Their flooding depends on asymmetrical events such as heavy rains or river runoffs (Devánová, A., et al., 2023). These wetlands may include floodplains and ephemeral ponds.

(3) Based on geographic location, the wetlands are divided into three categories- Coastal wetlands are located in coastal regions and are influenced by marine processes such as tides, waves, and saltwater intrusion. These wetlands often form the transition zone between land and marine environments (Keddy, 2010). These wetlands consist of estuaries, beaches, mangroves, and coastal lakes. Inland wetlands are situated away from the coast and are typically fed by freshwater sources such as rivers, lakes, or underground aquifers. These wetlands can be found in a variety of landscapes, including plains, forests, and deserts (Keddy, 2010). Located inside the land, including marshes, lakes, mudflats, and many wetland grasslands. Mountain wetlands are located in peak-level areas, regularly characterized by cooler temperatures and unique vegetation adapted to the harsh environment. These wetlands can be found in mountainous areas across the world (Ramsar Convention Secretariat, 2016), such as high-level lagoons and mountain swamps.

(4) Based on the biological diversity and atmosphere nature wetlands are categorized into three groups- Swamps are wetlands that are often permanently or seasonally inundated with water and are rich in organic material. They are usually dominated by trees or shrubs, making them different from marshes, which are dominated by herbaceous plants (Mitsch, W. J. et al., 2015). Typically, naturally wealthy lands help ferns, mosses, and aquatic plants. Mangroves are coastal wetlands enriched by salt-tolerant mangrove trees. These trees have specialized root systems that allow them to thrive in saline environments, and they play a crucial role in coastal ecosystems, which may include red mangroves and black mangroves. Wetland grasslands are wetlands dominated by various grasses and other herbaceous plants. These areas often experience periodic flooding and provide important habitats for wildlife, especially birds (Keddy, 2010). These wetlands may include Prairie Potholes and floodplain wetlands.

(5) Artificial Wetlands- these types of wetlands are created or changed by humans, including rice fields, ponds, and wastewater remedy wetlands utilized for water quality control, water first-class enhancement, and flora and fauna protection.

3. Ecological roles and Ecosystem Services of the Wetland Ecosystem

3.1. Biodiversity Provisioning Services

Wetland ecosystems are critical locales for diverse species, which include waterfowl, migrating birds, wetland vegetation, fish, reptiles, and invertebrates. They bid on meals and accommodation for aquatic creatures, birds, frogs, and other species that depend on wetland habitats. (Scott, D. A. et al., 1995; Lu, M., et al., 2024). Genetic Diversity is the diverse range of species in wetlands that contributes to genetic diversity, which is essential for ecosystem resilience and adaptability.

3.2. Water Quality Improvement and Water Regulation

The wetlands serve as an effective water sanitization structure by soaking up and breaking down pollutants, sieving wastewater, and decreasing the influx of nutrients into water bodies. This facilitates maintaining the pleasantness of water, guards the consumption of water supplies, and decreases the effect of water contamination (Lu, M., et al., 2024). They can absorb excess nutrients from agricultural runoff, reducing problems like eutrophication in downstream water bodies. Toxicant Breakdown wetlands can help break down and neutralize harmful substances, such as heavy metals and pesticides, through biogeochemical processes. Wetlands can control floods, which act as natural sponges, absorbing and storing surplus rainfall, which helps to decrease the severity of floods. They slow the water flow, allowing it to be released slowly over time. Wetlands play an important role in replenishing groundwater resources. They allow water to percolate down through the soil, recharging underground aquifers. Water surplus contains wetlands that play a vital role in contributing to maintaining groundwater supply, managing water flow, alleviative drought and flood hazards, safeguarding a stable water supply, and are important for water supply, agriculture, and industrial desires (Tiner, R. W., 2005).

3.3. Climate Regulation

The Carbon Sequestration potential of the wetlands stores large amounts of carbon in their plant biomass and soils, making them significant carbon sinks. They help moderate climate change by absorbing carbon dioxide from the atmosphere (Bhandari, M. P., 2024). The peat layers of the wetlands store the carbon, so they protect our earth by reducing greenhouse gas emissions and help to maintain global carbon stability (Bridgham, S. D. et al., 2006). Wetlands can regulate local climates by absorbing heat during the day and releasing it at night, which can influence local temperature patterns.

