2. ADVANCING NATURE-BASED SOLUTIONS FOR ECOSYSTEM RESTORATION AND CLIMATE RESILIENCE

Exploring ecological restoration, natural infrastructure, and ecosystem valuation.

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Reimagining Payments for Ecosystem Services: A Risk-Responsive and Institutionally Aligned Framework

Author: Vaishnavi Pandey

M.Sc Economics (Environment and Resource Management) Department of Policy and Management Studies, TERI School of Advanced Studies; Vaishnavi.pandey@terisas.ac.in

This work was derived from the Masters Thesis undertaken by the student under the supervision of:

Dr. Sukanya Das, Professor , Department of Policy and Management Studies, TERI School of Advanced Studies, Email: sukanya.das@terisas.ac.in

Executive Summary

Ecosystem services, from water purification to carbon sequestration, are foundational to human wellbeing, yet they remain largely undervalued in mainstream economic systems. Payment for Ecosystem Services (PES) offers a promising framework to bridge this gap by creating financial incentives for the conservation and sustainable management of natural resources. However, existing PES models are plagued by shortcomings: they rely on static valuations, ignore ecological uncertainty, and are often designed in isolation from the institutions responsible for implementation. This paper addresses these gaps by proposing an integrated PES model that combines dynamic valuation, risk-adjusted payments, and institutional efficiency to create a more adaptive, equitable, and scalable approach.

The research sets out three objectives: to explore how valuation mechanisms can evolve over time to reflect ecosystem change, to incorporate ecological risk into compensation structures, and to assess how institutional variables influence PES outcomes. Drawing on a theoretical framework informed by ecological economics, risk modeling, and governance theory, the study constructs a model that captures temporal variability, simulates ecological uncertainty, and adjusts transaction costs based on governance performance.

The findings demonstrate that static models underestimate service values and often misalign incentives. By contrast, this integrated model produces more accurate, fair, and adaptive payment structures. It enables PES schemes to function not only as financial transactions, but as tools for responsive environmental governance. This paper advances the position that PES must be reimagined not as a fixed payment mechanism but as a dynamic policy instrument, one that reflects ecological complexity, embraces uncertainty and strengthens institutions.

Context and Problem Statement

The global decline of ecosystem services poses a critical threat to both environmental sustainability and human development. Forests, wetlands, grasslands and other natural systems provide a variety of services: provisioning, regulating, supporting, and cultural, yet they continue to be degraded due to land use change, deforestation, and unsustainable development.. This disconnect stems from a fundamental market failure: ecosystem services are rarely priced or compensated for, leading to over exploitation and underinvestment in conservation. Payment for Ecosystem Services (PES) has emerged as a response to this failure aiming to internalize environmental benefits individuals or communities who maintain or enhance service flows. Despite this conceptual appeal, real-world PES programs face significant operational challenges. Most rely on static valuation techniques, assuming constant ecosystem service output over time.

They do not account for ecological risk, such as fire, flood, or disease, which can abruptly disrupt service provision. Nor do they reflect the complex institutional terrain in which these programs are implemented. Often, transaction costs are high, monitoring is weak, and local governance systems are fragmented or underresourced. These shortcomings limit both the equity and the effectiveness of PES initiatives, particularly in developing country contexts.

In India, PES remains largely experimental and unstandardized. Although there have been efforts at the state level to pilot PES schemes, notably in Himachal Pradesh, Karnataka, and Sikkim, the absence of a national policy framework, data infrastructure, or institutional coordination has hampered scalability. Most schemes focus only on afforestation or watershed protection and do not incorporate economic risk or governance constraints into the design. This research responds directly to these gaps. It challenges the static assumptions of traditional PES models and proposes an integrated approach that dynamically values ecosystem services, adjusts for risk, and reflects institutional realities. The aim is to bridge theory and practice by developing a model that is analytically robust yet practically implementable. The context demands nothing less: as climate change accelerates and ecological thresholds are breached, mechanisms like PES must evolve to become not only tools of compensation, but instruments of adaptive environmental governance.

Context and Problem Statement

The concept of Payments for Ecosystem Services (PES) emerged as a mechanism to address environmental externalities by compensating individuals or communities for actions that maintain or enhance ecosystem services. Wunder (2005) provided a widely accepted definition, framing PES as voluntary, conditional transactions between service users and providers. Since then, extensive literature has explored its theoretical underpinnings, practical applications, and ethical considerations. At the heart of early PES models lies a neoclassical logic: assign a monetary value to a service, establish a beneficiary-payer relationship, and enforce conditionality. While elegant in theory, this model has faced criticism for oversimplifying ecological systems and neglecting socio-political complexity. Scholars such as Muradian et al. (2010) and Vatn (2010) have argued that PES schemes must go beyond market efficiency to address fairness, power asymmetries, and governance.

A key critique centers on the static nature of PES valuation. Most schemes calculate payments based on one-time assessments, failing to account for temporal shifts in service quality or quantity (G´omez-Baggethun et al., 2010). This results in inefficient or unjust payments, particularly when ecosystem conditions degrade or improve over time. To address this, recent scholarship has advocated for dynamic valuation approaches that evolve with ecological data and stakeholder inputs (Farley & Costanza, 2010; Bagstad et al., 2013). Risk and uncertainty form another major gap. While ecological systems are inherently volatile, most PES contracts ignore environmental risks, treating them as exogenous or irrelevant. However, Ferraro (2008) and Guerry et al. (2015) emphasize that ignoring uncertainty leads to fragile outcomes. Incorporating risk through probabilistic modeling, scenario planning, or Bayesian updating is now seen as essential to the resilience of PES frameworks. The role of institutions has gained increasing attention. Transaction costs, property rights clarity, monitoring capacity, and legal enforceability all shape PES outcomes. Studies by Pagiola et al. (2008) and Verma & Negandhi (2011) show that institutional quality determines both cost-effectiveness and equity. The concept of governance-adjusted transaction costs has emerged to quantify these effects.

This research contributes by integrating these three critical debates valuation, risk, and institutions into a single framework. While previous studies have addressed each individually, few have synthesized them into a coherent, implementable model. In doing so, this paper positions itself at the intersection of ecological economics, risk management, and environmental governance, offering a holistic response to long-standing critiques of the PES paradigm.

Research Focus and Methodology

This research develops an integrated framework for Payments for Ecosystem Services (PES) that addresses the limitations of static, narrowly constructed compensation systems. It brings together three essential pillars, dynamic valuation, risk adjustment, and institutional efficiency,

to reimagine how PES programs can be made more equitable, adaptive, and scalable. The study is guided by three central research questions:

- How can dynamic valuation methods better capture the temporal variability of ecosystem services and enhance the precision of PES compensation structures?
- In what ways do risk-adjusted payment mechanisms improve resilience and fairness in PES contracts under ecological and institutional uncertainty?
- How do governance quality, institutional capacity, and transaction costs affect the implementation and scalability of integrated PES models?

To answer these questions, the study develops a conceptual framework that captures the evolving nature of ecosystem value, accounts for ecological risk, and incorporates institutional costs into PES design. Instead of relying on flat-rate compensation or one-time assessments, the model uses probabilistic techniques to simulate service flow variability and introduces adaptive features that allow payments to evolve with changes in risk and performance over time.

The model also incorporates institutional dimensions—including monitoring capacity, policy clarity, and transaction costs, as variables influencing the feasibility and effectiveness of PES schemes. By grounding the model in available secondary data from Himalayan forest ecosystems, the research demonstrates how theoretical principles can be translated into implementable policy tools. The result is a robust framework that can be tailored to diverse ecological and governance contexts.

Key Findings and Arguments

Conventional PES systems, while conceptually elegant, often lack the sophistication to respond to dynamic socio-ecological systems. One of the key findings of this research is that static PES models typically overgeneralize ecosystem service flows, treating them as homogenous and constant. In reality, service flows are highly variable over time, shaped by factors such as climatic cycles, land use transitions, and ecological degradation. The integrated model developed here demonstrates that PES schemes must reflect this variability through adaptive pricing mechanisms. This shift can significantly improve both payment accuracy and the legitimacy of PES among resource-dependent communities.

Another key contribution is the incorporation of ecological risk into payment design. The study illustrates that unforeseen disruptions, such as forest fires or degradation due to human activity, can drastically alter the capacity of ecosystems to deliver services. Traditional PES contracts either penalize providers in such cases or offer no recourse at all. By embedding ecological risk into the valuation framework, the model enables a more equitable distribution of both incentives and responsibilities. This feature not only protects service providers from external shocks but also encourages proactive ecosystem management **practices.**

The institutional component of the model adds further value. Using governance-adjusted transaction costs, the research shows that implementation success is closely tied to local administrative capacity, enforcement clarity, and property rights recognition. Regions with poor institutional infrastructure experience inflated transaction costs and program delays, whereas those with coordinated governance systems see better alignment between objectives and outcomes. This insight allows policymakers to pre-assess the institutional readiness of regions before deployment, enabling strategic targeting of interventions.

For example, PES pilots implemented in areas without clarified land tenure or coordination between forest and revenue departments have struggled with disbursal delays and compliance issues. In contrast, well-structured interventions supported by local forest user groups and panchayat institutions demonstrate smoother implementation. The integrated model allows these institutional factors to be internalized into payment structures, making PES schemes more adaptive and scalable.

