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Beyond carbon storage: A multifunctional ecosystem services framework for integrating restored wetlands into sustainable regional development planning in the Sahel

Dupe Oluwasesan *

Faculty of Environmental Science, Urban and Regional Planning Department. Modibbo Adama University of Technology, Yola. Nigeria.

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Abstract

Wetlands in arid and semi-arid regions are increasingly recognized as critical ecological infrastructures that provide services beyond their traditional role as carbon sinks. Within the Sahel region, rapid population growth, climate variability, desertification, water scarcity, and expanding urban settlements have intensified pressure on wetland ecosystems. While restoration efforts often emphasize carbon sequestration and biodiversity recovery, limited research has examined how restored wetlands contribute to broader regional development outcomes including water security, climate adaptation, livelihood stability, agricultural productivity, and sustainable land-use planning.

This study proposes a Multifunctional Wetland Ecosystem Services Framework (MWESF) designed specifically for dryland environments. The framework integrates ecological indicators, hydrological functions, socio-economic benefits, and spatial planning approaches to evaluate restored wetlands as nature-based infrastructure supporting sustainable development in the Sahel.

Using an interdisciplinary approach combining ecosystem service assessment, geospatial analysis, restoration ecology, and regional planning principles, this paper explores how restored wetlands can transition from isolated conservation areas into multifunctional assets embedded within climate-resilient development strategies. The proposed framework provides policymakers, planners, and environmental managers with an integrated decision-support model for balancing ecosystem protection with human development needs.

Keywords: Sahel; Wetland Restoration; Ecosystem Services; Urban and Regional Planning; Climate Adaptation; Nature-Based Solutions; Sustainable Development; Carbon Sequestration; Water Security; Dryland Ecosystems; Ecological Infrastructure

1. Introduction: Repositioning Restored Wetlands as Multifunctional Assets for Sustainable Regional Development in the Sahel

1.1. Background of the Study

Wetlands represent some of the most productive and ecologically significant landscapes on Earth, despite occupying only a relatively small fraction of the global terrestrial surface. Historically, wetlands were often perceived as marginal environments with limited economic value, leading to widespread drainage, conversion, and degradation for agricultural expansion, urban development, and infrastructure growth. However, advances in ecological science have demonstrated that wetlands function as complex natural systems that provide critical ecosystem services, including

* Corresponding author: Dupe Oluwasesan

climate regulation, hydrological stabilization, biodiversity support, nutrient cycling, and human livelihood benefits (Mitsch & Gosselink, 2015; Ramsar Convention Secretariat, 2016).

Global assessments estimate that wetlands provide disproportionately high ecosystem benefits compared with their spatial coverage. Costanza et al. (1997) demonstrated that wetland systems contribute significantly to global natural capital due to their ability to regulate environmental processes and support human economies. These findings influenced a transition in environmental management from viewing ecosystems primarily as conservation targets toward recognizing them as essential components of sustainable development infrastructure.

Despite their ecological importance, wetlands remain among the fastest declining ecosystems globally. Davidson (2014) estimated that natural wetland areas have experienced substantial losses over historical periods, with increasing degradation occurring due to land conversion, hydrological modification, pollution, and climate-related disturbances. This loss is particularly concerning in arid and semi-arid regions, where wetlands represent rare ecological refuges that sustain biodiversity, agriculture, pastoral systems, and water availability.

Within the Sahel region of Africa, wetlands perform an especially important function because they exist within a landscape characterized by environmental uncertainty. The Sahel, extending across Africa south of the Sahara Desert, represents a transition zone where climatic variability, population growth, land degradation, and resource competition create complex sustainability challenges. The region has experienced significant environmental pressure resulting from prolonged drought events, changing rainfall patterns, vegetation loss, and increasing demands on water resources (Nicholson, 2013; IPCC, 2014).

Sahelian wetlands such as the Lake Chad Basin, the Inner Niger Delta, and the Senegal River floodplain represent ecological lifelines within dryland landscapes. These systems provide seasonal water availability, fertile agricultural areas, fisheries, grazing resources, and biodiversity habitats that support millions of people (Zwarts et al., 2005). However, increasing pressure from climate variability and human activities has resulted in wetland degradation, reducing their capacity to sustain ecosystem services.

For example, Lake Chad represents one of the most widely recognized cases of environmental transformation within the Sahel. Once considered among Africa's largest freshwater systems, the lake experienced significant reductions in surface area during the late twentieth century due to interactions between drought, water withdrawals, and climatic variability (Coe & Foley, 2001). Although fluctuations in Lake Chad are complex and influenced by natural hydrological cycles, its transformation demonstrates the vulnerability of dryland wetland systems when ecological processes and human development pressures collide.

The traditional approach to wetland restoration has primarily emphasized ecological recovery, particularly biodiversity improvement and carbon sequestration. While carbon storage remains an essential function due to the role of wetland soils in global carbon cycling, an exclusive focus on carbon fails to capture the wider contributions wetlands provide to regional sustainability. Wetlands are not only carbon reservoirs; they are multifunctional systems capable of supporting climate adaptation, disaster risk reduction, food production, and socio-economic resilience (Millennium Ecosystem Assessment, 2005; Russi et al., 2013).

This study argues that restored wetlands in the Sahel should be reconsidered as ecological infrastructure capable of supporting sustainable regional development. By integrating restoration ecology with urban and regional planning principles, wetlands can be incorporated into broader strategies addressing climate adaptation, resource management, and sustainable settlement development.

1.2. Environmental Vulnerability and Development Challenges in the Sahel Region

The Sahel represents one of the most environmentally sensitive regions globally due to the interaction between climate variability and socio-economic vulnerability. Rainfall across the region demonstrates high spatial and temporal variability, making agricultural productivity, water security, and ecosystem stability highly dependent on seasonal hydrological patterns (Nicholson, 2013).

During the severe drought periods of the 1970s and 1980s, the Sahel experienced widespread vegetation decline, agricultural disruption, and food insecurity. These events contributed to global recognition of dryland vulnerability and highlighted the relationship between ecosystem degradation and human development challenges (Mortimore, 2005). Although some regions have demonstrated partial vegetation recovery associated with improved rainfall conditions, climate uncertainty continues to threaten long-term resilience.

Climate projections suggest that dryland regions, including parts of the Sahel, will face increasing challenges associated with temperature rise, rainfall variability, and extreme weather events (IPCC, 2014). These environmental changes are occurring simultaneously with rapid demographic growth. The Sahel contains some of the fastest-growing populations globally, increasing pressure on land resources, agricultural systems, and water availability.

Urbanization introduces an additional layer of complexity. Many Sahelian cities are expanding without sufficient integration of ecological planning principles. Wetlands located near urbanizing areas are frequently converted for housing, agriculture, and infrastructure because conventional land-use planning frameworks often underestimate their ecological and economic contributions.

This pattern reflects a broader limitation in regional planning approaches where natural ecosystems are treated separately from development systems. Traditional planning frameworks frequently emphasize engineered infrastructure while overlooking the ability of ecological systems to provide similar or complementary services. The growing recognition of nature-based solutions challenges this separation by promoting ecosystems as functional infrastructure capable of addressing human and environmental challenges simultaneously (Cohen-Shacham et al., 2016).

1.3. The Need to Move Beyond Carbon-Centered Wetland Evaluation

Carbon sequestration has become one of the dominant indicators used to justify wetland conservation and restoration because wetland soils contain significant amounts of stored organic carbon. Globally, wetlands influence carbon cycling by accumulating organic material under water-saturated conditions that slow decomposition processes (Mitsch et al., 2013).

However, while carbon-centered restoration frameworks provide valuable climate mitigation information, they may underestimate the full contribution of wetlands, particularly in developing regions where human communities depend directly on ecosystem services.

In the Sahel, the value of wetlands extends beyond their ability to store carbon. Seasonal wetlands regulate water availability, support agricultural productivity, maintain fisheries, provide dry-season grazing areas, and reduce vulnerability to climatic shocks. Therefore, evaluating restored wetlands exclusively through carbon metrics creates an incomplete understanding of their role in sustainable development.

The ecosystem services framework introduced by the Millennium Ecosystem Assessment (2005) provides a broader perspective by categorizing ecosystem benefits into provisioning, regulating, supporting, and cultural services. Applying this perspective to restored Sahelian wetlands allows restoration success to be evaluated not only by ecological recovery but also by improvements in human well-being and regional resilience.

1.4. Problem Statement

Despite increasing investment in ecosystem restoration and climate adaptation strategies, a significant knowledge gap remains regarding how restored wetlands contribute to sustainable regional development in arid and semi-arid environments. Existing wetland assessment approaches frequently emphasize individual ecological indicators such as vegetation recovery, biodiversity enhancement, or carbon accumulation, while insufficient attention is given to the combined ecological, hydrological, social, and planning functions of restored wetlands.

This limitation is especially important in the Sahel, where environmental restoration must address multiple interconnected challenges, including water scarcity, climate adaptation, food security, population growth, and sustainable land management. Without integrated assessment frameworks, policymakers may undervalue wetlands and continue development strategies that contribute to long-term ecosystem degradation.

Therefore, there is a need for a multifunctional framework capable of evaluating restored wetlands as ecological assets that simultaneously contribute to environmental protection and regional development objectives.

1.5. Research Gap and Scientific Contribution

Although extensive research has examined wetland ecosystem services globally, three major gaps remain.

First, most ecosystem service evaluation models have been developed from temperate or humid environments, creating uncertainty regarding their application in dryland systems where seasonal variability strongly influences ecological function.

Second, wetland restoration assessments continue to prioritize ecological indicators while giving limited consideration to spatial planning and regional development applications.

Third, there remains limited integration between restoration ecology and urban/regional planning disciplines, despite increasing recognition that future sustainability challenges require interdisciplinary solutions.

To address these limitations, this paper proposes the development of the **Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI)**, an integrated conceptual framework designed to evaluate restored wetlands across ecological, hydrological, climate adaptation, socio-economic, and planning dimensions.

1.6. Aim and Objectives of the Study

The primary aim of this study is to develop a multifunctional ecosystem services framework for evaluating restored wetlands as strategic assets supporting sustainable regional development in the Sahel.

The specific objectives are:

- To examine the ecological, hydrological, and socio-economic services provided by restored Sahelian wetlands.
- To identify limitations in existing carbon-focused restoration assessment approaches.
- To develop an integrated framework for measuring multifunctional wetland benefits.
- To establish connections between wetland restoration and sustainable regional planning.
- To provide policy recommendations for incorporating wetlands into climate adaptation and development strategies.

1.7. Research Questions

This study addresses the following research questions:

- How can restored wetlands contribute to sustainable development beyond carbon sequestration?
- What ecosystem service indicators are most relevant for evaluating restored wetlands in Sahelian environments?
- How can wetland restoration frameworks be integrated into regional planning strategies?
- Can multifunctional wetland assessment improve climate adaptation decision-making in dryland regions?

1.8. Significance of the Study

The significance of this research lies in its interdisciplinary approach to addressing environmental sustainability challenges in dryland regions. By connecting wetland science with urban and regional planning, this study expands the role of restoration from ecological recovery toward sustainable development transformation.

The proposed SM-WESI framework provides a foundation for policymakers, environmental managers, planners, and restoration practitioners seeking to evaluate wetlands as multifunctional landscapes. Such an approach aligns with global sustainability objectives, including climate adaptation, ecosystem restoration, and sustainable urban development.

Ultimately, the future resilience of the Sahel may depend not only on conserving remaining ecosystems but also on strategically restoring degraded landscapes and incorporating them into long-term regional development planning.