3.4. Erosion Control and Nutrient Cycling

Shoreline Stabilization, the wetland vegetation, such as mangroves and reeds, helps to stabilize shorelines and riverbanks, reducing erosion caused by waves and currents. The roots of wetland plants bind the soil, preventing it from being washed away (Costanza, R., et al., 1997). Wetlands are active systems in the Biogeochemical cycle, where nutrients like nitrogen and phosphorus are cycled through various processes, including decomposition, mineralization, and plant uptake. This cycling upholds soil fertility and supports the food web. The microorganisms in the soil break down the organic materials into small particles that support plant growth, ecosystem maintenance, and productivity (Mitsch, W. J. et al., 2015).

3.5. Provisioning Services Cultural and Recreational Values

Wetlands provide natural resources like fish, shellfish, timber, and medicinal plants. They are also sources of raw materials like peat and reeds. Some wetlands contribute to the renewal of freshwater resources, providing water for agricultural, drinking, and industrial use. Wetlands are home to natural medicinal plants used in traditional and modern medicine (Millennium Ecosystem Assessment, 2005). Many cultural significances have strong spiritual and historical influences on wetlands. They are often sites of cultural heritage and traditional practices. Recreational Opportunities in wetlands offer recreational activities such as birdwatching, fishing, hunting, and eco-tourism, contributing to local economies and raising awareness about management. Many cultures view wetlands as sacred spaces, and they are often used for environmental studies and research purposes (Ramsar Convention Secretariat, 2018).

3.6. Scientific and Educational Value

In the research and education field, wetlands offer chances for scientific research and environmental education. They serve as natural laboratories for studying ecological processes, species interactions, and environmental changes to promote environmental conservation and sustainable management (Craft, C.

B., et al., 1991). This will help implement policies and laws for degraded areas and make people aware of the conservation of natural resources.

4. Climate Change Impacts on Wetlands

4.1. Temperature Changes and Precipitation Patterns

Rising temperatures increase evaporation rates, leading to wetland drying, and the precipitation alternation leads to extreme weather events like drought and rainfall. It makes a huge impact on the surroundings and depending wetland ecosystem. Drought phenomena result in the drying of wetlands and affect the habitat functioning of the ecosystem (Zedler, J.B., et al., 2004). The extreme precipitative events lead to flooding, and affectation risks to the wetland ecosystems and their surroundings, mostly in the human population. These altered weather events also affect the hydrological sequence in wetlands. A rise in temperature leads to evaporation, decreasing hydrological levels in the wetland areas, affecting the wetland ecosystem and its management (Fraser, L. H., et al., 2005). Instabilities in the hydrological level affect the storage capacity of the reservoirs to contribute to and maintain the groundwater and river water levels. The reduced water level can lead to the drying of wetlands, and it can alter sedimentation rates and nutrient dynamics (Mitsch, W. J. et al., 2015).

4.2. Sea-Level Rise

The coastal wetlands face a serious threat from the sea levels rising which may affect numerous wetland fauna and flora species. The saline water intrusion in the natural wetland habitats is gradually changing to saline wetlands, and some are completely submerged. The saltwater intrusion impacts freshwater supplies, menacing agriculture, water intake, and industrial water usage. Also, saltwater intrusion damages wetland soil and vegetation, leading to a lowering of soil fertility and quality (Millennium Ecosystem Assessment, 2005; Lu, M., et al., 2024).

4.3. Extreme Weather Sequences

Extreme weather events increase the prevalence and intensity of storms and floods, damaging wetland infrastructure and altering habitats (Bhandari, M. P., 2024). Powerful storms and hurricanes may cause habitat destruction, coastal erosion, and water quality. This creates wetland ecosystems and surrounding communities badly, and their restoration takes long-term efforts. Coastal wetlands like mangroves are particularly vulnerable to storm surges intensified by rising sea levels (Ramsar Convention Secretariat, 2018). The wetlands, particularly the mangroves, serve as carbon sinks. The climate variation reduces the mangrove community and may lead to the oxidation of stored organic matter, liberating large amounts of carbon dioxide and methane into the atmosphere (Zedler, J.B. et al., 2005). This creates a feedback circle that intensifies global warming.