This research argues that PES is not simply a pricing mechanism but a policy architecture. By moving away from fragmented implementation and toward a systems-based approach, this model establishes PES as an instrument of institutional transformation as much as environmental compensation. The integration of ecological valuation, risk responsiveness, and institutional diagnostics marks a departure from minimalist models and brings PES in alignment with the complexities of the Anthropocene.

Policy and Practice Implications

The implications of this research are especially relevant for policymakers, environmental planners, and donor agencies designing or funding PES programs. Three core recommendations emerge, each backed by empirical modelling and contextual evidence.

1. Introduce Adaptive Payment Mechanisms in PES Guidelines

PES policies should explicitly mandate dynamic pricing updates, ideally on an annual or seasonal basis. The ecological data needed for this recalibration, such as land use changes, biomass regeneration, or service-specific performance indicators, are increasingly available through remote sensing, ground based monitoring, and participatory methods. By establishing protocols for periodic review, payment structures can remain aligned with real-time ecosystem function. Adaptive payments also help build trust among beneficiaries, who are more likely to participate if they see a clear link between conservation effort and compensation level.

2. **Integrate Risk Adjustment in Contract Design**

Risk-adjusted payments must become a core design element rather than a theoretical add-on. Contracts should specify conditions under which payments may vary in response to ecological stressors. For example, in regions prone to forest fire or landslides, a base compensation rate can be accompanied by a flexible buffer linked to event probabilities. Tools such as Bayesian updating or Monte Carlo simulations can inform these adjustments using data already collected by environmental departments.

3. Prioritize Institutional Readiness and Governance Assessment

Many PES initiatives fail not because of valuation flaws, but due to institutional constraints. This research quantifies how transaction costs vary with institutional quality and recommends integrating governance-readiness assessments into PES feasibility studies. Policymakers can use simplified governance diagnostics to evaluate whether agencies have the legal clarity, human resource capacity, and monitoring systems necessary to manage PES contracts. Including institutional criteria in project appraisal templates can ensure that investments are channelled into contexts where they are most likely to succeed.

Conclusion

This research advances a central argument: that Payments for Ecosystem Services, if properly designed, can move beyond being symbolic gestures or fragmented transactions. They can become structured interventions that reshape the relationship between state, community, and environment. However, this transformation requires abandoning simplistic assumptions and engaging deeply with the socio-ecological and institutional dimensions of service provision. The integrated model presented here takes a step in that direction. It acknowledges that ecosystem services are not static, that risks are inevitable, and that institutions matter. These acknowledgments are not limitations; they are opportunities. They provide an entry point for policy innovation that is both empirically grounded and normatively robust.

As climate shocks intensify and ecological thresholds near collapse, India, and other rapidly developing economies, must embrace policy instruments that are as dynamic as the challenges they address. PES, if restructured through the lens offered in this paper, can help build governance systems that are anticipatory, not reactive; participatory, not technocratic; and resilient, not brittle.

The next phase of PES must therefore focus not only on environmental valuation but on building capacity for environmental governance. Future work should explore how this model can be adapted for multiple ecosystem types, scaled through digital platforms, and aligned with green financing instruments. The groundwork laid by this study offers both a warning and a possibility: if we misprice nature again, it may not come back. But if we build policies that reflect its real value, economic, ecological, and institutional, there is still time to recover.

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Eco-Hydro Restoration of Wetlands in Blue Carbon Ecosystem of Sundarbans Biosphere Reserve, India

Author: Ratul Ghosh

Ratul Ghosh, Environmental Studies and Resource Management, TERI School of Advanced Studies, New Delhi, and ratul.ghosh@terisas.ac.in

This work was derived from the Masters Project undertaken by the student under the supervision of

Dr. Ranjana Ray Chaudhuri, Associate Professor, Head Department of Regional Water Studies & Department of Natural and Applied Science, TERI School of Advanced Studies, New Delhi, and ranjana.chaudhuri@terisas.ac.in

Executive Summary

The Sundarbans Biosphere Reserve (SBR), the world's largest continuous mangrove ecosystem, faces unprecedented threats from climate change and anthropogenic pressures, particularly affecting its inland freshwater aquatic systems. This study addresses the critical degradation of these water bodies through a comprehensive eco-hydrological restoration framework that integrates geospatial analysis, field data collection, and predictive modelling to enhance water quality, restore biodiversity, and increase carbon sequestration potential. Our multi-faceted approach revealed alarming trends in groundwater quality, with 20% of samples exceeding permissible Total Dissolved Solids (TDS) limits and 30% showing elevated electrical conductivity due to seawater intrusion. The Cl^-/HCO_3^- ratio analysis confirmed varying degrees of seawater influence across sampling sites, with ratios exceeding 6.6 mg/L indicating severe saltwater contamination. Sea level rise analysis spanning 1993-2024 demonstrates a consistent upward trend of around 4 mm/year, projecting 20-30 cm rise by 2050 and threatening 20-30 km² of critical coastal carbon storage areas. The integrated impact assessment reveals that projected sea level rise will result in a carbon loss of 70-80 Mt C by 2050, representing a reduction in total carbon stock and highlighting the urgent need for restoration interventions. Our findings demonstrate that degraded inland aquatic systems are transitioning from carbon sinks to carbon sources, undermining global climate mitigation efforts. Immediate implementation of science-based eco-hydrological restoration strategies is essential to preserve the Sundarbans' dual role as a biodiversity hotspot and critical blue carbon ecosystem. Without urgent intervention, continued degradation will compromise both local socio-economic resilience and global climate stability, making restoration not just an environmental imperative but a climate necessity.

Context & Problem Statement

The Sundarbans Biosphere Reserve (SBR), located at the confluence of the Ganges, Brahmaputra, and Meghna rivers, is not only the world's largest continuous mangrove ecosystem but also a UNESCO World Heritage Site and Ramsar wetland. It spans over 10,000 km², with a diverse array of flora and fauna, including endangered species such as the Royal Bengal tiger, Irrawaddy dolphin, and northern river terrapin. The region provides critical ecosystem services, including biodiversity conservation, carbon sequestration, flood control, and nutrient cycling. However, the ecological and socio-economic significance of the SBR is under threat due to climate change, anthropogenic pressures, and unsustainable resource management practices (Gopal & Chauhan, 2006) (Bhattacharjee & Ahmed, 2022). The key challenges facing the SBR is the degradation of its inland freshwater aquatic systems, essential for local livelihoods, agricultural productivity, and biodiversity, are increasingly impacted by sea-level rise, salinization, and pollution. Evidences highlights that these inland systems, traditionally used for aquaculture and domestic purposes, are now experiencing a decline in water quality and biodiversity.

The transformation of freshwater ponds into brackish water systems has adversely affected fish farming, irrigation, and other water-dependent activities, pushing local communities into economic vulnerability (Fawzy, et al., 2020) (Ghosh, et al., 2021).

The inland aquatic systems of the SBR also hold significant potential for climate change mitigation through carbon sequestration. Studies suggest that aquatic ecosystems can store carbon at rates comparable to or even exceeding terrestrial ecosystems. The historical degradation of these ecosystems, exacerbated by rising temperatures and changing hydrological patterns, has transformed many natural carbon sinks into carbon sources, thereby amplifying global warming impacts (Nellemann, 2009) (Banerjee & Mitra, 2015). To address these multifaceted challenges, there is an urgent need to develop a comprehensive eco-hydrological restoration suggestion. This model must integrate field data, geospatial analysis, and hydrological modelling to enhance water quality, restore biodiversity, and increase carbon sequestration. The restoration efforts may prioritize socio-economic benefits to local communities, through sustainable aquaculture and agriculture, enhancing water security, and building resilience against climate-induced disasters (Das, et al., 2022) (Mitra, et al., 2009). The significance of the proposed restoration strategies is underscored by their alignment with the United Nations Sustainable Development Goals (SDGs). Specifically, these initiatives contribute to Sustainable Development Goals (SDGs). (Hoques, et al., 2006) (Dasgupta, et al., 2014).

Through an integrated approach combining geospatial mapping, field surveys, and predictive modelling, this study aims to establish a robust framework for sustainable restoration and management of the inland aquatic systems in the SBR through case study approach. By doing so, it seeks to ensure the long-term ecological and socio-economic resilience of this globally significant region (Ghosh, et al., 2021) (Bhattacharjee & Ahmed, 2022).

Literature Review

The coastal area serves as the boundary between land and sea, representing a crucial zone of the global oceans from a human perspective. Coastal marine ecosystems, encompassing estuaries, seagrass beds, salt marshes, tidal flats, mangroves, coral reefs, and shelves, offer a rich reservoir of valuable services such as nutrient cycling, pollution detoxification, food production, habitats, as well as recreational and leisure activities (Costanza, et al., 1997).

The Sundarbans, recognized as the largest continuous mangrove forests globally, are exceptionally crucial and exceedingly susceptible to the impacts of climate change due to their intricate geomorphology and environment, coupled with their gradual reduction under rising sea levels. The inundation of inland freshwater bodies by saltwater resulting from cyclones and tidal surges, coupled with the prevalence of diseases, epidemics, and erratic rainfall, significantly contribute to the degradation of these inland aquatic ecosystems as highlighted in various works (Das, et al., 2022). (Chand, et al., 2012) have discussed that the intrusion of saline water due to flooding and rising sea levels poses a threat to inland freshwater ecosystems.