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2. Literature Review: Multifunctional Wetland Ecosystem Services, Restoration Science, and Sustainable Development Planning in the Sahel

2.1. Introduction

Wetlands have increasingly become recognized as strategic ecological assets capable of addressing interconnected environmental and socio-economic challenges associated with climate change, biodiversity loss, water insecurity, and unsustainable land-use transformation. The scientific understanding of wetlands has evolved from traditional conservation perspectives toward a broader recognition of wetlands as multifunctional socio-ecological systems that provide critical ecosystem services supporting both environmental stability and human development (Russi et al., 2013; Mitsch & Gosselink, 2015).

This transition is particularly important for dryland regions such as the Sahel, where ecological productivity and human livelihoods are strongly controlled by water availability. Unlike wetlands in humid environments, Sahelian wetlands represent concentrated ecological productivity zones surrounded by landscapes frequently affected by seasonal drought, rainfall uncertainty, and increasing climate stress. These systems provide essential services including agricultural support, livestock resources, fisheries, groundwater recharge, microclimate regulation, and biodiversity conservation (Zwarts et al., 2015).

However, despite increasing global recognition of wetland ecosystem services, restoration evaluation remains frequently dominated by limited ecological indicators, especially vegetation recovery, biodiversity return, and carbon sequestration. Although carbon storage is an important regulating service, recent studies emphasize that climate adaptation and sustainable development require broader ecosystem service evaluation approaches capable of integrating ecological, hydrological, economic, and social dimensions (Moomaw et al., 2018).

This chapter evaluates current knowledge regarding wetland ecosystem services, restoration assessment, dryland wetland vulnerability, and the integration of ecosystem restoration into regional planning. The chapter further identifies scientific limitations that justify the development of the proposed **Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI).**

2.2. Wetlands as Multifunctional Socio-Ecological Systems

Modern environmental management increasingly recognizes ecosystems as complex adaptive systems where ecological processes and human activities continuously interact. Wetlands represent one of the strongest examples of socio-ecological integration because their ecological functions directly influence human survival through water regulation, food production, climate adaptation, and economic activities (Mitsch & Gosselink, 2015).

The ecosystem service concept provides a framework for understanding these relationships by evaluating the benefits generated by ecosystem processes. Although early studies emphasized economic valuation of nature, recent approaches focus on integrating ecosystem services into decision-making, sustainability planning, and environmental governance (de Groot et al., 2012; Maes et al., 2016).

Wetland ecosystem services can be conceptualized as a pathway connecting ecosystem structure with human development outcomes:

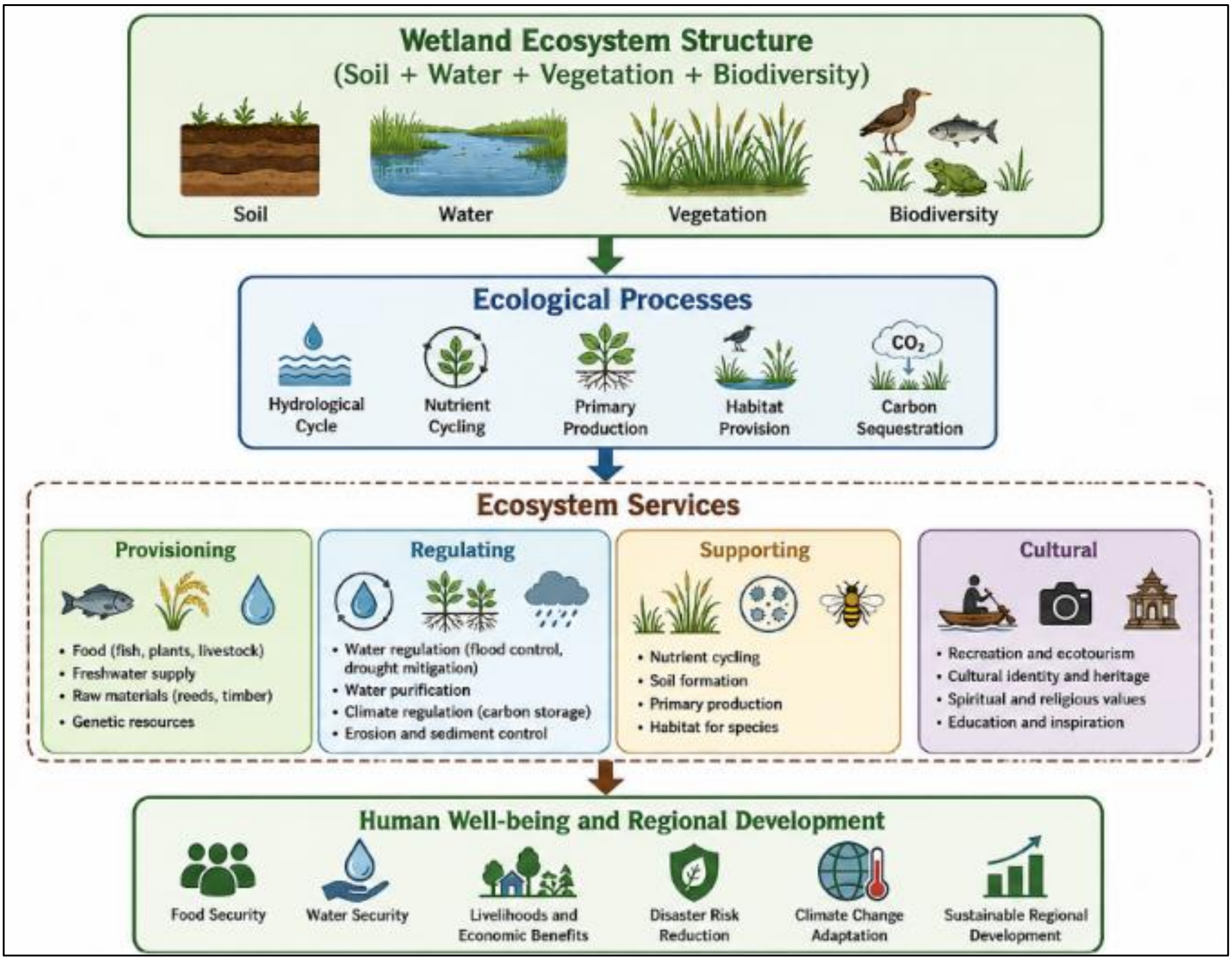

Figure 1 Conceptual relationship between wetland ecological processes and sustainable development outcomes

This approach is important because wetland degradation does not only represent biodiversity loss but also the disappearance of natural infrastructure supporting human resilience.

2.3. Status and Vulnerability of Wetlands in Dryland Regions

Drylands cover approximately 40% of the global terrestrial surface and support more than two billion people, making sustainable ecosystem management in these regions a major global challenge (Reynolds et al., 2017). Within these landscapes, wetlands provide disproportionately important ecological services because they maintain biological productivity in otherwise water-limited environments.

The Sahel region represents one of the world's most environmentally vulnerable dryland systems because climatic variability intersects with population growth, land degradation, and increasing demand for natural resources. The region has experienced historical drought periods, rainfall variability, and changing vegetation patterns that continue influencing ecosystem stability (Biasutti, 2019).

Climate projections indicate that warming trends across the Sahel are expected to exceed global averages, increasing pressure on water resources, agriculture, and ecosystems (Serdeczny et al., 2017). These environmental changes create significant challenges for wetlands because hydrological conditions strongly determine wetland function.

The vulnerability pathway of Sahelian wetlands can be represented as:

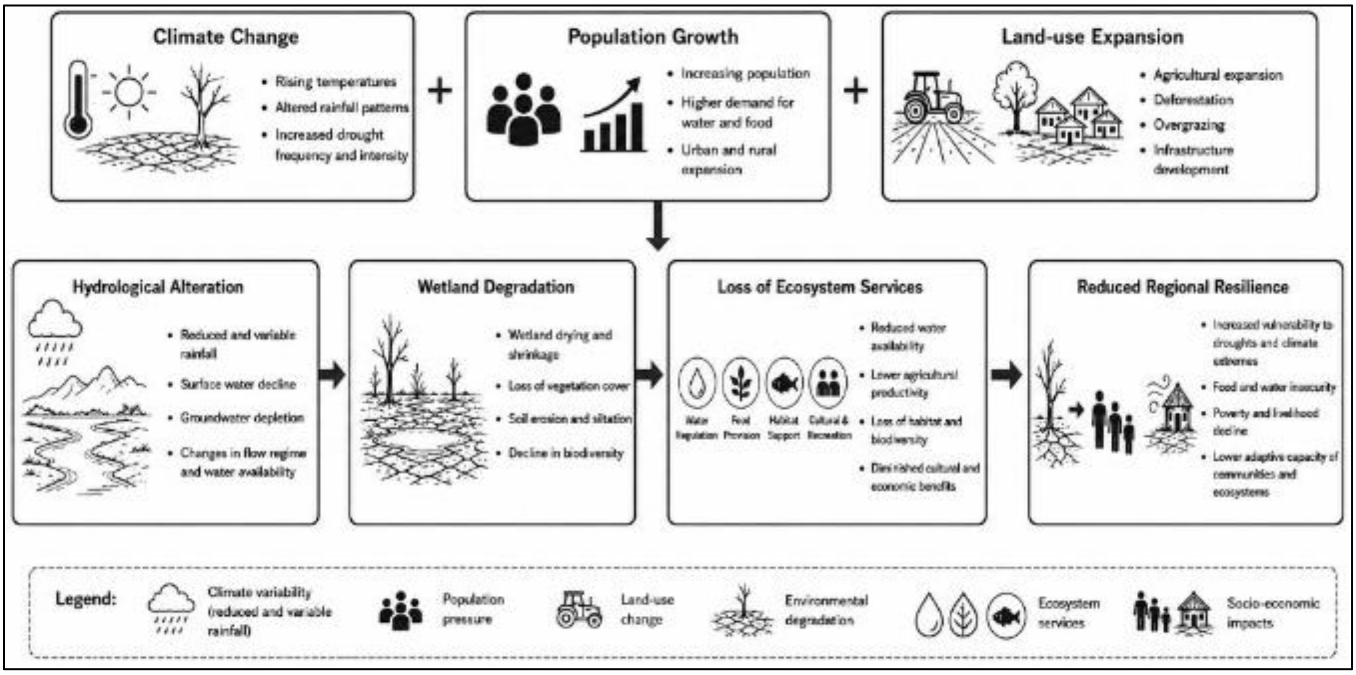

Figure 2 Drivers of wetland ecosystem service decline in Sahelian environments

2.4. Major Sahelian Wetland Systems and Regional Importance

2.4.1. Lake Chad Basin

The Lake Chad Basin remains one of the most important wetland landscapes in Africa due to its ecological, agricultural, and socio-economic importance. The basin historically supported millions of people through fisheries, irrigation agriculture, livestock production, and trade.

Satellite-based studies have documented substantial changes in Lake Chad's surface area during recent decades, caused by interactions between rainfall variability, drought events, and human water use (Pham-Duc et al., 2020). Although earlier interpretations described the lake as disappearing permanently, more recent studies demonstrate that Lake Chad represents a highly variable hydrological system controlled by complex climate and human interactions.

The Lake Chad case highlights the danger of managing wetlands without integrated environmental planning because hydrological changes can rapidly influence food security, migration patterns, and regional stability.

2.4.2. Inner Niger Delta

The Inner Niger Delta in Mali represents one of Africa's largest floodplain ecosystems and demonstrates the importance of seasonal hydrological processes in maintaining ecosystem services. Annual flooding supports agriculture, fisheries, livestock grazing, and biodiversity conservation.