4.4. Species and Habitat Shifts

Uncontrolled temperature rise at the global level results in an upward water temperature in the wetland areas, which badly changes the wetland habitat. Few wetland plants and animals can also additionally want to conform to new situations or search for new habitats (Ma, S., et al., 2011; Lu, M., et al., 2024). This should cause an environmental niche struggle; most species are tailored to the wetland lifecycle. This may surely threaten a particular species, and others may assimilate into novel conditions, which may harm biodiversity, mainly the unique species in the wetland surroundings (Pauls, S. U., et al., 2013).

5. Resilience and Adaptation Mechanisms

The resilience and adaptation strategies of wetlands are essential for their survival and functionality, especially in the face of environmental changes such as climate change, pollution, and human activities.

5.1. Hydrological Adaptations

Water storage and release wetlands act as innate sponges, gripping excess water during the floods and liberating it gradually, which helps maintain water balance in the ecosystem. This hydrological buffer capacity is vital for flood control and sustaining base flow in rivers during dry periods. In some wetlands, especially peatlands, organic matter gathers due to slow decay under wet conditions. This peat can store huge amounts of carbon, making these wetlands significant carbon sinks. Coastal wetlands like mangroves and salt marshes can trap sediments and build elevation, helping them keep pace with sea-level rise. This natural sediment accumulation enhances flexibility to coastal erosion and flooding

(Nicholls et al., 2007; Zhu, X., et al., 2010).

5.2. Biotic Adaptations

Vegetative adaptations in Wetland plants, or hydrophytes, have particular adaptations like aerenchyma (air spaces in tissues) that allow them to survive in low oxygen (anaerobic) conditions. Examples include cattails, reeds, and mangroves. Animal adaptations within the wetland fauna, such as amphibians, fish, and birds, have adapted to changeable water levels and the unique food resources found in these habitats. For example, amphibians can use vernal pools for breeding, which are impermanent water bodies that reduce predator pressure on larvae. Aquatic species are shifting their breeding and feeding places because of the changing availability of water (Zedler, J.B. et al., 2005).

5.3. Chemical Adaptations and Ecological Resilience

Biogeochemical Cycling in wetlands is crucial for nutrient cycling, including nitrogen, phosphorus, and sulfur. Processes like denitrification (conversion of nitrates to nitrogen gas) help eradicate excess nutrients from water, reducing the risk of eutrophication in downstream aquatic systems. Toxin Filtration in wetlands can filter and break down pollutants, including heavy metals and organic contaminants, through sedimentation, adsorption, and microbial processes. Peatlands like sphagnum mosses have special characteristics to acidify the soil by releasing hydrogen ions, acidifying the environment, and inhibiting microbial decomposition, allowing organic material to accumulate over time. This adaptation enhances carbon storage and chemical balance to support life. Many wetlands produce tannins, phenolics, and alkaloids to deter behaviors and pathogens. These compounds also contribute to nutrient cycling and carbon sequestration (Zedler, J.B. et al., 2005).

Wetland microbes form biofilms that protect them from toxins and help in nutrient acquisition and pollutant degradation (Mitsch, W. J. et al., 2015). High biodiversity in wetlands contributes to resilience by providing a range of species that can respond to environmental fluctuations. This diversity ensures that ecosystem functions can be maintained even if some species decline. Wetland plant species often have seed banks or dormant life stages that can survive unfavorable conditions and renew when conditions improve.

5.4. Human-Induced Adaptations and Management

Restoration and Conservation efforts to restore and conserve wetlands often focus on re-establishing natural hydrology, replanting native vegetation, and removing invasive species. These actions help maintain the ecological integrity and amenities provided by wetlands. Creating buffer zones around wetlands can protect them from pollution and human infringement. These zones can act as provisional areas that absorb runoff and diminish nutrient loading. Implementing integrated water resources management ensures sustainable water allocation to wetlands, even during periods of scarcity. Controlled water releases from dams and reservoirs can mimic natural flood cycles to maintain the ecological integrity of floodplain wetlands (Millennium Ecosystem Assessment, 2005).