The intrusion of saline water into inland areas is a recurrent phenomenon exacerbated by regular tropical cyclones. The escalating salinity levels, stemming from the limited water exchange, pose a significant threat to the ecosystem. The expansion of brackish shrimp farming not only endangers the mangrove ecosystems but also jeopardizes the agrobiodiversity and aquifer ecosystems of the inland regions (Dasgupta, et al., 2014). Prolonged exposure to saline water in shrimp farms leads to a decline in soil organic matter, subsequently diminishing agricultural productivity (Bazzaz & Sombroek, 1996). In the Indian Sundarbans, inland aquatic bodies form intricate socio-ecological systems deeply intertwined with the cultural fabric of the region, playing a crucial role in delivering vital ecosystem services. These aquatic bodies often suffer from undervaluation and contamination of their water sources. The concentrations of inland aquatic bodies known as pondscapes, which have been demonstrated to harbour rich biodiversity that significantly enhances the overall aquatic biodiversity of the surrounding catchment area compared to lakes, streams, and rivers (Davies, et al., 2008). These aquatic ecosystems are indispensable natural assets for advancing the UN Sustainable Development Goals (SDGs), which are designed

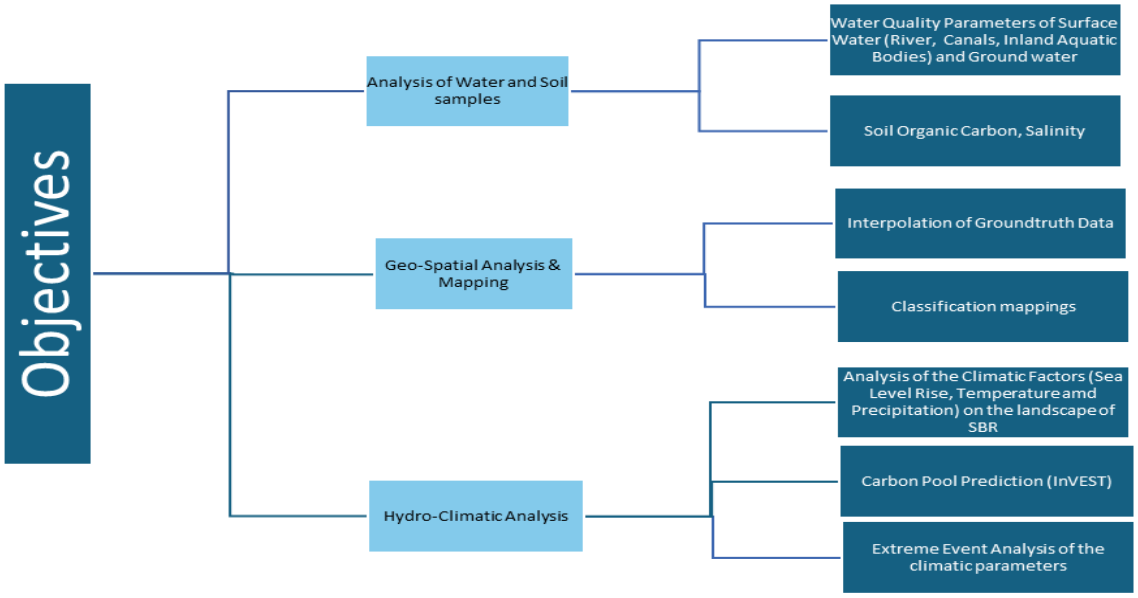
to promote strategies fostering improvements in health, education, inequality reduction, economic growth, global environmental management, and ecosystem conservation. In the context of the Indian Sundarbans, inland aquatic bodies play a pivotal role in the daily lives of the local population, provide beneficial ecosystem services to the communities which needs to be measured.

Research Methodology

This study seeks to explore the degradation of inland freshwater bodies within the SBR and develop a scientifically grounded restoration model. The key research objectives guiding this study are:

- Assessment of Hydro-Climatic changes in Sundarbans Biosphere Reserve (SBR), India.
- Primary data collection of the Soil and Water, to conduct the chemical dynamics.
- To identify the change in the Carbon Dynamics due to Sea level rise.

To accomplish the specified aims and address the research inquiries, a multifaceted approach will be utilized, integrating field surveys, secondary geospatial analysis, and primary soil and water data collection. The methodology is organized into distinct components. The primary segment entails study of secondary geospatial analysis, secondary data analysis and mapping with ground truthing. The process will involve obtaining satellite imagery (e.g., Landsat, Sentinel-2) and additional remote sensing data for the SBR, alongside compiling historical data on land use and land cover (LULC) and Digital Elevation Models (DEM). GIS software like ArcGIS and QGIS will be used to process and categorize the satellite images to detect map the Wetlands and LULC. Both supervised and unsupervised classification methods will be applied, followed by an accuracy evaluation using ground truth information.



The subsequent segment concentrates on field data collection of the ground water and surface water to evaluate the chemical dynamics of the ecosystem and the collected qualitative and quantitative data will be assessed utilizing statistical tools like Excel and Python to evaluate key patterns and effects. The chemical analysis of groundwater samples was conducted using standard laboratory procedures to ensure precision and accuracy. Various physicochemical parameters, including pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness, Calcium, Magnesium, Chloride, and Alkalinity, were measured following established analytical techniques.

The results obtained from these chemical analyses provided critical insights into the groundwater quality and were further used for spatial interpolation using the Inverse Distance Weighting (IDW) method to understand spatial variations across the study area. The Inverse Distance Weighting (IDW) interpolation method is a widely used spatial interpolation technique that estimates unknown values based on the weighted average of known data points. Using InVEST model to estimate the change in the Carbon Stock and the future predictions

Key Findings and Arguments

LULC analysis across approx 10,000 km² reveals water bodies dominating (45.5%), followed by mangroves (17.6%) and croplands (16.9%). Wetlands mapping identifies estuarine open water approx 4,000 km²) as the largest component, with aquaculture operations (approx 500 km²) correlating with groundwater salinization patterns observed in chemical analysis.

TDS exceeded permissible limits in 20% of the samples, highlighting concerns related to seawater intrusion and dissolved solids accumulation, which could affect groundwater suitability for drinking purposes. The analysis of calcium and magnesium concentrations showed that 92.5% and 70% of samples, respectively, fell within acceptable limits, while a small percentage exceeded permissible thresholds, suggesting localized hardness issues influenced by aquifer mineral composition. These findings emphasize the need for continuous monitoring and sustainable groundwater management to mitigate potential salinity impacts and ensure long-term water quality in the region. The pH levels across all three islands remain within the acceptable range, indicating stable acidity-alkalinity conditions. Notable differences are observed in Total Dissolved Solids (TDS) and Electrical Conductivity (EC)

The analysis of groundwater samples from the islands reveals a clear trend of increasing Cl^-/HCO_3^- ratios with rising chloride concentrations, signifying varying degrees of seawater influence. Based on established classification criteria, groundwater with a Cl^-/HCO_3^- ratio below 0.5 mg/L is considered unaffected by seawater, whereas samples with ratios ranging from 0.5 to 6.6 mg/L indicate moderate seawater influence, and those exceeding 6.6 mg/L are classified as highly affected by seawater intrusion.

The sea level rise analysis spanning 1993-2024 reveals a consistent upward trend with significant implications for coastal inundation and blue carbon vulnerability corresponding to approx. rate of 4 mm/year, which closely matches the global mean sea level rise rate but represents a substantial threat to low-lying coastal ecosystems. Long-term projections to 2100 indicate an average approx. rate of 4 mm/year, with confidence intervals suggesting potential acceleration under high emission scenarios. This translates to approximately 30 -40 cm of sea level rise by 2100, representing a critical threshold for mangrove survival and coastal carbon storage stability.

Extreme sea level events analysis using the 5th/95th percentile method identified 40 extreme events over the study period. The temporal distribution shows 1990s: limited extreme events, 2000s: moderate increase, 2010s: elevated frequency, and 2020s: continued high frequency, suggesting an acceleration in extreme event occurrence.

The analysis of tidal height data from 1948-2022 provides the longest temporal perspective in this study, revealing subtle but significant changes in tidal dynamics. The linear trend ($y = 0.0038x - 0.45$) indicates a tidal height increase of 0.003-0.004 m/year, contributing to the overall relative sea level rise affecting the Sundarbans. Extreme tidal event analysis shows evolving patterns in both high-tide (≥95th percentile) and low-tide (≤5th percentile) frequencies across decades. The frequency trends suggest potential changes in tidal asymmetry, which could affect sediment transport, nutrient cycling, and carbon burial processes in mangrove ecosystems. These changes may be linked to both sea level rise and morphological changes in the coastal zone. The precipitation analysis (1980-2020) reveals substantial inter-annual variability in average daily rainfall without a clear long-term trend. This variability has important implications for freshwater input to the Sundarbans, affecting salinity gradients that control mangrove species distribution and productivity.

Temperature analysis (1983-2016) shows trends in yearly average maximum, minimum, and mean temperatures. The distribution analysis of daily temperatures reveals the frequency patterns of extreme temperature events, which are critical for understanding thermal stress on mangrove ecosystems. The combined temperature-precipitation analysis reveals complex relationships between these variables, with scatter plot analysis suggesting weak correlations that vary seasonally. The daily temperature and precipitation heatmaps illustrate clear seasonal patterns and inter-annual variations.