Research has demonstrated that changes in flood extent strongly influence ecological productivity and human livelihoods, emphasizing the importance of maintaining natural hydrological variability in restoration planning (Aich et al., 2016).

2.4.3. Senegal River Wetlands

The Senegal River Basin illustrates the relationship between infrastructure development and wetland sustainability. While water management projects provide benefits such as irrigation and energy production, changes to natural flooding regimes may reduce ecosystem service delivery if ecological requirements are not incorporated into planning frameworks (Zarfl et al., 2015).

These examples demonstrate that wetland conservation cannot be separated from regional development decisions.

2.5. Beyond Carbon: Expanding Wetland Restoration Assessment

Carbon sequestration has become a central component of ecosystem restoration because natural systems contribute significantly to climate regulation. Wetlands are particularly important because saturated soil conditions reduce decomposition rates and allow organic carbon accumulation (Moomaw et al., 2018).

The basic wetland carbon balance can be represented as:

$$C_{net} = C_{input} - C_{loss}$$

Where:

$\boldsymbol{C_{net}}$ = Net ecosystem carbon storage, $\boldsymbol{C_{input}}$ = Organic carbon added through biological productivity, and $\boldsymbol{C_{loss}}$ = Carbon released through decomposition and greenhouse gas emissions

However, focusing only on carbon creates an incomplete evaluation of restoration success. A restored wetland in a dryland region may provide moderate carbon benefits but extremely high-water security and livelihood benefits.

A more appropriate multifunctional evaluation can be represented as:

$$MWV = C + H + B + L + A$$

Where:

MWV = Multifunctional Wetland Value, C = Carbon storage, H = Hydrological regulation, B = Biodiversity contribution L = Livelihood support, A = Adaptation capacity

This expanded approach recognizes that restoration success should be measured according to multiple sustainability outcomes.

2.6. Wetlands, Water Security, and Climate Adaptation

Water scarcity represents one of the greatest sustainability challenges facing the Sahel. Wetlands contribute to water security by regulating hydrological cycles, storing seasonal water, improving water quality, and maintaining ecosystem productivity during dry periods.

Nature-based solutions have gained international attention because they provide climate adaptation benefits while maintaining biodiversity and ecosystem health (Cohen-Shacham et al., 2016).

In Sahelian landscapes, restored wetlands can contribute to:

- Reducing flood vulnerability during intense rainfall events,
- Maintaining agricultural productivity during dry periods,
- Supporting groundwater recharge,
- Improving ecosystem resilience.

Wetlands therefore function as climate adaptation infrastructure rather than passive conservation areas.

2.7. Integrating Wetland Restoration into Urban and Regional Planning

Rapid urbanization across Africa creates increasing pressure on ecological landscapes. By 2050, Africa is projected to experience some of the fastest urban population growth globally, requiring new approaches that integrate ecological sustainability into development planning (UN DESA, 2018).

Traditional planning approaches frequently separate environmental conservation from economic development. However, green infrastructure and landscape planning approaches increasingly recognize ecosystems as functional components of urban and regional systems (Ahern, 2011).

The relationship can be expressed as:

Traditional model:

$$Development = InfrastructureGrowth - NaturalSystems$$

Sustainable ecological planning model:

$$Development = BuiltInfrastructure + EcologicalInfrastructure$$

This shift is essential for Sahelian cities and regions because wetlands provide services that engineered systems alone may not replace.

2.8. Remote Sensing and GIS Approaches for Wetland Ecosystem Assessment

Recent advances in geospatial technology have improved the ability to monitor wetlands, particularly in remote dryland regions where field data collection is challenging.

Satellite platforms such as Landsat and Sentinel allow researchers to analyze:

- wetland extent changes,
- vegetation dynamics,
- land-use conversion,
- surface water availability.

Vegetation condition is commonly assessed using the Normalized Difference Vegetation Index (NDVI):

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Where: *NIR* = Near infrared reflectance, *RED* = Red wavelength reflectance

Higher NDVI values generally indicate greater vegetation productivity and ecosystem condition.

Remote sensing studies have become particularly important in the Sahel because wetlands experience seasonal expansion and contraction that traditional mapping methods often fail to capture (Pekel et al., 2016).

2.9. Research Gap: Need for a Sahel-Specific Multifunctional Framework

Existing literature demonstrates substantial progress in ecosystem service assessment, wetland restoration, and climate adaptation research. However, three major limitations remain.

First, many ecosystem service frameworks were developed in humid or temperate regions and do not adequately represent seasonal dryland wetlands.

Second, restoration assessment remains heavily influenced by ecological and carbon indicators without sufficient integration of socio-economic resilience.

Third, limited research connects wetland restoration outcomes directly with regional planning systems in the Sahel.

Therefore, this study proposes the Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI):

Table 1 Conceptual Structure of the Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI)

SM-WESI Component	Code	Key Indicators	Associated Ecosystem Service Dimension	Contribution to Regional Sustainability
Ecological Health	EH	Vegetation recovery, biodiversity status, habitat quality, species diversity	Supporting services	Measures ecosystem integrity and restoration success
Hydrological Function	HF	Water availability, flood regulation, groundwater recharge, seasonal flow stability	Regulating services	Improves drought adaptation and water security
Carbon Regulation	CR	Soil organic carbon storage, biomass accumulation, greenhouse gas mitigation potential	Climate regulation services	Supports climate change mitigation and carbon management
Livelihood Security	LS	Agricultural productivity, fisheries, resource access, community benefits	Provisioning and socio-economic services	Enhances food security and community resilience
Planning Integration	PI	Policy alignment, restoration prioritization, land-use compatibility, governance inclusion	Institutional sustainability services	Links ecosystem restoration with long-term regional development

The conceptual equation becomes:

$$SM - WESI = EH + HF + CR + LS + PI$$

This framework shifts wetland evaluation from conservation-centered measurement toward sustainable development assessment.

2.10. Summary

This chapter reviewed current scientific understanding of wetland ecosystem services, emphasizing the need to move beyond carbon-focused restoration evaluation. Evidence from Sahelian wetland systems demonstrates that wetlands contribute simultaneously to ecological stability, water security, climate adaptation, and human development.

Recent research increasingly supports the integration of ecological infrastructure into planning systems; however, existing approaches remain insufficiently adapted to dryland environments. The proposed SM-WESI framework addresses this limitation by creating an integrated evaluation model specifically designed for restored wetlands within the Sahel.

3. Methodological Framework: Development of a Multifunctional Ecosystem Services Assessment Model for Restored Sahelian Wetlands

3.1. Introduction

The increasing complexity of environmental challenges within the Sahel requires methodological approaches capable of integrating ecological processes, climate interactions, human development pressures, and spatial planning decisions. Traditional wetland restoration assessments have often relied on individual ecological indicators such as vegetation recovery, hydrological restoration, or carbon accumulation; however, these approaches provide limited understanding of the broader role wetlands play within vulnerable socio-ecological landscapes (Moomaw et al., 2018).

The Sahel presents a unique methodological challenge because wetlands in this region are not isolated ecological systems but rather interconnected landscapes supporting agriculture, livestock production, settlements, biodiversity conservation, and regional climate adaptation. Therefore, measuring restoration success requires an integrated framework that evaluates ecological recovery alongside human development benefits (Reynolds et al., 2017).

This chapter introduces the methodological foundation for developing the **Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI)**, a composite assessment framework designed to evaluate restored wetlands through ecological, hydrological, climate regulation, socio-economic, and spatial planning dimensions.

The proposed approach integrates:

- ecosystem service assessment,
- geospatial analysis,
- environmental indicator modeling,
- climate adaptation evaluation,
- sustainable regional planning principles.

The purpose is not only to determine whether wetlands have recovered ecologically but also to determine whether restored wetland systems improve regional resilience under increasing environmental uncertainty.

3.2. Study Context: Sahelian Wetland Landscapes

The Sahel extends across Africa between the Sahara Desert to the north and the Sudanian savannas to the south, covering approximately 3 million km^2 across multiple countries including Senegal, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, and Sudan. The region experiences strong seasonal rainfall variability, with annual precipitation generally increasing from approximately 100–200 mm in northern zones to more than 700 mm in southern transitional areas (Biasutti, 2019). This rainfall gradient creates highly variable hydrological conditions where wetlands become critical ecological concentration zones.

A conceptual geographical representation of the study region is shown below.

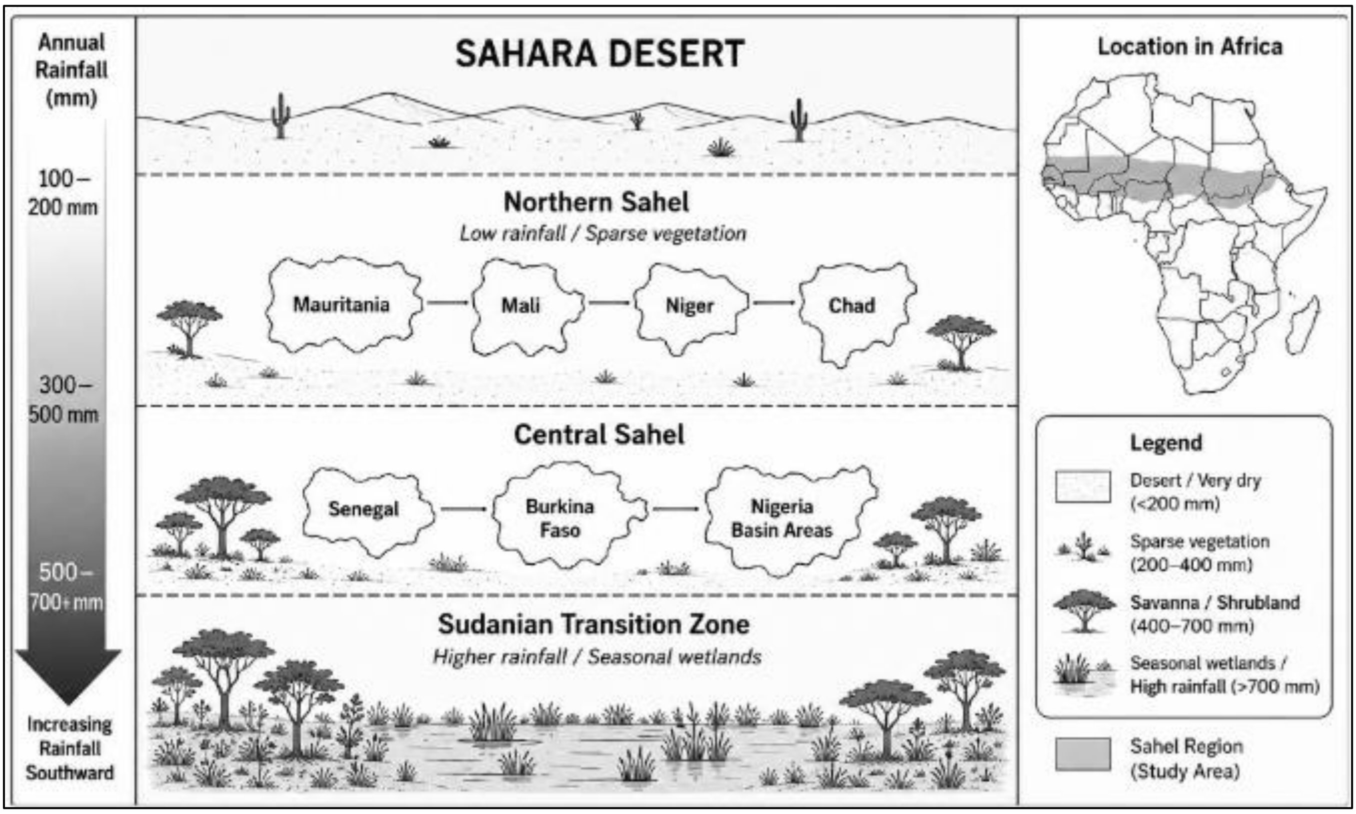

Figure 3 Conceptual ecological gradient of the Sahel region showing rainfall and wetland distribution zones

Unlike permanently flooded wetlands in humid regions, Sahelian wetlands commonly experience seasonal hydrological expansion and contraction controlled by precipitation cycles, river flow variability, and groundwater interactions. These characteristics require restoration assessment methods capable of capturing temporal changes rather than static ecological measurements.