5.5. Climate Change Adaptation

Sea-level rise in coastal wetlands, for example, mangroves and salt marshes, is mainly vulnerable. Adaptation strategies include allowing wetlands to migrate inland, constructing protective barriers, and restoring natural sedimentation processes. In drought and Water Management in regions experiencing increased drought, water management strategies can be implemented to ensure that wetlands receive adequate water supplies. This can include artificial water distribution or the use of constructed wetlands for water storage.

5.6. Socio-Economic Adaptations

The sustainable use of wetland conservation, combined with sustainable economic activities such as eco-tourism, fishing, and agriculture, can help confirm that local communities value and protect these ecosystems. Policy and Legislation are necessary for effective wetland management, which often requires strong policies and legal frameworks that protect these areas from drainage, pollution, and development.

6. Challenges and Barriers Facing Wetlands

Wetlands are vital ecosystems with a range of ecological, social, and economic benefits. However, they face frequent challenges and barriers that can threaten their existence.

6.1. Urbanization and Land Development

Drainage and wetlands are often drained or covered to create space for urban expansion, agriculture, or infrastructure projects (Karmakar, S. et al., 2024). This not only diminishes the area of wetlands but also destroys habitats and alters the ecosystem. Residential and Commercial Development demand for land for housing, businesses, and industrial activities can lead to the direct alteration of wetlands into developed areas. The construction of roads, bridges, and other infrastructure can divide wetlands into smaller, isolated patches. This fragmentation disrupts wildlife movement and can lead to the loss of species that rely on larger, continuous habitats. Due to agricultural conversion and urbanization, more than 35% of the world's wetlands have disappeared since 1970 (Davidson, 2014).

6.2. Pollution Sources

Excessive utilization of fertilizers and pesticides in agricultural fields can lead to the runoff of additional nutrients like nitrogen and phosphorus into nearby wetlands. This causes eutrophication, leading to detrimental algal blooms, oxygen depletion, and the deterioration of aquatic life (Pandey, P. C., 2024). Urban runoffs from urban areas can carry pollutants like oil, heavy metals, and other contaminants into wetlands, affecting water quality and the well-being of aquatic ecosystems. The use of fertilizers and herbicide substances in agriculture and pest control can lead to their accumulation in wetlands, where they can be toxic to plants, animals, and microorganisms. The industrial discharges from industries may release pollutants directly into water bodies, which can settle in wetlands and have long-term ecological impacts (Zedler, J.B., et al., 2005).

6.3. Climate Change Scenario

Sea-level rise and altered hydrology of coastal wetlands like saltwater marshes and mangroves are mostly dangerous due to sea level rise, which can lead to flooding and loss. The loss of these wetlands diminishes coastal protection against storms and erosion. Changing precipitation patterns can alter the timing, intensity, and distribution of rainfall, affecting the water balance in wetlands. This can lead to more frequent flooding or drying, disrupting the ecosystem. Increased extreme weather events are more frequent, and severe storms, droughts, and heatwaves can stress wetland ecosystems, leading to habitat loss and reduced biodiversity. The sea level rise leads to submerging the wetlands, leading to habitat loss and life within that ecosystem (Nicholls, R. J., et al., 2007). Long-term flooding or desiccation caused by human interference, like dam construction, irrigation, and flow interruption in urban drainage systems, destroys the wetland's natural capacity to hold water. Changes in hydrology also affect the biogeochemical cycles (Zedler J. B. et al., 2005).

6.4. Invasive Species

The outcompeting of non-native species can surpass native species for their needs, leading to a decline in biodiversity. For instance, invasive plants can alter the physical structure and nutrient cycling in wetlands. Predation and Disease: Invasive animal species may prey on native species or introduce new diseases, further threatening wetland ecosystems.

6.5. Water Management and Hydrological Changes

Altered Flow Regimes of dams and water diversions can significantly alter the normal flow of rivers and streams, reducing the amount of water that reaches downstream wetlands (Pandey, P. C., 2024). This can lead to the desiccation of wetlands and a loss of biodiversity. Over-extraction of groundwater for agricultural, industrial, or municipal use can lower water tables, drying out wetlands that depend on groundwater inputs. It leads to the forfeiture of wetland vegetation and the dependent species population.