Notable features include warmer periods corresponding to drier conditions and cooler periods aligning with higher precipitation, reflecting monsoon dynamics typical of the region. The integrated sea level rise impact analysis combines mean SLR rate of approx. 4 mm/year with median land subsidence of -2.0 mm/year, calculating net relative rise of approx. 6 mm/year projecting 0.2-0.3 m total rise to 2050. DEM-based inundation modelling predicts aprrox 21 km² land submergence by 2050, representing 0.2% of total area but including critical coastal margins with high carbon storage potential. This submergence results in projected carbon loss of approx 70-72 Mt C. The carbon loss represents 11% of total projected net sequestration for 2020-2050, highlighting sea level rise as a critical threat multiplier for blue carbon systems.

Policy and Practice Implications

Three key recommendations emerge from this comprehensive analysis, each supported by robust empirical evidence and designed to address the interconnected nature of climate change, water quality degradation, and carbon loss.

Recommendation 1: Establish Integrated Blue Carbon Management Zones

Policymakers should immediately designate and legally protect integrated blue carbon management zones that encompass both mangrove forests and inland aquatic systems. Our carbon stock analysis demonstrates that sea level rise threatens around 70-72 Mt C of stored carbon by 2050, representing approximate 11% of projected net sequestration. The establishment of these zones should include: mandatory environmental impact assessments for all development projects within 5 km of designated areas; implementation of buffer zones with restricted agricultural and aquaculture activities; and creation of community-based monitoring programs that engage local stakeholders in long-term ecosystem stewardship. The spatial analysis revealing vulnerable land provides precise boundaries.

Recommendation 2: Implement Adaptive Groundwater Management Systems

Given that 30% of water samples exceed electrical conductivity thresholds and 20% surpass TDS limits, immediate implementation of adaptive groundwater management systems is crucial. This should include: deployment of real-time salinity monitoring networks using the Cl^-/HCO_3^- ratio methodology validated in this study; establishment of freshwater harvesting and storage infrastructure during monsoon periods to reduce dependency on increasingly saline groundwater; and development of alternative water sources including treated rainwater harvesting systems for communities showing severe seawater intrusion (ratios >6.6 mg/L). Financial incentives should support community adoption of water-efficient technologies and alternative livelihood strategies that reduce pressure on degraded freshwater systems.

Recommendation 3: Develop Climate-Resilient Restoration Financing Mechanisms

The projected sea level rise rate and accelerating extreme event frequency demand innovative financing approaches that recognize the global climate benefits of Sundarbans restoration. Policymakers should: establish payment for ecosystem services programs that compensate local communities for carbon sequestration and biodiversity conservation activities; create blue carbon credit systems that monetize the net sequestration potential identified in our projections; and develop climate adaptation funds specifically targeting eco-hydrological restoration projects with demonstrated carbon storage benefits. International climate finance mechanisms should prioritize Sundarbans restoration given its global significance for climate regulation of priority protection areas.

These recommendations require coordinated action across multiple governance levels, from local community organizations to international climate policy frameworks. The scientific evidence presented supports immediate policy action, as delays will exponentially increase restoration costs and reduce ecosystem recovery potential. Success depends on integrating traditional ecological knowledge with scientific data, ensuring that restoration efforts enhance both environmental outcomes and community resilience. Regular monitoring using the methodological framework established in this study will enable adaptive management and continuous improvement of restoration strategies.

Conclusion

This research provides critical scientific evidence for the urgent need to implement comprehensive eco-hydrological restoration strategies in the Sundarbans Biosphere Reserve, advancing our understanding of the complex interactions between climate change, water quality degradation, and blue carbon ecosystem stability. The integration of geospatial analysis, field data collection, and predictive modelling has revealed the alarming pace of environmental degradation, with sea-water intrusion affecting 30% of groundwater samples and sea level rise threatening significant carbon storage capacity.

The study's value extends beyond documenting environmental decline to providing actionable solutions that address both local socio-economic needs and global climate imperatives. By quantifying the relationship between sea level rise and carbon loss, this research establishes a clear economic and environmental case for immediate restoration investment. The methodological framework developed here offers replicable approaches for similar coastal ecosystems globally, contributing to the broader scientific understanding of blue carbon system dynamics under climate change. Future research should focus on developing cost-effective restoration technologies, refining carbon sequestration monitoring protocols, and establishing long-term community engagement strategies. Critical knowledge gaps remain regarding the optimal balance between conservation and sustainable resource use, requiring continued interdisciplinary collaboration. The window for effective intervention is rapidly closing, making the implementation of evidence-based restoration strategies not just environmentally beneficial but essential for regional and global sustainability. Success in the Sundarbans will provide a model for coastal ecosystem restoration worldwide, demonstrating that scientific rigor combined with community engagement can address even the most complex environmental challenges.

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Accounting for Nature: A Monetary Assessment of India's Forest Ecosystems

Author: – Kheya Ghosh Dastidar

M.Sc. Economics, Department of Policy and Management Studies, TERI School of Advanced Studies, Email: kheya.dastidar@terisas.ac.in

This work was derived from the Masters Thesis undertaken by the student under the supervision of:

Dr. Sukanya Das, Professor , Department of Policy and Management Studies, TERI School of Advanced Studies, Email: sukanya.das@terisas.ac.in

Executive Summary

Amidst mounting concerns over the relaxation of environmental safeguards in India, this study explores the economic value of the country's forest ecosystems to critically examine the sustainability of current land-use and development policies. Leveraging the System of Environmental-Economic Accounting: Ecosystem Accounting (SEEA EA) framework, the research constructs a national and zonal ecosystem accounting structure for forests, integrating both physical and monetary flows for selected provisioning services—specifically timber and firewood—for the financial year 2022–23. The study adopts a novel valuation methodology, combining predictive estimation and a tailored pricing mechanism to address data heterogeneity across sources. While detailed results are withheld here, the accounting exercise captures changes in forest extent and ecosystem condition, linking these to economic asset values that are often excluded from conventional measures of national income.

To demonstrate the implications of such exclusions, the research introduces two integrated indicators—Forest Gross Ecosystem Product (FGEP) and Forest Adjusted Domestic Product (FADP)—designed to embed forest ecosystem values within national macroeconomic metrics. These indicators highlight how ecological degradation and natural capital dynamics materially alter the economic picture, particularly when regional disparities in forest condition and management are considered.

By reframing forests as economic assets rather than passive environmental backdrops, this study emphasizes the need to treat degradation not only as an ecological issue but as an erosion of national wealth. As India continues to revise forest governance mechanisms, including recent regulatory relaxations, this work advocates for the systematic integration of ecosystem accounts into economic planning. Embedding such valuations can serve as a critical corrective to the underestimation of ecological costs in development decisions and help steer the economy toward a more sustainable and equitable growth trajectory.

Context & Problem Statement

India's recent development trajectory has increasingly prioritised rapid industrial growth and infrastructural expansion, often sidelining environmental safeguards in the process. Policy shifts, including recommendations by the 2014 Subramanium Committee and the amendments introduced through the Forest Conservation Rules (2022), reflect a growing tendency to streamline environmental clearance procedures in favour of economic activity. A key concern is the removal of mandatory consent from local forest-dwelling communities for diverting forest land, thereby weakening decentralised oversight and community-based forest governance, and oilseeds, along with poor utilization of livestock, aggravates the nutritional crisis. Climate vulnerabilities, small and fragmented landholdings, and poor market access further constrain agricultural diversification. Public distribution policies, focusing on cereals, reinforce unhealthy dietary patterns.

This position paper responds to a critical gap: the lack of district-level assessment of the nutritional contribution of agriculture

Such regulatory relaxations risk incentivising large-scale land-use changes that may degrade forest ecosystems, whose long-term economic contributions are often underrepresented in conventional planning. In this context, a robust economic valuation of forest resources becomes essential—not simply as a conservation exercise, but as a foundational input to evaluate the sustainability and opportunity costs of current policy directions.

This study addresses this gap by undertaking an ecosystem-based valuation of Indian forests within the structure of national economic accounts. Using the updated System of Environmental-Economic Accounting: Ecosystem Accounting (SEEA EA), it develops a framework that recognises forests as dynamic economic assets. The SEEA EA represents a shift from earlier static accounts by explicitly incorporating ecosystem condition, extent, and the flow of services—provisions critical to understanding long-term resource sustainability.

By adapting and applying this framework to India's forest resources, the research aims to estimate and integrate these values into macroeconomic indicators. Doing so will enable more informed policy decisions, support the case for ecological accounting in economic planning, and promote strategies that harmonise developmental goals with the preservation of natural capital. Ultimately, this exercise highlights the need to rethink growth metrics to reflect both economic performance and ecological well-being.

Literature Review

The inadequacy of conventional economic indicators in accounting for environmental degradation has long been acknowledged. Scholars have pointed out that when natural resources—particularly forests—are depleted without proper valuation, national income statistics can present a misleading picture of economic well-being. These findings underscore the importance of integrating ecological dimensions into economic measurement systems to ensure that the consequences of natural capital depletion are not overlooked in growth assessments (Repetto, 1989; Torras, 2000).

Within this broader discourse, several researchers have explored methods to better reflect the value of forest ecosystems in national accounts. In the Indian context, studies have highlighted how traditional valuation techniques tend to underestimate the contribution of forests by excluding the full range of services they provide (Gundimeda et al., 2007; Haripriya, 2001). These contributions have sparked ongoing efforts to develop more comprehensive approaches to valuation that account for both market and non-market benefits.

The System of Environmental-Economic Accounting (SEEA), and more specifically its updated ecosystem component—the SEEA Ecosystem Accounting (SEEA EA)—offers a robust structure for integrating ecosystem services and asset values into economic decision-making (United Nations, 2021). The framework's focus on capturing ecosystem condition, extent, and service flows provides a more holistic basis for evaluating the role of ecosystems in supporting economic systems.