3.3. Selected Representative Wetland Systems

The methodological framework is designed to be applicable across major Sahelian wetland landscapes, including three representative systems.

3.3.1. Lake Chad Basin

The Lake Chad Basin provides an important example of the interaction between climate variability, water management, and human dependency. The basin supports agriculture, fisheries, and pastoral activities across Nigeria, Niger, Chad, and Cameroon.

Remote sensing studies have shown major historical variations in Lake Chad's water extent, demonstrating the sensitivity of dryland wetlands to changes in rainfall patterns and human water withdrawals (Pham-Duc et al., 2020).

The Lake Chad system highlights the importance of evaluating restoration beyond physical water recovery because wetland sustainability depends on ecological function and community resilience.

3.3.2. Inner Niger Delta

The Inner Niger Delta in Mali represents one of the largest seasonal floodplain wetlands in Africa. Its annual flooding cycle supports rice farming, livestock grazing, fisheries, and migratory bird habitats.

The relationship between flooding and ecosystem productivity can be represented as:

$$EP = f(FD + WD + VP)$$

Where:

EP = Ecosystem Productivity, *FD* = Flood Duration, *WD* = Water Distribution, *VP* = Vegetation Productivity

This relationship demonstrates that hydrological processes determine ecological and socio-economic outcomes.

3.3.3. Senegal River Wetlands

The Senegal River wetlands demonstrate the importance of integrating ecological considerations into water infrastructure and regional planning decisions. Human modification of river systems through dams and irrigation expansion has improved some economic outcomes but also altered natural floodplain processes that maintain ecosystem services (Zarfl et al., 2015).

These examples collectively represent the environmental conditions targeted by the proposed SM-WESI framework.

3.4. Research Design and Analytical Approach

This study adopts an interdisciplinary conceptual modeling approach combining restoration ecology, ecosystem service assessment, geospatial analysis, and regional planning theory.

The research framework follows five sequential stages:

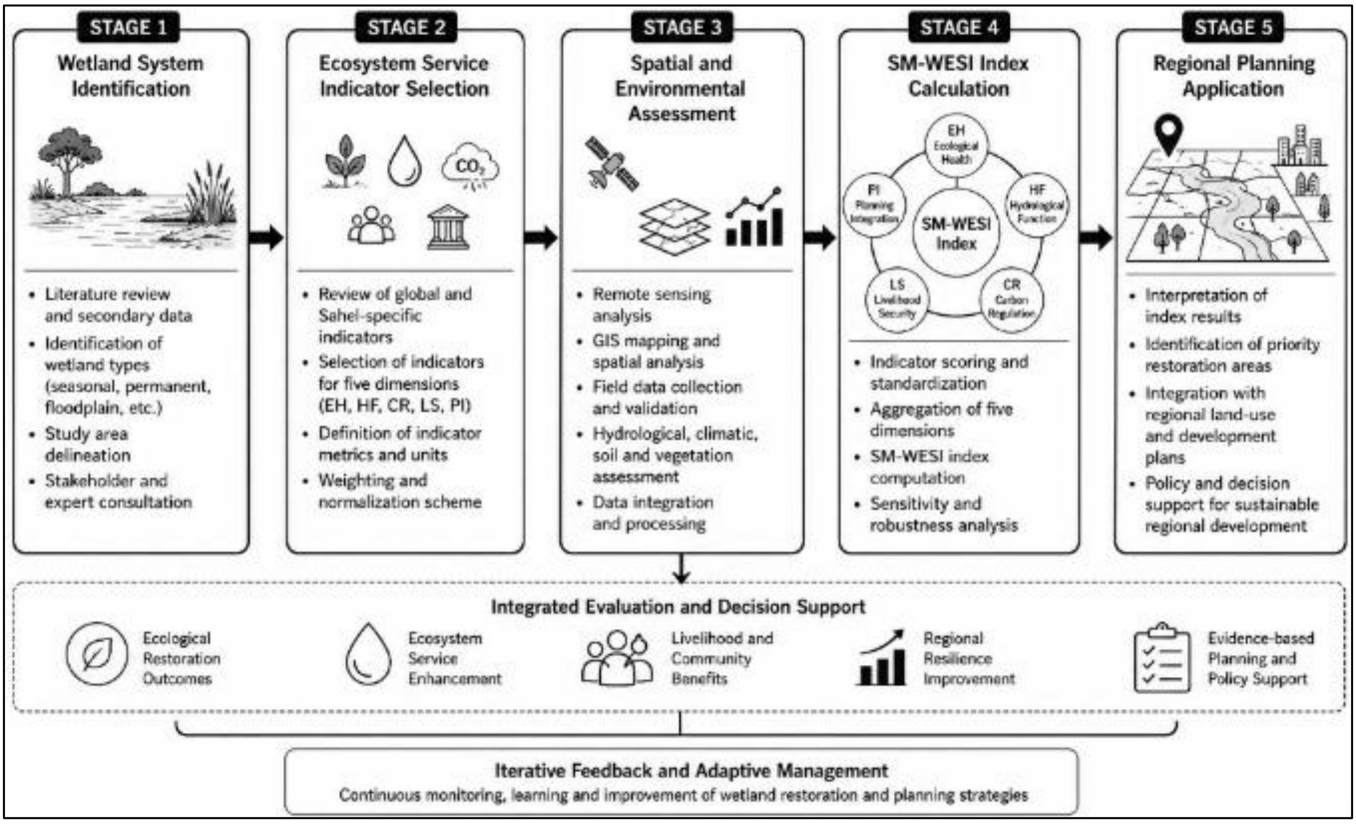

Figure 4 Research design pathway for multifunctional wetland ecosystem service evaluation

This structure allows wetland restoration outcomes to be evaluated from both ecological and human development perspectives.

3.5. Development of the Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI)

Existing ecosystem assessment frameworks provide valuable tools; however, many were designed for ecosystems with more stable hydrological conditions and stronger environmental monitoring systems. The Sahel requires an approach that integrates environmental variability and human dependence.

The proposed SM-WESI framework evaluates five major dimensions:

$$SM - WESI = f(EH, HF, CR, LS, PI)$$

Where:
EH = Ecological Health, HF = Hydrological Function, CR = Climate Regulation, LS = Livelihood Security. and
PI = Planning Integration

The normalized index equation is expressed as:

$$SM - WESI = \frac{(W_1EH) + (W_2HF) + (W_3CR) + (W_4LS) + (W_5PI)}{\sum W}$$

Where:

W = assigned weighting factor based on regional priority.

A higher SM-WESI score represents a wetland system delivering greater multifunctional benefits.

3.6. Ecological Health Assessment Component (EH)

Ecological health represents the ability of restored wetlands to maintain biological productivity, habitat quality, and ecosystem processes.

Indicators include:

$$EH = f(VI + BD + SQ)$$

Where: VI = Vegetation Index, BD = Biodiversity, SQ = Soil Quality

Vegetation recovery can be monitored through satellite-derived vegetation indices such as NDVI:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Remote sensing approaches have become essential for monitoring Sahelian ecosystems because they provide long-term observations across large and inaccessible landscapes (Pekel et al., 2016).

3.7. Hydrological Function Assessment Component (HF)

Hydrology represents the foundation of wetland ecosystem function. Without appropriate water conditions, restoration efforts cannot maintain long-term ecological stability.

Hydrological performance is calculated as:

$$HF = f(WA + FR + GR)$$

Where:

WA = Water Availability, FR = Flood Regulation and GR = Groundwater Recharge Potential

Satellite-based surface water datasets developed by Pekel et al. (2016) demonstrated the potential of long-term Earth observation for tracking changes in global water resources, making such approaches highly applicable for Sahelian wetland monitoring.

3.8. Climate Regulation Component (CR)

Climate regulation evaluates the ability of restored wetlands to contribute to mitigation and adaptation processes.

Carbon storage remains a major indicator:

$$SOC = BD \times D \times OC$$

Where:

SOC = Soil Organic Carbon Stock, BD = Soil Bulk Density, D = Soil Depth, OC = Organic Carbon Concentration

However, unlike traditional assessments, this framework combines carbon storage with adaptation functions.

Therefore:

$$CR = f(CS + TR + DR)$$

Where:

CS = Carbon Storage, TR = Temperature Regulation, and DR = Drought Resilience

This approach reflects the increasing recognition that ecosystems must be evaluated based on both mitigation and adaptation functions (Moomaw et al., 2018).

3.9. Livelihood Security Component (LS)

In the Sahel, wetland restoration cannot be separated from human systems because communities directly depend on ecosystem resources.

Livelihood security is represented as:

$$LS = f(AP + FS + EI)$$

Where:

AP = Agricultural Productivity, FS = Food Security Contribution, and EI = Economic Importance

The inclusion of livelihood indicators recognizes that ecological restoration without social sustainability may fail because communities experiencing resource insecurity are unlikely to maintain conservation strategies.

3.10. Planning Integration Component (PI)

A major limitation of existing wetland assessments is the separation between ecological science and regional planning.

The planning integration component evaluates:

$$PI = f(LU + PC + GI)$$

Where:

LU = Land-use Compatibility, PC = Protection Capacity and GI = Green Infrastructure Integration

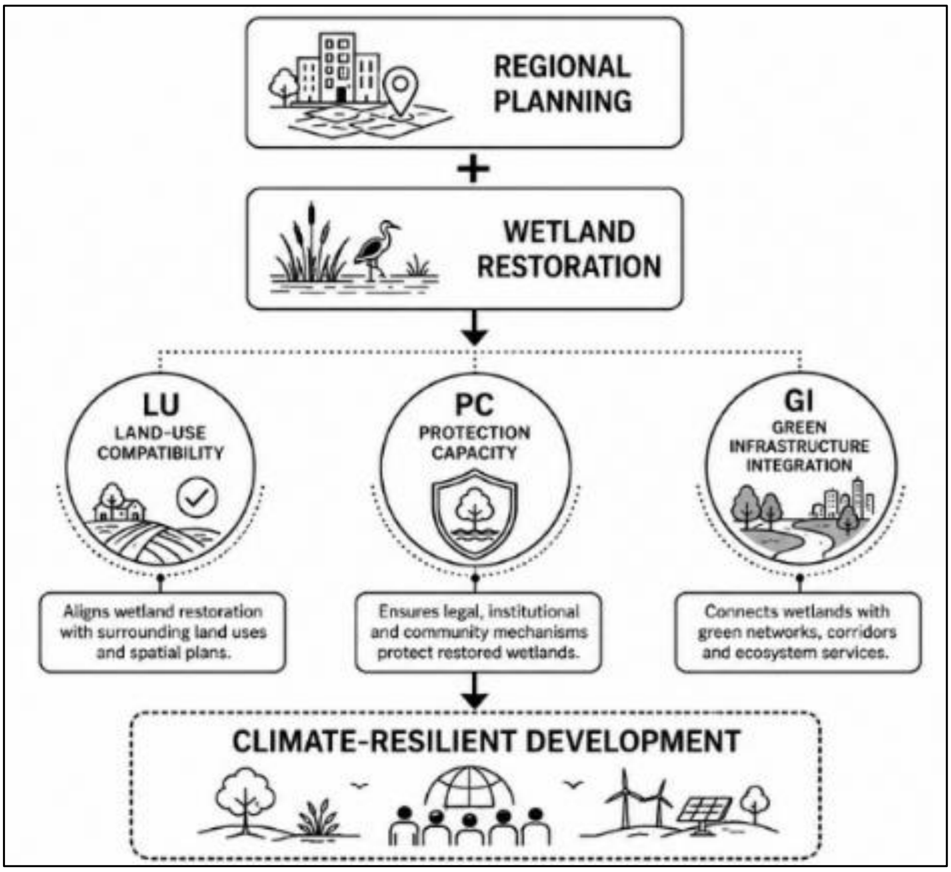

Figure 5 Integration of restored wetlands into regional development planning

3.11. Spatial Analysis and GIS-Based Decision Support

Geographic Information Systems provide a mechanism for translating ecological information into planning decisions.