6.6. Overexploitation of Resources

Unmanaged fishing and hunting can deplete populations of fish, birds, and other wildlife in wetlands, troublesome food webs, and disturb ecosystem balance. Overharvesting of wetland plants for food, medicine, or other uses can reduce plant diversity and alter habitat structures. The over-exploitation of water, fish, timber, and agricultural land.

6.7. Regulatory and Policy Challenges

Feeble Legislation, many wetlands lack inclusive legal protection, leaving them vulnerable to development and degradation. Existing laws may also be poorly enforced. Lack of Integration of policies related to water, land use, and biodiversity conservation may not be well integrated, leading to

contradictory objectives and unproductive management. Economic vs. Environmental Priorities, which may be economic activities like agriculture, industry, and urban development, often take precedence over environmental conservation, leading to the degradation of wetlands.

6.8. Public Awareness and Community Involvement

Undervaluation of Ecosystem services: Many people are unaware of the benefits wetlands provide, like water filtration, flood regulation, and carbon absorption potential (Karmakar, S.et al., 2024). This lack of awareness can lead to undervaluation and negligence. Education and Outreach include insufficient public education on the importance of wetlands, and their conservation can hinder efforts to protect and restore these ecosystems. Stakeholder Engagement: Effective conservation often requires the involvement of local communities, stakeholders, and indigenous groups. However, engaging these groups can be challenging due to socio-economic, cultural, or logistical barriers.

7. Methodology

7.1. Data Design and Collection Methods

The review was conducted by gathering information from peer-reviewed journal articles, books, and conference papers related to wetlands, ecosystem services, and climate change resilience. Meta-analysis is another method used for comparing and synthesizing the findings from multiple studies to identify trends, patterns, and gaps in the review area. Also used are government reports, international agreements (such as IPCC reports and the Ramsar Convention report), and environmental policies and laws related to wetland and climate adaptation strategies. Examining unpublished reports, theses, working papers, case studies, and institutional documents adds additional points. Also, collect and read news articles and experts' opinions. The collected data and concepts are categorized into different sections, such as the role of wetlands in climate resilience, threats, and management strategies.

7.2. Search Strings and Academic Repositories

For this review, we searched Google Scholar, Web of Science, Scopus, and reference texts with the keywords “wetlands” and “climate change”. We segregated the papers based on the present interference of human activities taking place in the wetlands. CitNetExplorer is a software tool for visualizing and analyzing citation networks of scientific publications. The Citation Network Analysis method was used to identify the total studies conducted on this topic, interpret the data in the Sci2 Tool, and get a network like rooted cited reference papers that are rooted in each other (Figure 1).