Recent applications of the SEEA EA framework in other countries and at regional levels in India suggest its potential to bridge ecological valuation with policy planning (Campos et al., 2022; Maes et al., 2023; Ramachandra et al., 2024). These studies have highlighted broader trends in ecosystem decline and demonstrated how ecosystem accounting can guide more sustainable land-use and resource management strategies.

However, a gap remains in the application of the SEEA EA at the national scale in India. Moreover, there is little discussion on how the framework might be adapted to fit the complexities of India's institutional and ecological landscape. This research aims to address these gaps by applying and refining the SEEA EA to comprehensively value India's forest ecosystems in a manner that aligns with national accounting practices.

Research Focus and Methodology

This study seeks to explore how forest resources in India can be economically assessed and more effectively reflected within national-level accounting systems. The aim is to provide a broad and integrated understanding of the role forests play in supporting economic activity and environmental stability. The research involves developing ecosystem accounts—both physical and monetary—for select forest-related services.

Particular attention is given to generating value estimates for extractive use, reflecting changes in forest conditions and extent over time, and examining how these valuations might inform broader macroeconomic indicators.

In doing so, the study considers how existing accounting approaches can be adapted to better reflect ecological realities, and how ecosystem degradation and resource use may translate into tangible economic terms. Ultimately, the goal is to highlight the significance of integrating forest values into formal economic planning and assess whether current methods of economic measurement adequately account for the contributions and losses associated with forest ecosystems.

The overarching research question guiding this work is - *To what extent can ecosystem accounting provide a more comprehensive and policy-relevant measure of the economic contribution and degradation of forest resources in India?*

The study draws on a variety of national and state-level data sources to construct a comprehensive view of forest resource dynamics for a recent financial year. Key information related to forest stock and ecosystem flows is synthesized from public datasets and institutional reports, allowing for the development of accounts that reflect both the physical and economic dimensions of forest contributions. These sources provide the foundation for tracking the extent and use of forest resources over time.

To address data gaps and temporal inconsistencies, predictive techniques based on observed trends are employed to estimate values where direct figures are unavailable. In particular, trends from the past decade are used to project values for key indicators in the reference year, including those related to ecological disturbances such as forest fires. For these disturbances, estimation techniques rely on consistent historical relationships between event frequency and ecological impact.

The accounting framework used in the study draws broadly from internationally recognized approaches that integrate environmental assets into economic measurement. Both physical and monetary accounts are developed, incorporating stock and flow measures. Following this, valuation strategies are applied to assign economic worth to various resource use categories and ecosystem changes. These techniques incorporate market-based and imputed pricing structures, drawing from observed prices, reported expenditures, and policy documents. Different categories of forest use and change—such as extraction, degradation, or regeneration—are valued using tailored approaches that reflect their characteristics and data availability.

Where direct valuation was not feasible due to data limitations, composite or proxy pricing methods were employed to approximate economic values. The final output includes aggregate metrics designed to integrate these valuations into broader economic analysis. These measures offer a pathway to reflecting forest-related contributions and losses within national-level indicators, aiming to inform more ecologically attuned economic policy.

Key Findings and Arguments

This study undertakes a national-level assessment of India's forest ecosystem by constructing physical and monetary accounts for a recent financial year, guided by the principles of the SEEA EA framework. Through this approach, forests are treated as economic assets that provide measurable benefits to society. The study attempts to quantify changes in forest stock and the economic value associated with these changes, offering a lens to evaluate the broader implications of forest resource use on the economy. By assigning monetary value to ecological flows and changes, the research frames forest ecosystems as natural capital—whose depletion or enhancement carries direct macroeconomic consequences.

The analysis reveals that India's forest ecosystem has undergone measurable physical and economic shifts. While there have been gains in some areas, overall national trends point to a net decline in both forest extent and value. These outcomes are shaped by multiple factors, including resource extraction, land-use change, and ecological disturbances. While certain restoration and regeneration efforts have been recorded, they have not been sufficient to counterbalance the pace of extraction and damage across the country.

Monetary accounts, developed through valuation of select ecosystem services, show a decrease in the overall asset value of forest ecosystems. Though the relative percentage change appears small, the scale of absolute losses is notable, raising concerns about the long-term sustainability of forest resource use.

The contribution of forests to national income, when properly accounted for, stands at a significant share of the economy—even when only a limited set of ecosystem services is considered. This underlines the importance of incorporating forest values into macroeconomic frameworks to better reflect ecological dependencies.

The study also introduces two integrative metrics—Forest Gross Ecosystem Product (FGEP) and Forest Adjusted Domestic Product (FADP)—to capture the forest ecosystem's contribution to national income more effectively. While FGEP quantifies the gross value of ecosystem contributions, FADP adjusts national income by accounting for both the benefits and losses associated with forest stock changes. These measures demonstrate that even a partial inclusion of ecosystem services alters conventional income estimates, offering a more ecologically informed view of development. Disaggregated zonal analysis further illustrates the heterogeneity of forest dynamics across regions. Certain regions exhibit more resilient patterns, with relatively better performance in terms of forest conservation and economic valuation. These areas are likely influenced by a combination of institutional, ecological, and sociocultural factors that support sustainable forest practices. In contrast, other zones show marked declines, suggesting high extraction pressure, insufficient regeneration, and ecological stress. These trends signal the importance of tailoring forest management policies to regional contexts.

Zones emerged with net positive trends in both physical and monetary terms, pointing toward successful conservation and restoration initiatives. While others, despite experiencing a decrease in forest area, recorded notable gains in economic value—possibly due to the quality and density of remaining forest stock. These contrasts highlight the necessity of distinguishing between quantity and quality in ecological assessments. Several other zones experienced moderate to severe losses, with extraction pressures, fire events, and land-use changes driving negative outcomes. In particular, zones recording the sharpest declines in both area and value, underlining the urgent need for targeted intervention in forest governance, fire prevention, and land use planning.

The study also reveals a discrepancy between physical and monetary drivers of forest loss. While physical accounts are primarily influenced by high-volume resource use, monetary losses are more strongly tied to high-value disruptions like forest fires. This contrast reflects the differentiated economic worth of ecosystem components, and underscores the limitations of relying solely on biophysical indicators for policy formulation.

Overall, the findings call attention to the widespread undervaluation of forest resources in conventional economic systems. Even within a limited scope, the inclusion of forest ecosystem values produces measurable divergences from official income estimates, pointing to hidden costs of economic development that often go unrecorded. Adjusting macroeconomic metrics to reflect changes in natural capital can offer a more realistic and sustainable measure of progress.

By integrating ecological valuation into national accounting structures, this study offers a framework for rethinking the role of forests in economic development. The results underscore the importance of region-specific strategies and institutional strengthening to preserve ecosystem services while pursuing growth. As the ecological and economic functions of forests become more interlinked in a changing climate, their inclusion in planning and budgeting frameworks becomes not only desirable but essential for sustainable development.

Policy and Practice Implications

The findings of this study underscore the urgent need for targeted policy measures to address regional differences in forest resource conditions and to promote sustainable forest management practices across India. The economic significance of forests demonstrated here calls for their recognition as critical natural assets within national economic planning. Integrating forest valuation into broader accounting and policy frameworks can help reflect their true contribution, not only in terms of provisioning services but also through ecosystem functions that sustain biodiversity and local livelihoods.

Institutionalizing green economic indicators that capture these values—such as the Forest Gross Ecosystem Product and Forest Adjusted Domestic Product—can support a more comprehensive understanding of the trade-offs between development and ecological health.

This integration would allow policymakers to better track the economic impacts of forest depletion and regeneration, guiding decisions toward sustainability in the long term.

Recent regulatory changes, particularly amendments to forest conservation laws, raise concerns about weakening environmental safeguards and potentially marginalizing communities that depend on forests. Reinstating participatory decision-making processes involving local institutions is critical to ensure more equitable and ecologically sensitive forest governance.

Compensatory afforestation policies, while aiming to offset forest loss, need to be carefully revisited to avoid unintended consequences such as the establishment of monoculture plantations that fail to restore natural biodiversity. Encouraging afforestation efforts that prioritize ecological diversity and are adapted to local climatic and terrain conditions will enhance the long-term resilience of forest ecosystems.

Strengthening the legal and institutional frameworks governing forest management is essential to improve enforcement and reduce illegal or unrecorded resource extraction, which currently contributes to significant ecological and economic losses. Building the capacity of environmental agencies and local forest institutions will be vital to ensure that conservation regulations are effectively implemented.

Overall, the evidence presented points to the need for comprehensive reforms that combine improved data collection, more rigorous monitoring, and adaptive enforcement strategies. Addressing regional disparities through customized approaches, reassessing recent regulatory relaxations, and fostering community involvement can collectively pave the way for more sustainable forest management. By embedding the economic value of forests within planning and governance systems, India can better safeguard its forest ecosystems while supporting inclusive and environmentally sustainable growth.

Conclusion

This study underscores the critical need to fundamentally rethink how forests are valued and incorporated into India's economic planning. By applying the SEEA EA framework to construct detailed physical and monetary accounts for timber and firewood flows, the research provides a nuanced assessment of the state and economic value of India's forest ecosystems for 2022–23. The observed declines in forest area and volume, coupled with significant monetary losses, highlight the urgent challenge posed by unsustainable resource use and inadequate restoration efforts.