Spatial datasets incorporated include:

- land-use/land-cover change,
- vegetation condition,
- water distribution,
- settlement expansion,
- restoration priority zones.

The integration of remote sensing and ecosystem service modeling has become increasingly important for regional sustainability planning because it allows environmental changes to be evaluated across large spatial scales (Maes et al., 2016).

3.12. Expected Framework Output and Interpretation

The SM-WESI framework classifies restored wetlands into performance categories:

Table 2 Classification of restored wetland multifunctional performance based on the proposed Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI)

SM-WESI Score	Interpretation
0.80–1.00	Very high multifunctional value
0.60–0.79	High ecosystem service contribution
0.40–0.59	Moderate restoration success
0.20–0.39	Limited functionality
<0.20	High restoration priority

The classification system provides planners with a practical method for identifying wetlands requiring protection, restoration, or improved management.

3.13. Summary

This chapter developed the methodological foundation for assessing restored Sahelian wetlands as multifunctional systems rather than isolated carbon reservoirs. The proposed SM-WESI framework integrates ecological health, hydrological function, climate regulation, livelihood security, and planning integration into a single decision-support model.

By combining field-based indicators, remote sensing technologies, ecosystem service evaluation, and regional planning principles, the framework provides a pathway for transforming wetlands from conservation spaces into strategic assets supporting sustainable development across the Sahel.

The following chapter applies this framework conceptually to evaluate expected ecosystem service outcomes and demonstrate how restored wetlands can influence regional resilience strategies.

4. Application of the Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI): Restoration Outcomes, Regional Planning Integration, and Sustainable Development Implications

4.1. Introduction

The increasing recognition of ecosystems as functional infrastructure has transformed how restoration outcomes are evaluated within environmental management and regional development planning. Traditional restoration approaches commonly assessed success through ecological recovery indicators such as vegetation establishment, hydrological improvement, and biodiversity enhancement; however, increasing climate vulnerability and socio-economic pressures require broader evaluation systems capable of measuring how restored ecosystems contribute to human resilience and sustainable development (Meli et al., 2017).

This need is especially significant within the Sahel, where wetlands represent critical environmental resources existing within landscapes experiencing climate variability, population expansion, land degradation, and increasing competition for natural resources. Unlike wetland systems located within water-abundant regions, Sahelian wetlands function as ecological concentration zones where hydrological processes directly influence agricultural production, food security, biodiversity conservation, and settlement patterns (Reynolds et al., 2017).

The purpose of this chapter is to demonstrate the application of the proposed **Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI)** as an integrated evaluation and decision-support framework. Rather than measuring restoration success through carbon sequestration alone, the framework evaluates restored wetlands according to their contribution toward five interconnected sustainability dimensions:

$$SM - WESI = f(EH + HF + CR + LS + PI)$$

where:

EH = Ecological Health, HF = Hydrological Function, CR = Climate Regulation Capacity, LS = Livelihood Security and PI = Planning Integration

The chapter further discusses how SM-WESI outputs can support restoration prioritization, regional planning decisions, climate adaptation strategies, and sustainable development policies throughout the Sahel.

4.2. Conceptual Application Across Sahelian Wetland Landscapes

The Sahel represents a diverse ecological region where wetland functions vary according to climate gradients, hydrological conditions, and human land-use systems. Therefore, a single restoration metric cannot accurately represent the multifunctional value of different wetlands.

The SM-WESI framework is designed to accommodate spatial variability by evaluating wetlands according to their dominant ecosystem service contribution.

A conceptual spatial application model is presented below:

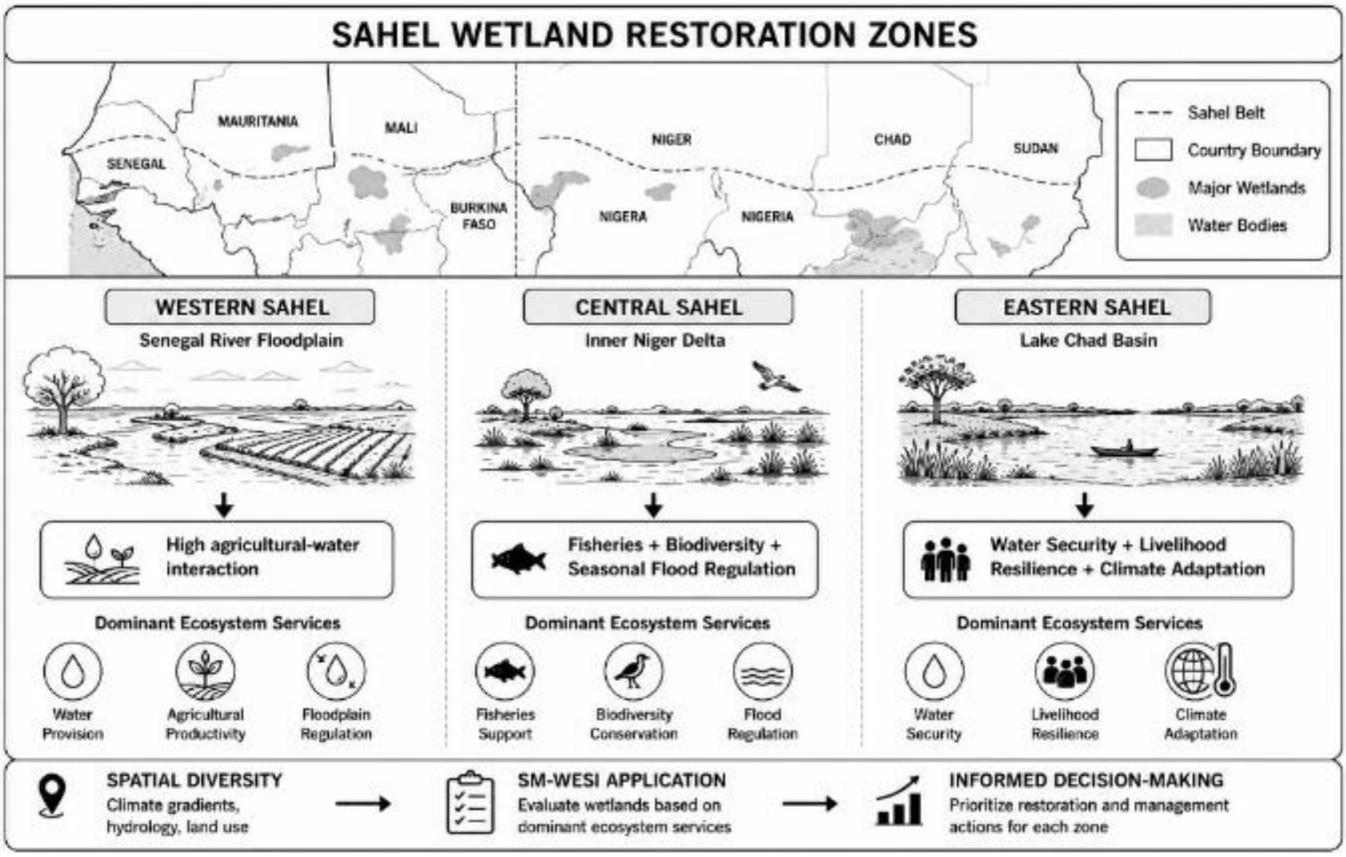

Figure 6 Conceptual spatial classification of major Sahelian wetland ecosystem service zones

This geographical variation demonstrates that restoration planning cannot rely exclusively on universal ecological indicators. A restored wetland with moderate carbon accumulation may still represent a highly valuable regional asset if it supports water security, agricultural productivity, or climate adaptation.

4.3. Scenario-Based Evaluation of Wetland Restoration Outcomes

To demonstrate practical application, SM-WESI can be used to compare different wetland restoration scenarios.

A conventional carbon-centered restoration model follows:

$$RS = C + B + V$$

Where:

RS = Restoration Success, C = Carbon Storage, B = Biodiversity Recovery, and V = Vegetation Improvement

Although this approach captures important ecological characteristics, it fails to represent broader regional benefits.

The proposed multifunctional model expands restoration evaluation:

$$RS_{multi} = EH + HF + CR + LS + PI$$

Where restoration success is determined by combined ecological and human development outcomes.

A hypothetical restored wetland comparison is shown below

Table 3 Example interpretation of multifunctional wetland restoration performance.

Ecosystem Service Indicator	Wetland A	Wetland B	Wetland C
Ecological Health	High	Moderate	High
Hydrological Function	Moderate	High	High
Carbon Storage	High	Moderate	Moderate
Livelihood Support	Low	High	High
Planning Integration	Low	Moderate	High
Overall SM-WESI Value	Medium	High	Very High

The interpretation demonstrates that wetlands cannot be ranked only according to carbon performance because ecosystem services interact differently depending on regional conditions.

4.4. Ecological Restoration Outcomes and Biodiversity Recovery

Ecological recovery represents a foundational component of successful wetland restoration because biodiversity supports ecosystem stability, nutrient cycling, vegetation productivity, and long-term resilience. However, restoration outcomes vary depending on historical degradation, hydrological recovery, climate conditions, and land-use pressures (Moreno-Mateos et al., 2015).

Within Sahelian wetlands, biodiversity conservation is especially important because wetlands provide refuge habitats within otherwise water-limited landscapes. Seasonal wetlands support migratory birds, aquatic species, vegetation communities, and wildlife populations that depend on temporary availability of water resources.

The ecological health component of SM-WESI evaluates recovery as:

$$EH = (0.35VI) + (0.35BD) + (0.30SQ)$$

where: VI = Vegetation Index, BD = Biodiversity Diversity Score, and SQ = Soil Quality

The weighting structure recognizes that restored wetland health depends on interactions between vegetation, biological communities, and soil processes.

Remote sensing indicators such as NDVI provide useful methods for monitoring vegetation recovery:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Large-scale satellite assessments have demonstrated the effectiveness of Earth observation approaches for tracking ecosystem changes, especially across regions where field monitoring remains difficult (Pekel et al., 2016).

4.5. Hydrological Restoration and Water Security Benefits

Water availability represents one of the most important limiting factors influencing ecological and socio-economic systems across the Sahel. Therefore, hydrological restoration may provide greater regional benefits than carbon accumulation alone.