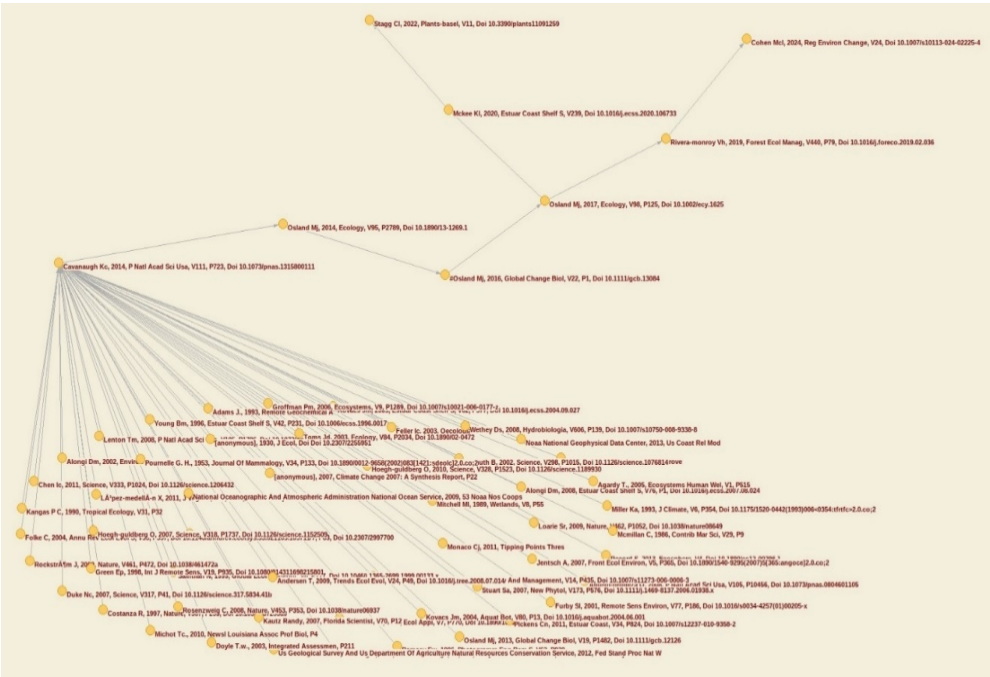


Figure 1. The Citation Network Analysis method was used to identify the number of studies conducted on this topic.

Databases	Search string/Keywords	Filters Applied
Web of Science	“wetlands” and “climate change” or “ecosystem services” or “wetland restoration” or “rewetting”	Publication year: 2000-2024, English
Scopus	“wetland” and “climate change” or “carbon cycle” or “climate adaptation”	Publication year: 2000-2024, English
Science direct	“wetland” and “climate change resilience” or “carbon sequestration”	Publication year: 2000-2024, English
Google scholar	“wetland” and “climate change” or “biodiversity conservation” or “restoration techniques” or “adaptive strategies”	Publication year: 2000-2024, English
Shodhganga	“wetland” and “climate change” or “adaptive strategies”	Publication year: 2000-2024, English
CitNetExplorer software	“wetland” and “climate change”	More than 100 cited reference papers. Publication year: 2000-2024, English
Unpublished documents/ reports	“wetland” and “climate change” or “carbon absorption” or “ecosystem services”	Publication year: 2000-2024, English
Published documents/ reports	“wetland” and “climate change” or “ecosystem services” or “adaptive strategies” or “policy recommendations”	Publication year: 2000-2024, English

8. Wetland Refurbishment for Climate Change Resilience

8.1. Carbon Stock in Wetlands

The wetland plants and soil can consume a large amount of carbon biomass, which can be accumulated in the soil's organic matter. The wetland soil holds 35% or more of the Earth's total organic carbon on its land surface (Mitsch, W. J., et al., 2015). The peat plants act as carbon storage packs. They can amass over thousands of years and form an estimated peat accumulation in the world forest, combined in between 180-450 gigatons (Joosten, H. et al., 2016). The coastal wetlands act as carbon sequestrators, also known as blue carbon. Blue carbon is high-density carbon that accumulates in coastal wetland ecosystems (McLeod E. et al., 2011).

8.2. Wetland Restoration Techniques

Rewetting is an effective method for restoring and conserving wetlands. This method can be used for the ecological restoration of degraded wetlands, which may be caused by drainage, agriculture, and climate change. Ditch blocking is another method for constructing barriers in drainage ditches to retain water. Blocking larger canals and drainage ways within a site can rewet larger areas (Dommain R. et al., 2010). Rewetting wetlands significantly reduces carbon emissions.

The water diversion technique is another method used for directing the water source to a wetland for its restoration. In this method, the water is collected and channeled to a degraded wetland to conserve it. It helps to avoid seasonal flooding due to climate change.

Paludiculture is another technique that uses plants to aid water retention and restore the natural vegetation of the wetland. Water-tolerant plants like reed, cattail, and sphagnum moss are cultivated for maintaining wetlands. It provides economic benefits and ecosystem services. Planting native wetland vegetation along water edges to stabilize soil and enhance water retention (Wichtmann, W., et al., 2016).

8.3. Ramsar Convention Strategies

Ramsar Convention (Ramsar, Iran, 1971) is an inter-governmental treaty whose mission is wetland conservation through local, regional, and national actions and international cooperation for the

contribution towards achieving sustainable development throughout the world ([Ramsar Convention Secretariat, 2016](#)). The Ramsar Conservation strategic plans 2015-2024 include climate change mitigation and adaptation through Target 12. Target 12 focuses on wetland restoration, which is relevant for biological diversity conservation, disaster risk reduction, livelihoods, and climate adaptation ([DCCEEW, 2023](#)).