The introduction of forest-augmented indicators such as the Forest Gross Ecosystem Product and Forest Adjusted Domestic Product offers a practical pathway to integrate ecosystem services into national accounts, revealing the substantial yet often overlooked contribution of forests to the economy. Regional disparities in forest conditions emphasize the need for location-specific policy responses that address the distinct challenges faced by different zones.

This study advocates a paradigm shift in treating forests as dynamic economic assets rather than passive resources. Current regulatory relaxations that weaken community participation and environmental safeguards must be reassessed to prevent further degradation. Strengthening legal and institutional mechanisms is essential to safeguard forest ecosystems from overexploitation.

Ultimately, embedding natural capital accounting into mainstream economic frameworks is vital for ensuring that India's development remains both economically prosperous and ecologically sustainable. .

The true cost of neglecting forest values extends beyond environmental damage to encompass the erosion of national wealth and resilience, underscoring the imperative for sustainable forest management in securing India's long-term future.

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Study of morphological and physiological parameters of *Azolla sp.* in response to growth parameters and optimisation for carbon capture

Author: Brahamtej Kaur Grewal[+*]

[+]M.Sc. Biotechnology, Department of Biotechnology, TERI School of Advanced Studies, Email: mishraapoorva73@gmail.com

*This work was derived from the Masters Project undertaken by the student under the supervision of

Dr. Shashi Bhushan Tripathi, Associate Professor, Department of Plant Biotechnology, TERI School of Advanced Studies, New Delhi

Prof (Dr.) Naqui Anwer; Professor and Head, Department of Sustainable Engineering, TERI School of Advanced Studies, New Delhi

Prof (Dr.) Shaleen Singhal, Director, Emerson Centre of Excellence for Sustainability Studies, TERI School of Advanced Studies, New Delhi

Executive Summary

Carbon capture, utilisation, and storage have received attention lately as a measure to mitigate climate change. However, the artificial routes of carbon capture are economically inadequate to be scaled in the global South. This study presents a novel approach to capture atmospheric carbon via enhanced cultivation of the aquatic fern Azolla, which has one of the lowest biomass doubling times (i.e., 2 to 5 days) among photosynthetic species. Due to Azolla's ability to capture atmospheric nitrogen, the harvested Azolla can be used as a bio-fertiliser, reducing the demand for nitrogenous fertilisers like urea and diammonium phosphate. This could reduce the emissions associated with the production and use of synthetic fertilisers. Besides capturing carbon dioxide, this practice could also reduce the dependence of small and marginal farmers on expensive synthetic fertilisers, making the agricultural community more resilient to the impacts of climate change.

The high growth rate of azolla can be leveraged to sequester atmospheric carbon dioxide (CO_2) through the process of photosynthesis. This study explores a model of enhanced cultivation of azolla through vertical integration and soilless liquid fertiliser to establish year-round carbon capture operations at minimal cost.

Context & Problem Statement

This study represents a pioneering effort in the large-scale, sustainable cultivation of *Azolla*, offering foundational insights for future research in its use as fodder, fertiliser, biofuel feedstock, and a scalable carbon capture solution. Unlike prior studies that primarily relied on synthetic fertilisers or organic solids like soil and cow dung, this research prioritised water-use efficiency and system simplicity. Consequently, solid nutrient inputs were minimised to maintain optimal water quality parameters—such as dissolved oxygen (DO), biochemical oxygen demand (BOD), and chemical oxygen demand (COD). Instead, liquid nutrient solutions derived from processed organic waste streams were developed and standardised, aligning nutrient delivery with environmental sustainability.

A major innovation of this study lies in the implementation of vertically integrated cultivation systems. While vertical farming is common in hydroponics, it has not been extended to aquatic ferns like *Azolla*. This research explored tiered meta-structures to increase land-use efficiency without compromising biomass productivity, marking a novel contribution to the cultivation of shade-tolerant aquatic species. In contrast to algae, which require high solar radiation and costly photobioreactor systems for vertical scaling, *Azolla* demonstrates inherent compatibility with low-light conditions, making it suitable for stacked or rooftop farming models. The operational simplicity and adaptability of the proposed system are crucial for scalability, especially in contexts lacking reliable electricity, arable land, or high-tech infrastructure.

By eliminating dependence on soil characteristics and electrical input, the study lays the groundwork for decentralised, low-tech *Azolla* farming across varied geographies and socio-economic contexts. This approach has significant implications for rural livelihoods, peri-urban farming systems, and climate-resilient agriculture. Most importantly, the study highlights a substantial research gap in using *Azolla* explicitly for carbon capture. Historically, interest in *Azolla* has focused on its utilitarian value, overlooking its potential as a nature-based climate mitigation tool. Yet, geological records indicate that ancient *Azolla* blooms played a major role in past atmospheric carbon drawdowns. Building on this premise, the present study advocates for the strategic use of *Azolla* in carbon capture operations, potentially at a gigatonne scale a perspective that could shift the global research agenda on aquatic ferns.

This study thus provides the first practical framework for standardised, scalable, and low-impact *Azolla* cultivation systems that could support certification for carbon credits and contribute meaningfully to meeting international climate goals under the Paris Agreement. Future research can build on this exploratory work by optimising vertical integration designs, enhancing nutrient cycling using waste streams, and quantifying carbon sequestration rates under varied climatic and structural conditions.

Literature Review

The genus *Azolla* (*Azo*: to dry; *ollyo*: to kill) (Lumpkin and Plucknett, 1980) is a small-leafed aquatic fern that doubles itself in a mere time of 2 to 5 days. It is a small-leafed, floating aquatic fern native to the tropics, subtropics, and warm temperate regions of Africa, Asia, and America. (Sabetraftar *et al.*, 2013) (Bujak and Bujak, 2024) Among cyanobacteria-plant associations, the relationship between Azolla and *Anabaena-azollae* stands out as unique. The Azolla symbiosis with Anabaena is the only known permanent symbiosis, living in Azolla throughout all its life stages. It gets passed down from one generation to the next, whether it produces sexually or vegetatively.

Azolla is an excellent source of biofertilizer because of its rapid biomass doubling time and therefore widespread distribution. (Jama *et al.*, 2023) Azolla as a biofertilizer can mitigate the CO_2 emissions which would otherwise be produced from fossil fuels that are being utilised in producing inorganic fertilisers such as urea. It alters the soil microbial communities as well (Widiastuti, 2017). Azolla as a biofertilizer offers a promising way in order to achieve better nitrogen use efficiency (NUE) by utilising the biological nitrogen fixation (BNF) potential. (Yao *et al.*, 2018)

When the process of trans-esterification is performed and Fatty Acid Methyl Esters (FAME) are obtained from *Azolla/ Anabaena azollae,* the lipids, particularly C16:0, C18:2 & C18:3, meet the essential fuel criteria required in the EN14214 standards of biodiesel, which includes the Cetane Number (CN), fuel density & the iodine value. Due to this distinct chemical composition, Azolla becomes a great & environmentally friendly resource for the production of biofuel.

Azolla – Anabaena symbiosis was used to treat wastewater as it grows by fixing nitrogen from the atmosphere, and therefore it can be expected that even when the N is consumed, still P removal can take place (Shiomi and Kitoh, 1987). As *Azolla,* the aquatic fern, can grow on wastewaters, it makes it an attractive species for utilisation as bioenergy (Miranda *et al.*, 2018). *Azolla* can act as a decontaminant as it binds in very high concentrations with heavy metals and with effectiveness (Cohen-Shoel *et al.*, 2002)

Research Focus & Methodology

The research objectives and underlying research questions for the study have been enumerated as under:

1. To optimise the composition, dose and frequency of nutrient addition, and standardise feasible strategies for integrated pest management
2. To empirically quantify the CO_2 captured through biomass growth
3. To analyse plant physiology and establish macro and micro-parameters of *Azolla* health and productivity

.On successful completion of standardisation and optimisation of operations at small-scale implementation, operations were scaled to medium scale by vertically integrating *Azolla* containers on top of each other, with a median distance of 0.25 m between two vertical levels.

A meta-structure for large-scale *Azolla* cultivation was constructed, with financial sponsorship from the Emerson Centre of Excellence for Sustainability Studies. While initially, the meta-structure was planned to have a capacity of $1tCO_2yr^{-1}$, due to space constraints within TERI SAS premises, the approved meta-structure had a cumulative carbon capture capacity of about 635 $kgCO_2yr^{-1}$, under optimal operating conditions

Table 3.1: *Summary of structural details of the carbon capture meta-structure*

Specification	Details
Available area	6.7 m x 3.1 m
Structure footprint	6.5 m x 3 m
Inter-level height	2 m
Design water load (per level)	1650 kg
Cumulative design water load	8250 kg
Effective azolla area	82.5 m^2
Annual carbon capture capacity	635.25 kg

The process of calculating captured CO_2 from the fresh weight of the harvested biomass is as follows:

- **Fresh weight of harvested *Azolla* (FW):** The *Azolla* is harvested once the double bedding condition is reached. The excess water is allowed to drain out, and the fresh weight of the biomass is recorded.
- **Dry weight of *Azolla* biomass (DW):** DW=0.07 x FW [Fresh weight samples are dried every week to obtain an average ratio of dry to fresh weight. For our study, the observed ratio is 0.07.]
- **Carbon content of biomass (CB):** CB=0.42 x DW [The carbon content of the dry biomass is estimated through ultimate analysis. The carbon content of azolla is fairly constant, regardless of species and growing conditions. For our study, we have assumed a carbon content of 42%, pending empirical tests on harvested azolla samples (Bocchi and Malgioglio, 2010).]
- **Captured CO_2:** CC=3.67 x CB [The captured atmospheric CO2 can be quantified by the stoichiometric relationship between atomic carbon and molecular carbon dioxide.]
- **The empirical equation thus becomes:** CC=0.107898 x FW

Chlorophyll a and b occur in higher plants, ferns and mosses. Chlorophylls c, d, and e are found in algae and certain bacteria. Chlorophyll is extracted in 80% acetone, and the absorbance at 663nm, 652nm and 645nm is read in a spectrophotometer. Using the absorption coefficients, the amount of chlorophyll is calculated.