The hydrological component is expressed as:

$$HF = (WR + FR + GW)$$

where:

WR = Water Retention, FR = Flood Regulation GW = Groundwater Interaction

Wetlands contribute to regional water security by capturing seasonal rainfall, slowing runoff movement, improving groundwater interactions, and maintaining productive landscapes during dry periods.

The relationship between wetland hydrology and regional resilience can be illustrated as:

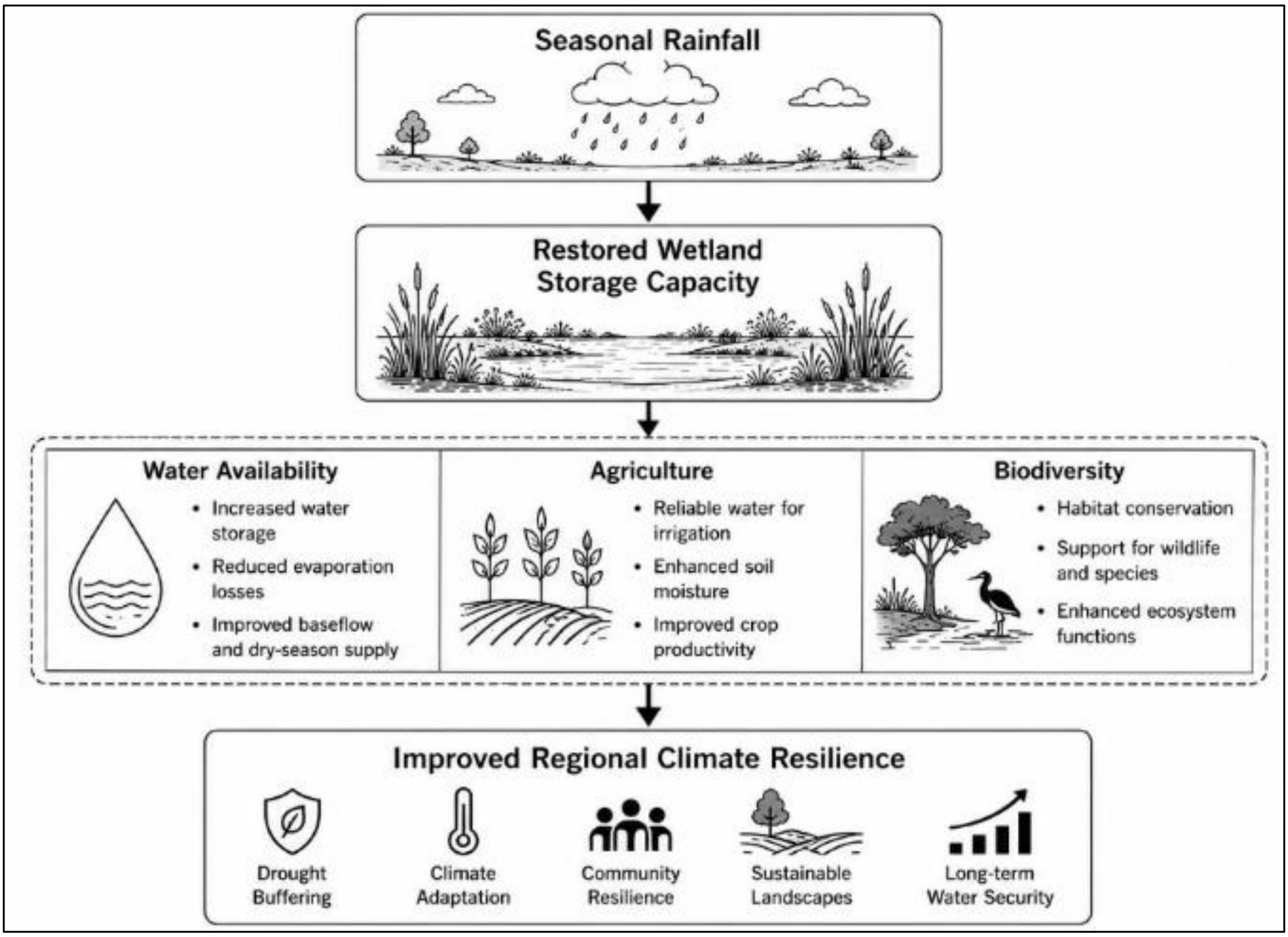

Figure 7 Hydrological pathway linking wetland restoration with Sahelian resilience

As rainfall patterns become increasingly uncertain under climate change conditions, restored wetlands provide natural adaptation mechanisms capable of reducing vulnerability (Serdeczny et al., 2017).

4.6. Climate Regulation and Carbon Storage Interpretation

Although this study argues for moving beyond carbon-centered evaluation, carbon storage remains a critical ecosystem service. Wetland soils contribute to long-term carbon regulation because saturated conditions slow organic matter decomposition and promote carbon accumulation (Moomaw et al., 2018).

The carbon stock calculation is represented as:

$$SOC = BD \times D \times OC \times CF$$

Where: SOC = Soil Organic Carbon Stock, BD = Bulk Density, D = Soil Depth, OC = Organic Carbon Percentage, and CF = Conversion Factor

However, the Sahel presents unique challenges because wetland carbon dynamics are influenced by seasonal drying and flooding cycles. Therefore, carbon assessment must be interpreted alongside hydrological and socio-economic functions.

The expanded climate regulation score is:

$$CR = (SOC + CA + DR)$$

Where: SOC = Carbon Storage, CA = Climate Adaptation Contribution, and DR = Drought Resilience Capacity

This recognizes that wetland climate benefits occur through both mitigation and adaptation pathways.

4.7. Livelihood Security and Socio-Economic Benefits

Wetlands within the Sahel function as livelihood-support systems rather than isolated ecological reserves. Millions of people depend on wetland resources for agriculture, fishing, livestock grazing, and seasonal economic activities.

The relationship between wetland health and livelihood security can be expressed as:

$$LS = f(F + A + E)$$

where: F = Fisheries Support, A = Agricultural Productivity, E = Economic Contribution

Unlike conservation models that separate humans from ecosystems, the SM-WESI approach recognizes that sustainable restoration requires maintaining ecological processes while supporting communities.

The relationship follows:

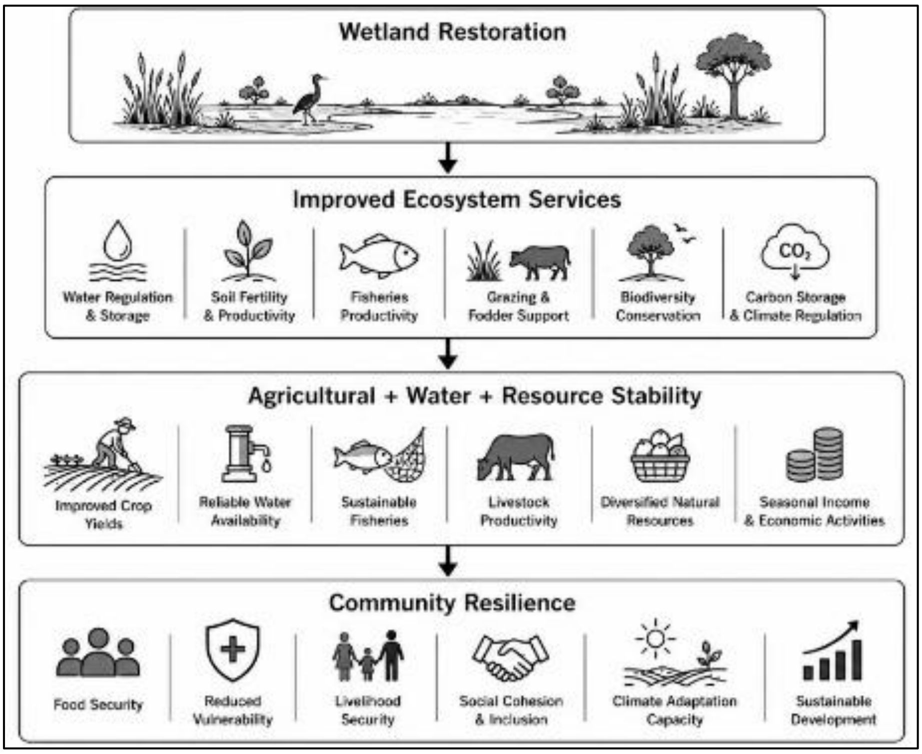

Figure 8 Wetland restoration and livelihood security pathway

Ignoring these social dimensions can create restoration programs that succeed ecologically but fail institutionally because local communities are excluded from long-term management processes.

4.8. Integration into Regional Planning and Climate-Resilient Development

One of the primary contributions of SM-WESI is connecting restoration science with spatial planning.

Historically, urban expansion and infrastructure development frequently treated wetlands as available land rather than functioning ecological systems. However, increasing climate risk has encouraged planners to recognize ecosystems as green infrastructure capable of supporting development resilience (Ahern, 2011).

A new Sahel planning model is proposed:

Traditional planning pathway:

$$Development = Built\ Infrastructure + Land\ Conversion$$

Sustainable ecological planning pathway:

$$Development = Built\ Infrastructure + Restored\ Natural\ Infrastructure$$

The proposed planning integration structure is shown below:

Figure 9 Integrated wetland-regional planning framework

This approach positions restored wetlands as essential components of future climate adaptation strategies.

4.9. Restoration Priority Mapping Using SM-WESI

The SM-WESI framework can support decision-making by identifying priority restoration zones.

The restoration priority equation is:

$$RP = (D \times V)/(SM - WESI)$$

Where: *RP* = Restoration Priority, *D* = Degree of Degradation, *V* = Vulnerability Score, *SM-WESI* = Current multifunctional performance

A wetland with severe degradation and low ecosystem service performance receives a higher restoration priority score.

GIS-based visualization would classify landscapes as:

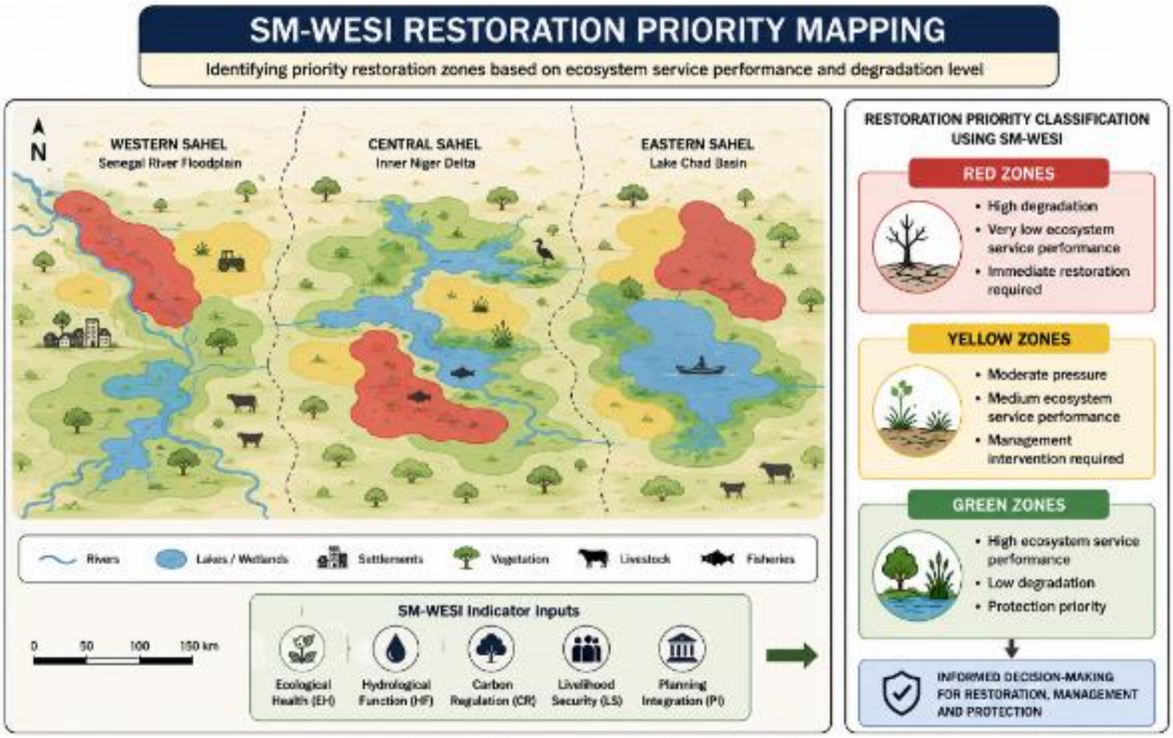

Figure 10 Conceptual restoration priority classification map

Such spatial outputs allow governments and planners to allocate limited conservation resources more effectively.