9. Future Directions and Recommendations

9.1. Monitoring and Research

Long-term monitoring initiatives are essential to track wetland ecological changes. These programs should focus on water levels, water quality, temperature, species composition, carbon sequestration rates, and climate change impacts ([Mitsch, W. J., et al., 2015](#)). Climate Modelling specific to wetlands can support forecasting the climate change impact. Tools that are used in this modelling process are IPCC climate models (global climate model, regional climate model, Earth system models, integrated assessment model, etc.) can be adapted for wetland-specific predictions. Research on Adaptation funding research on how wetlands can naturally adapt to climate change is crucial. Understanding the resilience mechanisms of different species and ecosystems is essential ([Erwin, K. L., 2009](#)).

9.2. Conservation and Restoration Policy and Legislation

Protecting existing wetlands for implementing consolidated policies and regulations to protect them is vital. The Ramsar Convention delivers a framework for wetland conservation at an international level. Restore degraded wetlands in Large-scale renovation projects should be implemented to rehabilitate degraded wetlands. This includes re-establishing normal hydrology, cultivating native vegetation, and eradicating invasive species ([Zedler, J.B., 2000](#)). Creating new wetlands can compensate for those lost to climate change or human activities, which are causative of biodiversity and ecosystem services. Climate change Considerations should be integrated into wetland management policies at all governmental stages. Strengthening International Agreements supporting international agreements aimed at wetland conservation is crucial for coordinated global efforts. Financial Incentives for developing financial incentives for private property owners and communities to conserve and restore wetlands can inspire sustainable practices.

9.3. Community Engagement and Education

Raise Awareness to public awareness campaigns and educational programs can highlight the necessity of wetlands and the climate change impact. The local Community's involvement in the management and renovation efforts confirms sustainable practices and local stewardship ([Reed, M.S., 2008](#)). Encouraging sustainable land-use practices that diminish pressure on wetlands and encourage their resilience is essential.

9.4. Innovative Management Strategies

Adaptive Management implementing adaptive management practices permits flexible and receptive approaches to wetland conservation ([Holling, C.S., 1978](#)). Nature-based solutions will promote nature-based explanations, such as using wetlands for flood management, and deliver sustainable benefits ([Barbier, E.B., 2011](#)). Ecosystem-based approaches involve managing wetlands as part of greater landscapes, confirming connectivity and ecological integrity ([Noss, R. F., 1983](#)).

9.5. Mitigation and Resilience Building

Carbon Sequestration Enhancing wetlands' role in carbon sequestration is critical. Protecting and reestablishing peatlands, in particular, is essential ([Joosten, H., et al., 2002](#)). Resilience-building measures to increase wetlands' resilience include restoring hydrological regimes, planting climate-resilient species, and making buffer zones ([Erwin, K. L., 2009](#)). Disaster Risk Reduction methods using wetlands as ordinary infrastructure for disaster risk reduction can mitigate the impacts of floods, storms, and sea-level rise ([Costanza, R., et al., 2008](#)).

9.6. Technological and Innovative Solutions

Utilizing remote sensing and GIS for mapping, monitoring, and managing wetlands delivers real-time true data (Turner, W., et al., 2015; Pandey, P. C., et al., 2024). Exploring biotechnology solutions, such as developing stress-resistant plant varieties and bioremediation techniques, can aid in wetland restoration (Reddy, K. R., et al., 2008). Environmental DNA (eDNA) is an advanced practice in ecology and biodiversity research fields, which provides a non-invasive and effective technique to investigate biodiversity and ecosystem functioning in wetland surroundings.

eDNA technology is dependent on the organism's released DNA fragments into their nearby surroundings (Shokralla, S., et al., 2012). These DNA fragments can be noticed through the collection and analysis of the samples of water, soil, and sediments. By analyzing these DNA fragments, scientists can detect the existence of species in the wetlands without the necessity of directly capturing or observing these species. This is a highly specific and sensitive method that allows for the observation of trace amounts of DNA even when rare species or widely distributed species (Dejean, T., et al., 2011). This makes eDNA technology an influential tool for identifying difficult-to-observe species or rare ones. Water Management Innovations, implementing advanced water management solutions to maintain wetland hydrology amid changing precipitation patterns and water usage, is vibrant.