Table 3.2: *Readings of the lower phase*

Absorbance (nm)	Reading 1	Reading 2	Reading 3
645	0.277	0.300	0.283
652	0.394	0.408	0.394
663	0.703	0.724	0.710

Table 3.3: *Reading of the upper phase*

Absorbance (nm)	Reading 1	Reading 2	Reading 3
645	0.072	0.064	0.069
652	0.094	0.087	0.091
663	0.154	0.148	0.155

Table 3.4: *Chlorophyll a and b values of both the phases*

Phases	Chlorophyll a	Chlorophyll b
Lower Phase	0.414	0.162
Upper Phase	0.088	0.043

Calculations:

Calculate the amount of chlorophyll present in the extract (mg chlorophyll per gram of tissue) using the following formula:

a. Chlorophyll a (mg/g) = 12.7 (A_{663}) – 2.69 (A_{645}) × V/1000 × W

B. Chlorophyll b (mg/g) = 22.9 (A_{645}) – 4.68 (A_{663}) × V/1000 × W

C. Total chlorophyll (mg/g) = 20.2 (A_{645}) – 8.02 (A_{663}) × V/1000 × W

Where, *A= Absorbance at specific wavelengths; V= Final volume of chlorophyll extract in 80% acetone; W= Weight of the fresh tissues extracted*

Key Findings & Arguments

Chlorophyll analysis was performed using the protocol mentioned in the resources and methods section, and the following were the results.

As given under the equations under the preceding section, the following graph indicates the quantum of biomass harvested from the meta-structure in the period from 08.03.2025 to 28.05.2025, spanning a period of 81 days, with a cumulative harvest of 177.41 kg wet *Azolla* biomass, and consequently a direct air capture quantum of 19.142184 $kgCO_2$.

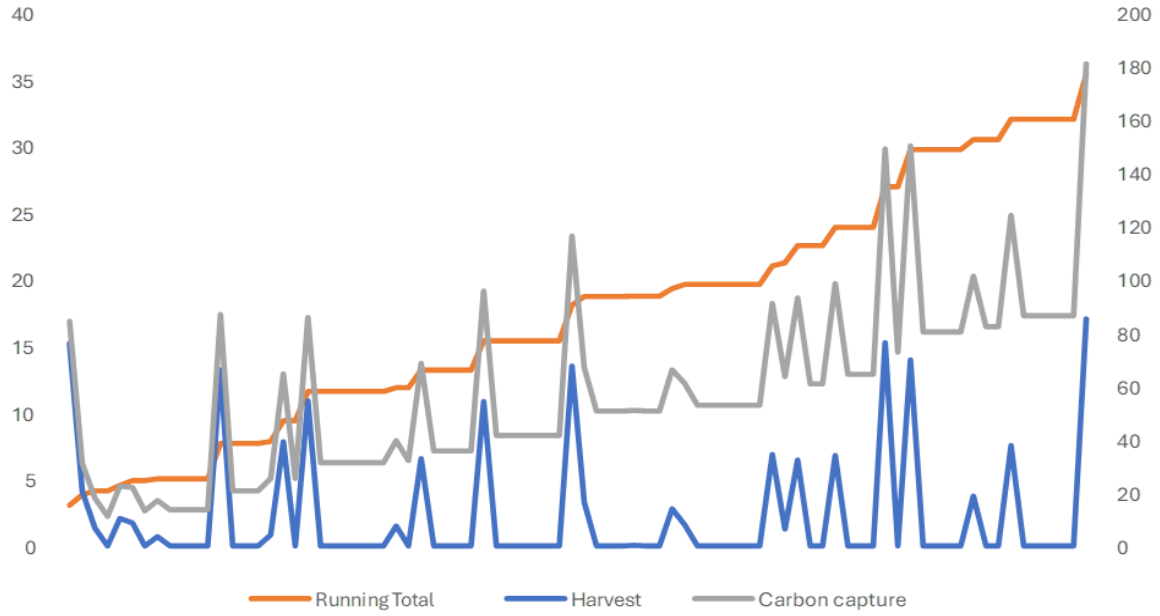


Figure 3.1: *Graph of running total, harvest and carbon capture*

The corresponding fresh weight harvest rate becomes 30.420 g/m^2-day against the optimal figure of about 200 g/m^2-day. Learning curves as well as local limiting factors have to be taken into consideration while evaluating the efficacy of such exploratory studies.

High Performance Conditions:

A7, A8, A12 – All used Soil + Fresh Cow Dung + No Netting. Vigorous, sustained growth.

Moderate Performance:

A2, A5, A13 – Soil + Fresh Dung + Partial Netting: Steady but slower growth.

A3, A9 – No Soil + Fresh Dung + Full Netting: Poorer performance

Low/Failed Performance:

A1 – No inputs: complete failure.

A4 – Fermented dung: yellowing, stagnation.

A6, A10, A11 – Biofertilizer-only: poor sustainability.

Variable-Specific Analysis

- **Soil Presence:** Essential for nutrient buffering and microbial activity. All high-performing trials included soil.
- **Fertiliser Type:** Fresh cow dung was most effective. Fermented dung and biofertilizer were suboptimal.

  Shade Netting: Partial shade (30–40%) was optimal. Full shade suppressed growth. No shade led to overheating above 36–37°C.
- **Solar Radiation:** Needed for proliferation. Overexposure (>37°C) caused yellowing.

Emergent Patterns and Thresholds

- Best Growth: Soil + Fresh Dung + Full Sun (up to ~36°C ambient).
- Growth Inhibition: Begins above ~37°C or under >50% shade.
- Color Loss: Low light, nutrient stress, or thermal stress.

- Frond Decay: Ammonia buildup, dehydration, or zero inputs.

Proposed Next Steps – Phase 2 Trials

B1 – Soil + Fresh Dung + 30% Shade Net: Optimal configuration.

B2 – Soil + Fermented Dung + Partial Net: Test impact of anaerobic input.

B3 – Soil + Fresh Dung + White Diffuse Film: Investigate light spectrum.

B4 – Soil + Fresh Dung + Biofertilizer: Test synergy.

B5 – Soil + Fresh Dung + Mist Cooling: Thermal resilience.

B6 – Soil + Fresh Dung + Azospirillum Inoculation: Nitrogen fixation enhancement.

Policy & Practice Implications

The empirical findings from sustained Azolla cultivation across diverse microclimates offer actionable insights with profound implications for Indian policy-making. Given India's heavy reliance on fertilizer imports, pressing energy security concerns, and global climate commitments, Azolla emerges as a strategic biological asset capable of addressing multiple policy priorities simultaneously.

Fertilizer Import Independence: India currently imports over 30% of its urea and significant quantities of phosphorus- and potassium-based fertilizers, placing a considerable burden on the national exchequer and exposing agriculture to global supply volatility. *Azolla,* with its proven capacity for atmospheric nitrogen fixation via symbiosis with *Anabaena azollae*, provides a sustainable and scalable alternative to synthetic nitrogen fertilisers.

Government policy can encourage decentralised Azolla cultivation through the National Mission for Sustainable Agriculture (NMSA) frameworks, linking it to local Krishi Vigyan Kendras (KVKs) and Panchayati Raj institutions. Incentivising Azolla production and integration into paddy fields, vegetable farms, and livestock systems can significantly reduce nitrogen fertiliser demand. Inclusion of Azolla-based biofertilizers in the PM-PRANAM scheme (Promoting Reduction of Nitrogenous Input Application for Minimising Fertiliser Subsidy) could catalyse farmer uptake and align with nutrient-use efficiency targets.

Biofuel Production and Energy Transition: India's National Bio-Energy Policy aims to boost biofuel production, especially second-generation (2G) feed stocks, to reduce dependency on fossil fuels and mitigate rural energy poverty. Unlike food-based biofuel crops, Azolla does not compete for arable land or freshwater, and it thrives on nutrient-rich wastewater, enhancing its viability in peri-urban and rural wastewater recycling systems.

Policy instruments such as the National Bio-Energy Mission can support pilot-scale Azolla-to-biofuel initiatives, especially in conjunction with rural biogas programs or municipal waste-to-energy schemes. Additionally, subsidies or viability gap funding for Azolla-based bio-digesters in Gram Urja Swaraj schemes can integrate energy self-sufficiency.

Carbon Capture and Climate Policy Alignment: This aligns with India’s Long-Term Low Emission Development Strategy (LT-LEDS), which emphasises nature-based solutions and ecosystem restoration. The rooftop and structural pool trials demonstrate the potential for urban and peri-urban carbon capture infrastructure based on living biomass, a model not yet tapped in India’s climate action portfolio.

Incorporating *Azolla* cultivation into India’s Green Credit Programme and afforestation-linked carbon trading platforms could unlock new incentives for individuals and communities. Moreover, *Azolla’s* role in nutrient cycling, shade moderation, and biotic stress resistance offers co-benefits for climate-resilient agriculture under PM-KUSUM and MGNREGS-supported eco-restoration works.