4.10. Implications for Sustainable Development Goals (SDGs)

The multifunctional restoration approach aligns directly with global sustainability priorities.

Wetland restoration contributes to the following:

SDG 2: Food security through agricultural support
SDG 6: Water availability and quality improvement
SDG 11: Sustainable cities and communities
SDG 13: Climate adaptation
SDG 15: Ecosystem conservation

The United Nations Decade on Ecosystem Restoration (2021–2030), announced before 2020, further highlights the importance of restoration-based solutions for achieving sustainability goals (UNEP & FAO, 2019).

4.11. Discussion: Repositioning Sahelian Wetlands as Development Infrastructure

The application of SM-WESI demonstrates that restored wetlands should no longer be considered only conservation landscapes or carbon reservoirs. Instead, they represent multifunctional systems that simultaneously address environmental degradation, climate vulnerability, and regional development challenges.

The Sahel provides an important global case because future sustainability depends on balancing population growth with ecosystem limitations. Restoration strategies that ignore human development needs may fail, while development strategies that ignore ecosystem functions may increase vulnerability.

Therefore, integrated wetland planning represents a transition from protecting nature from development toward designing development around ecological systems.

4.12. Chapter Summary

This chapter demonstrated the practical application of the Sahel Multifunctional Wetland Ecosystem Services Index as a decision-support framework for evaluating restored wetlands. Through ecological, hydrological, climate, livelihood, and planning dimensions, SM-WESI provides a broader understanding of restoration success beyond carbon storage.

The framework supports restoration prioritization, spatial planning, climate adaptation, and sustainable development strategies by recognizing wetlands as critical infrastructure within Sahelian landscapes.

The final chapter will synthesize these findings, provide policy recommendations, identify implementation pathways, and establish future research directions for multifunctional wetland planning.

5. Results Synthesis, Conclusions, and Strategic Pathways for Multifunctional Wetland Restoration in the Sahel

5.1. Introduction

The growing environmental complexity of the Sahel requires a transformation in how wetlands are evaluated, restored, and integrated into regional development systems. Traditional approaches that measure wetland restoration success primarily through ecological recovery or carbon sequestration provide valuable but incomplete assessments because they do not fully capture the wider role wetlands play in supporting climate adaptation, livelihood security, water availability, and long-term regional resilience (Moomaw et al., 2018).

The analysis presented throughout this study demonstrates that restored wetlands in dryland environments function as interconnected socio-ecological systems rather than isolated environmental resources. Within the Sahel, where rainfall uncertainty, land degradation, rapid population growth, and resource competition continue to influence development pathways, wetlands represent strategic ecological infrastructure capable of supporting sustainable regional transformation (Reynolds et al., 2017).

This chapter synthesizes the major findings generated from the proposed **Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI)** framework and discusses its implications for ecosystem restoration, climate adaptation planning, and sustainable regional development. The chapter further provides recommendations for policymakers, environmental agencies, and regional planners seeking to incorporate restored wetlands into future development strategies.

5.2. Summary of Major Findings

5.2.1. Finding One: Carbon Storage Alone Is an Insufficient Indicator of Wetland Restoration Success

A central finding emerging from this study is that although carbon sequestration represents a critical ecosystem function, it cannot independently represent the total value of restored wetlands, particularly in dryland environments where communities depend directly on ecosystem resources.

Wetland carbon assessment has gained significant importance because wetlands store large quantities of organic carbon within vegetation and soils. Under saturated conditions, decomposition processes slow down, allowing carbon accumulation over long periods (Mitsch & Gosselink, 2015). However, the Sahel presents different ecological conditions compared with permanently saturated wetlands because seasonal flooding, drought cycles, and fluctuating hydrology influence ecosystem processes.

Therefore, evaluating Sahelian wetlands exclusively through carbon metrics may underestimate systems that provide lower carbon storage but extremely high adaptation value.

For example:

A restored seasonal wetland may produce:

$$Carbon\ Storage = Moderate$$

but simultaneously generate:

$$Water\ Security + Agriculture + Livelihood + Biodiversity = High$$

The expanded wetland value relationship proposed in this study is therefore:

$$TWV = CS + HR + BD + LS + PI$$

Where: TWV = Total Wetland Value, CS = Carbon Storage, HR = Hydrological Regulation, BD = Biodiversity Support LS = Livelihood Security, and PI = Planning Integration

This result supports emerging arguments that ecosystem restoration should transition from single-benefit evaluation toward multifunctional ecosystem service assessment (Meli et al., 2017).

5.2.2. Finding Two: Restored Wetlands Function as Natural Climate Adaptation Infrastructure

The second major finding is that restored wetlands provide essential climate adaptation services that directly address several environmental challenges affecting the Sahel.

Climate projections indicate that dryland regions are expected to experience increasing stress due to rising temperatures, rainfall variability, and extreme climatic events (Serdeczny et al., 2017). Under these conditions, traditional engineered infrastructure alone may be insufficient to address water scarcity and environmental vulnerability.

Restored wetlands provide adaptation benefits through multiple pathways:

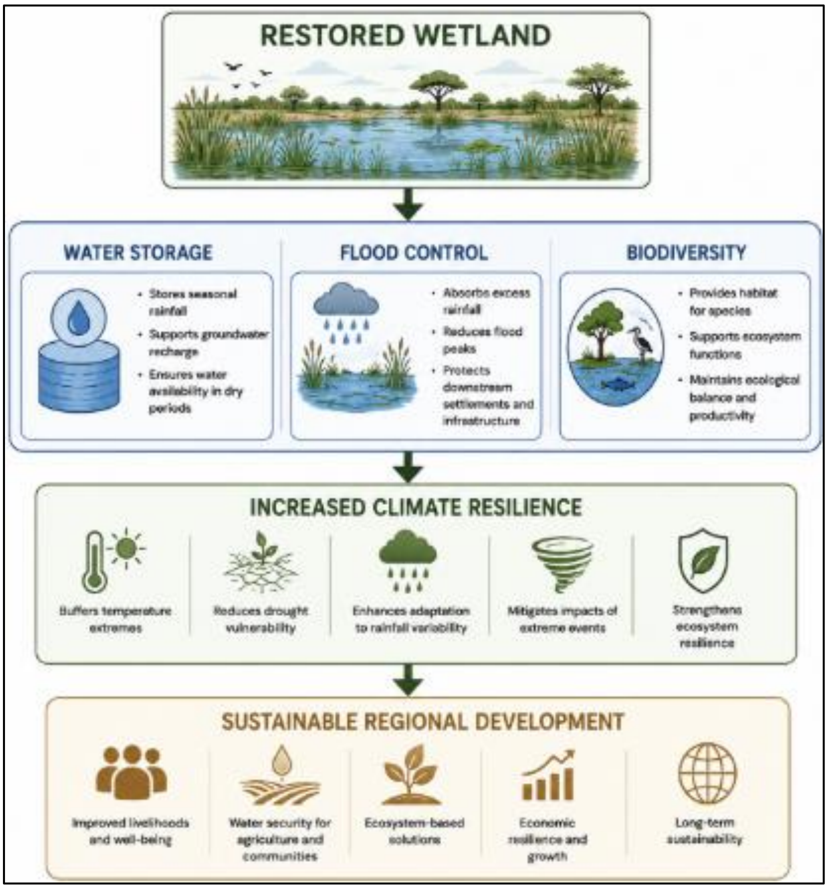

Figure 11 Wetlands as natural climate adaptation infrastructure in Sahelian regions

This study demonstrates that wetland restoration should therefore be considered part of regional climate adaptation planning rather than only biodiversity conservation.

Nature-based solutions have gained increasing recognition because they allow societies to address climate challenges while simultaneously improving ecosystem conditions and human well-being (Cohen-Shacham et al., 2016).

5.2.3. Finding Three: Hydrological Function Represents the Foundation of Sahelian Wetland Sustainability

Unlike wetlands in humid regions, Sahelian wetlands operate within water-limited environments where hydrological conditions determine ecosystem productivity.

The analysis indicates that hydrological restoration should be considered the foundation upon which other ecosystem services depend.

The relationship follows:

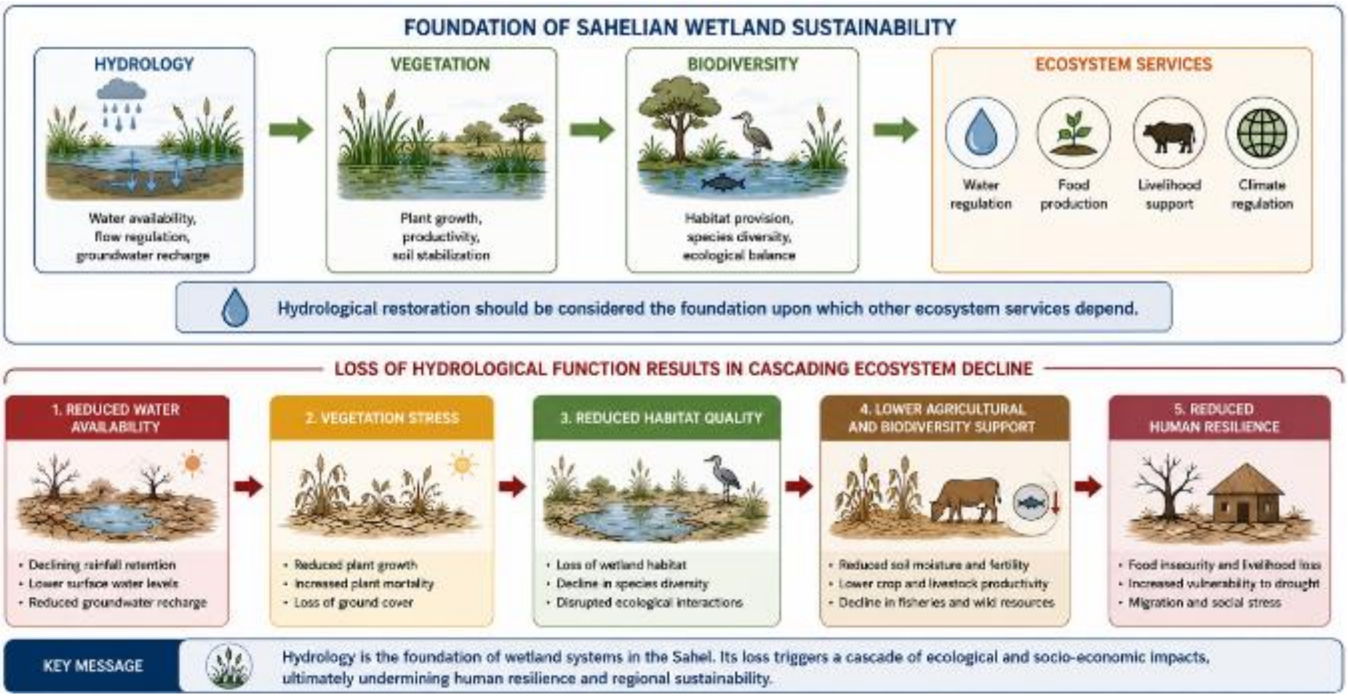

Figure 12 Hydrological degradation pathway in Sahelian wetland systems

Remote sensing observations have demonstrated significant variability in surface water availability across global landscapes, reinforcing the importance of continuous monitoring systems for wetland management (Pekel et al., 2016).