10. Policy Recommendations

The mainstreaming of wetlands into National Climate strategies for promoting nature-based solutions in climate mitigation and adaptive strategies, and strengthening the existing agreements and policies like the Ramsar Convention. Develop region-specific policies for high-value ecosystems and promote community-based management strategies that support participatory conservation models that involve local and indigenous communities. Provide economic incentives like payment for ecosystem services and tourism for wetland stewardship. Adapt wetland rewetting and ecological restoration large-scale projects and monitoring outcomes for adaptive management. Integrate the economic assessment of the ecosystem services and implement cost-benefit analysis for a sustainable future.

11. Future Research Priorities

For future development, develop ecosystem service models to quantify carbon sequestration, water retention, and biodiversity value of wetland and climate change scenarios. Climate-wetland interaction models for studying the wetland degradation and local to global climate systems. Implement long-term monitoring frameworks and GIS technologies for real-time wetland health assessment. Examine the socio-economic and cultural dimension research works and assess the effectiveness of governance models, especially in transboundary or community management wetlands. Explore the innovative financing mechanisms of carbon credits, biodiversity offsets, and green bonds to fund wetland restoration and protection.

12. Discussion

Wetlands are the most productive and ecologically significant ecosystem, which acts as a natural climate change resilience. The reviewed literature showed that wetlands play a crucial role in carbon sequestration, biological cycles, flood regulation, water purification, biological life, nutrient cycling, climate change, species distribution, and sustaining local livelihoods. The ability of wetlands to store large amounts of carbon acts as a natural carbon sink, helping regulate atmospheric greenhouse gas emissions.

The wetlands reduce the impact of extreme weather events such as floods, droughts, and storm surges. The agricultural practices, urbanization, and infrastructure development are major threats facing wetlands. The international frameworks like the Ramsar Convention, national policy implementations, strict laws and policies, regular monitoring of the implemented systems, or community arrangement strategies are necessary to conserve wetlands.

Rewetting and restoration techniques are cost-effective and nature-based solutions to compete with alternative weather events. Blocking drainage, collecting water, reintroduction, and paludiculture are natural solutions to restore wetlands. Future generations can focus on region-specific studies and long-term effective restoration policies and actions to conserve wetlands to compete with climate variations. Also, integrating local and indigenous knowledge into conservation planning. The policy formation is essential for focusing on economic valuation based on sustainable development.

13. Conclusion

Wetlands are critical ecosystems that offer several ecological benefits and are essential for extreme

weather resilience. Protecting and improving wetland resilience calls for an aggregate of herbal mechanisms and human-led strategies. Continued research, conservation efforts, and coverage improvement are critical to shield those essential ecosystems. The interplay between wetlands and climate change is complex. On the one hand, intact and well-managed wetlands can act as resilient carbon sinks, absorbing and storing carbon dioxide for centuries. On the other hand, when these ecosystems are drained, degraded, or otherwise disturbed, they can become substantial sources of greenhouse gases, including carbon dioxide and methane. This dual nature underscores the urgency of protecting and restoring wetlands to mitigate climate change effectively. Addressing the climate change impact on wetlands requires a comprehensive and multi-faceted approach involving monitoring, conservation, policy, community engagement, innovative management, mitigation, and technological solutions. By taking practical steps, we can protect and improve these dynamic ecosystems for future generations.

Author Contributions

Jeethu J C: Conceptualization, investigation, data curation, conducted the literature search, screened the studies, and compiled the relevant data, methodology, software, and writing review. Kaladevi V: Resources, supervision, and validation. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest Statement

The authors affirm that they have no known financial or interpersonal conflicts that would have appeared to impact the research presented in this study.

Data Availability Statement

- The Citation Network Analysis method was used to identify the total studies on this topic and interpret the data in the Sci2 software (cited in Figure 1)
- Online and print resources were searched for studies (all are cited in the reference section).
- unpublished dissertations, reports, and websites (using internet search engines and accessing copies at university and institutional libraries).

Consent for Publication

Not applicable, as the manuscript does not include any identifiable personal data from participants.

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