5.2.4. Finding Four: Wetland Restoration Must Be Connected to Regional Planning Systems

One of the most important conclusions from this study is that ecological restoration and regional planning cannot remain separated disciplines.

Many historical wetland losses occurred because wetlands were perceived as unused or economically inefficient landscapes. However, modern sustainability science increasingly recognizes ecosystems as infrastructure systems that provide measurable services (Ahern, 2011).

The proposed planning transition is:

Traditional development model:

$$Economic\ Growth = Land\ Conversion + InfrastructureExpansion$$

Sustainable Sahel development model:

$$Regional\ Resilience = Built\ Infrastructure + Ecological\ Infrastructure$$

The SM-WESI framework supports this transition by providing planners with measurable indicators that connect restoration outcomes with development objectives.

5.3. Final Structure of the Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI)

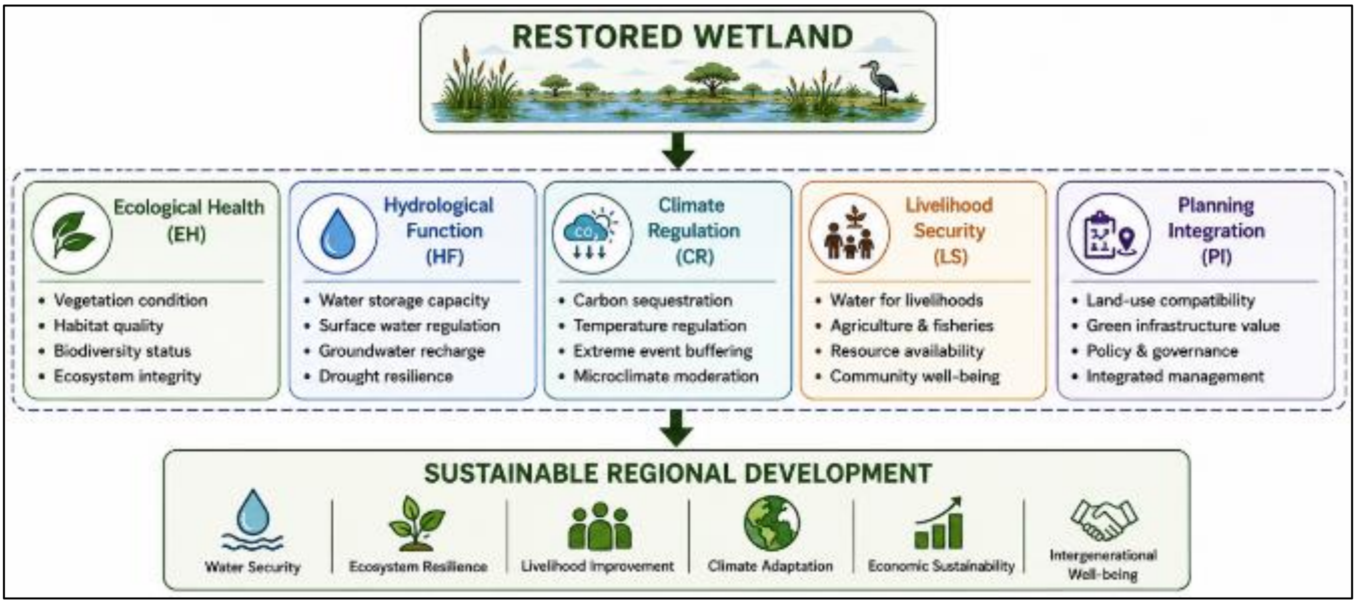

Figure 13 Final Sahel Multifunctional Wetland Ecosystem Services Framework

The final mathematical representation is:

$$SM - WESI = \frac{W_1(EH) + W_2(HF) + W_3(CR) + W_4(LS) + W_5(PI)}{\sum W}$$

Where: W = Weight assigned according to regional development priorities.

This flexible structure allows different Sahelian regions to adjust the framework depending on whether their primary concern is water security, biodiversity conservation, climate adaptation, or livelihood improvement.

5.4. Policy Implications and Recommendations

5.4.1. Integrate Wetlands into Regional Development Planning

Governments and regional authorities should transition from viewing wetlands as conservation boundaries toward recognizing them as ecological infrastructure.

Future regional plans should identify wetland protection corridors, restoration priority zones, climate adaptation landscapes, and sustainable agricultural interfaces.

Such integration supports climate-resilient development and reduces conflicts between environmental protection and economic growth.

5.4.2. Establish Sahel Wetland Monitoring Systems Using GIS and Remote Sensing

Effective restoration requires continuous environmental monitoring.

Satellite-based approaches provide opportunities to evaluate: seasonal water availability, vegetation recovery, land-use change, and degradation patterns.

The combination of remote sensing and ecosystem service modeling provides decision-makers with improved restoration planning tools (Pekel et al., 2016; Maes et al., 2016).

5.4.3. Incorporate Local Communities into Restoration Governance

Wetland restoration strategies must recognize that Sahelian wetlands are human-linked landscapes.

Community involvement is necessary because local populations maintain historical knowledge of seasonal flooding patterns, vegetation conditions, resource availability, and environmental changes.

Restoration approaches that exclude local communities may achieve short-term ecological recovery but fail to maintain long-term sustainability.

5.4.4. Develop Regional Wetland Climate Adaptation Policies

Climate adaptation strategies in the Sahel should formally include wetland restoration as a nature-based solution.

Below is a recommended governance structure:

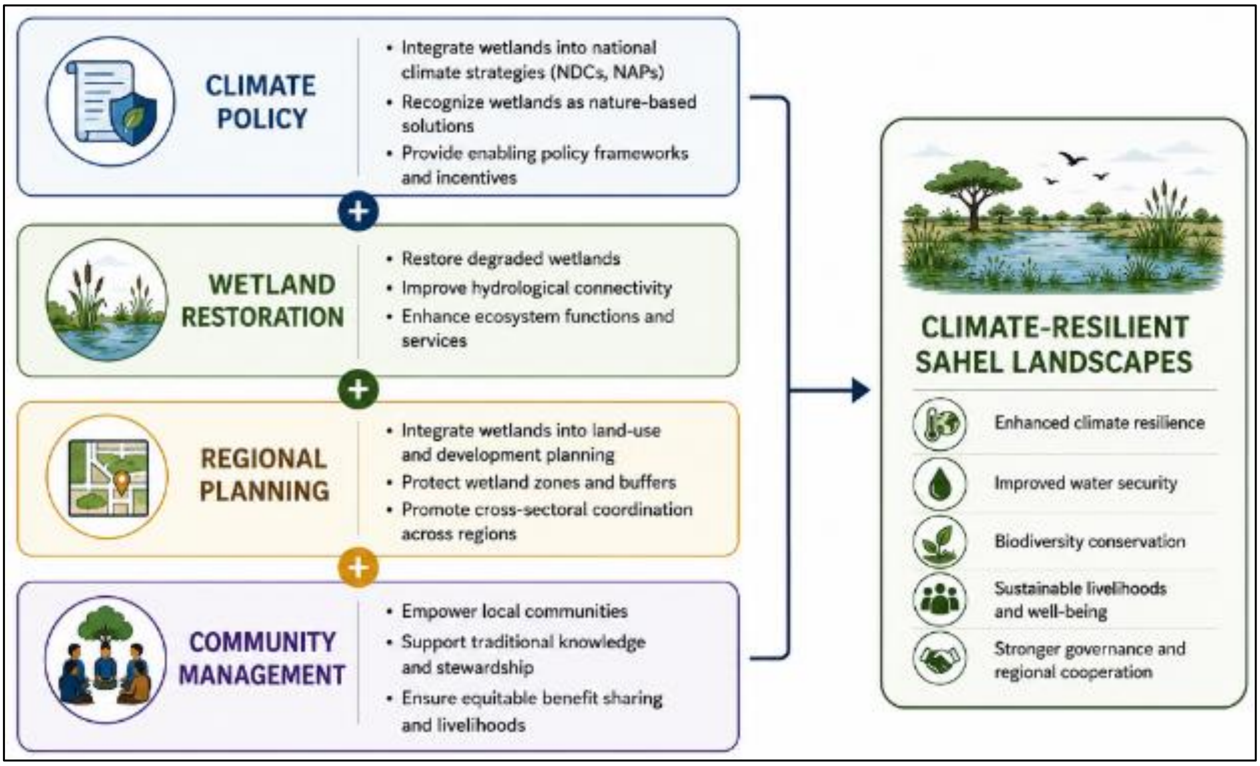

Figure 14 Proposed governance pathway for wetland-based climate adaptation

5.5. Contribution of the Study

This study contributes to existing wetland restoration and planning literature in three primary ways.

First, it challenges carbon-centered restoration evaluation by demonstrating that restored wetlands generate multiple ecosystem services essential for dryland sustainability.

Second, it introduces the **Sahel Multifunctional Wetland Ecosystem Services Index (SM-WESI)** as a new conceptual decision-support framework that integrates ecological and development indicators.

Third, it establishes stronger connections between restoration ecology and urban/regional planning by positioning wetlands as essential components of sustainable development infrastructure.

5.6. Limitations and Future Research Directions

Although SM-WESI provides a conceptual advancement, future research should focus on field validation across multiple Sahelian wetland systems.

Future studies should examine one or more of the following:

- **Machine Learning and Predictive Wetland Monitoring:** Artificial intelligence methods could improve prediction of wetland degradation by integrating satellite imagery, climate data, and land-use trends.
- **Long-Term Ecosystem Service Valuation:** Future research should quantify economic benefits associated with water storage, agriculture, climate adaptation, and avoided infrastructure costs.
- **Climate Migration and Wetland Stability Research:** As environmental pressures increase, future studies should examine whether restored wetlands can reduce climate-induced displacement by improving local resource security.

6. Conclusion

Wetlands in the Sahel exist at the intersection of environmental vulnerability and development opportunity. Although historically undervalued, these ecosystems provide essential services capable of addressing some of the region's most urgent challenges, including climate variability, water insecurity, biodiversity loss, and livelihood instability.

This study demonstrates that the value of restored wetlands extends far beyond carbon storage. While carbon sequestration remains an important ecological function, the future sustainability of Sahelian landscapes depends on recognizing wetlands as multifunctional systems that regulate water, sustain communities, protect biodiversity, and support regional resilience.

The proposed Sahel Multifunctional Wetland Ecosystem Services Index provides a new framework for evaluating restoration success through a broader sustainability perspective. By integrating ecological science, climate adaptation, and regional planning, restored wetlands can transition from protected environmental spaces into active foundations for sustainable development.

Ultimately, achieving resilience in the Sahel will require moving beyond the question of how much carbon wetlands store toward a more comprehensive question: *How much ecological, social, and developmental stability can restored wetlands provide for future generations?*

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