Conclusion

While the dominant majority of studies on azolla focus on its multitudinous uses as fodder, fuel and fertiliser, there is a research gap in the context of using azolla as a means for enhanced carbon capture. The limited scalability of azolla cultivation operations over the past few decades can be attributed to the intent of research carried out in the context of azolla morphology, physiology and utilisation. None of the extant studies focus on the widespread utilisation of azolla for the primary purpose of combating global warming, which can catalyse the scalability of azolla cultivation operations to a gigatonne order of magnitude.

Future studies on similar topics include, but are not limited to, the following areas of research:

- Genetic enhancement of azolla species for greater tolerance to extreme temperature and humidity conditions in local micro-climates
- Imparting a certain degree of salinity tolerance to the azolla species
- Backwards integration for resource efficiency can be streamlined to allow for decoupling of necessary resources, such as freshwater, from anthropogenic requirements. Studies in this domain can focus on the cost-effective desalination of ocean water using renewable energy technologies such as parabolic/paraboloid solar thermal collectors.
- Spore extraction technologies can be developed to increase the ease of inoculation and transportation in the event of the initialisation of operations at a new location.

The present study offers an exploratory approach for standardisation, optimisation and eventual certification of enhanced azolla cultivation processes for the generation of carbon credits and subsequent offsetting of greenhouse gas emissions through planned end use of the harvested biomass. Future research can be built on the foundation of this face validity study on the potential of this tiny fern to draw down greenhouse gases, while providing co-benefits pertaining to social, economic, and environmental dimensions.

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1. Mangroves and Ponds as Natural Barriers: Protecting Freshwater for Millions in a Climate-

Author: Aakash Gosh[+]*

[+] M.Sc. Economics, Department of Policy and Management Studies, TERI School of Advanced Studies; New Delhi; email: aakash.ghosh@terisas.ac.in

*This work was derived from the master's thesis undertaken by the student under the supervision of:

Prof. Saudamini Das; Senior Visiting Fellow, Former NABARD Chair, Section Professor, Institute of Economic Growth, University Enclave; and

Prof. Sukanya Das; Dean (Research and Partnership), Department of Policy and Management Studies, TERI School of Advanced Studies, New Delhi

Executive Summary

The Sundarbans delta, supporting 4.6 million people, faces a critical water security crisis due to accelerating subsurface water salinisation driven by sea-level rise (3.14 mm/year), cyclones, and embankment failures. This research provides the first evidence quantifying mangroves as essential natural buffers against saltwater intrusion. A study of subsurface water samples across the region revealed an important relationship, which holds statistically: mangrove patches prevent saltwater intrusion and help in maintaining salinity levels in subsurface water.

Along with this, surveys of households confirmed ponds as vital socio-ecological infrastructure for irrigation, domestic use, aquaculture, and cultural practices. However, communities reported severe decline: multiple observations were made regarding increased frequency in drying of the ponds, waning water quality and aquatic life, and their failure to serve as dry season reserves. Crucially, most residents were unaware that mangrove loss increased flooding and salinity problems they ranked as severe.

Our position is unequivocal: Mangrove restoration as coastal buffers, integrated with improved pond systems and community outreach, offers the most effective, equitable, and sustainable pathway to safeguard freshwater security in the Sundarbans and similar climate-vulnerable deltas. Ignoring this nature-based approach risks catastrophic water scarcity for millions.

Problem Statement

Coastal deltas globally, home to over 500 million people, are on the frontlines of climate change. The Sundarbans, a UNESCO World Heritage site and the world's largest contiguous mangrove ecosystem, epitomises this vulnerability. Its inhabitants face an existential threat: the rapid salinisation of their primary freshwater source – subsurface water. Accelerated relative sea-level rise (50% faster than global averages), intensifying cyclones, and pervasive embankment breaches are driving saltwater into underground aquifers, contaminating drinking water and irrigation supplies. This crisis forces communities to purchase water or rely on deep, expensive borewells, deepening poverty in a region where 44% already live below the poverty line.

The salinisation crisis overlaps with acute socio-environmental vulnerabilities. Declining river sediment flows weaken embankments, while upstream freshwater diversions reduce flushing of estuarine salts. Subsurface water over-extraction exacerbates saltwater intrusion. Crucially, the degradation of mangrove forests – natural coastal defences – removes a critical barrier against saline inundation. The problem transcends environmental degradation; it is a profound threat to human health, food security via salinized agricultural land, economic stability, and cultural survival.

Despite widespread recognition of mangrove benefits for surface wave attenuation, a critical knowledge gap persisted: evidence delineating mangroves' specific role in mitigating subsurface water salinisation in complex deltaic systems like the *Sundarbans* was absent. Furthermore, the potential of integrating traditional water systems (household ponds) with mangrove conservation for holistic water security remained unexplored. This research directly addresses these gaps, providing actionable scientific evidence for nature-based adaptation.

Literature Review

Nature-based Solutions (NbS) have emerged as a vital paradigm for climate adaptation, emphasising ecosystem protection, restoration, and management to address societal challenges while benefiting biodiversity. Coastal NbS, particularly mangrove conservation and restoration, are globally recognised for reducing wave energy, storm surge impacts, and erosion. Extensive literature documents mangroves' role in surface water dynamics and coastal protection post-2004 tsunami. However, understanding of their subsurface hydrological functions, specifically concerning subsurface water salinity regulation, remains underdeveloped.

Subsurface water salinisation in deltas is a well-documented but escalating problem, driven by sea-level rise, reduced sediment flows, over-extraction, and physical infrastructure failure. Monitoring techniques (hydraulic head measurements, geophysical surveys, tracer analysis) confirm saltwater intrusion pathways, yet studies integrating ecological buffers like mangroves into salinisation models are scarce. Research specific to the Sundarbans details alarming salinity gradients, species shifts indicating salt stress (e.g., decline of *Heritiera fomes*), and embankment vulnerabilities. While acknowledging mangroves' overall protective value, existing Sundarbans literature lacks empirical quantification of their direct impact on aquifer salinity and fails to integrate community-managed freshwater ponds into resilience strategies.

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This research bridges these critical gaps. It builds upon NbS theory and coastal hydrogeology but provides novel evidence: clarifying the mangrove width -subsurface water salinity. It uniquely integrates hydrogeological analysis with socio-ecological assessment of household ponds, positioning both as complementary NbS for integrated delta water security, thus advancing beyond purely ecological or purely engineering approaches prevalent in current literature.

Research Focus & Methodology

The research approach combined scrutiny of the subsurface water quality with qualitative socio-ecological assessment of the ponds, which are a feature observed in almost every single household of the region. Forty subsurface water samples from tubewells/borewells were collected. Geographic coordinates enabled spatial analysis using QGIS to map distances. Well depth and operational years were recorded via user interviews. A Multiple Linear Regression (MLR) model quantified relationships. Community understanding of ponds was assessed via structured surveys with respondents across the islands, selected using snowball sampling due to logistical constraints and the

near-universal presence of household ponds (ensuring topic relevance).

The questionnaire covered environmental awareness, pond uses, ecological value, livelihood importance, observed changes, and socio-cultural significance. This mixed-methods design was essential. The MLR provided robust evidence of the mangrove-salinity relationship while the perception survey captured the irrefutable yet vulnerable role of ponds a crucial, community-managed NbS component revealing real-world vulnerabilities and socio-cultural dimensions absent from purely physical data. Combining these approaches generated a broad understanding of NbS efficacy for delta water security.

Key Findings

A. Mangroves are Highly Effective Natural Barriers against subsurface water salinisation:

1. **Robust Statistical Evidence:** Regression analysis revealed a highly significant negative relationship between mangrove patch width and sub-surface water salinity. This finding provides proof of mangroves directly mitigating saltwater intrusion into aquifers in the Sundarbans.
2. **Spatial Context:** While proximity to saline sources generally correlated with higher salinity (intuitive negative correlation), the influence of mangrove width demonstrates that physical distance alone is insufficient; the presence and extent of this natural vegetation barrier is the primary factor controlling subsurface salt intrusion in this deltaic environment.

B. Household Ponds are Vital but Climate-Threatened Socio-Ecological Infrastructure:

1. **Multifunctional Lifelines:** Surveys confirmed ponds are near-universal (virtually every household) and serve diverse, critical functions: irrigation, domestic chores, aquaculture, and cultural/religious practices. They are embedded in daily life and local economies, with maintenance costs reflecting use intensity.
2. **Strong Ecological Awareness:** Communities highly value ponds' ecological roles, with the majority in agreement that they support biodiversity and the importance of pond-side trees for shade and wildlife habitat.
3. **Severe Climate Impacts:** Despite their value, ponds are failing under climate stress. A strong consensus of respondents agrees with the following: ponds are drying up more frequently, and there is a reduction in the quality of the water, as well as fauna and flora species in the pond. Critically, ponds do not provide reliable backup water during dry periods due to their design and vulnerability to drought. This highlights a dangerous vulnerability in community water security.
4. **Cultural Transition:** While the ponds' cultural importance was affirmed, only a few reported active ritual use, suggesting a shift from practical social spaces towards symbolic heritage, partly driven by environmental constraints. However, they remain vital seasonal spaces for children.
5. **Critical Awareness Gap Undermines Resilience:** Despite identifying cyclones, flooding, embankment breaches, soil salinity, and water scarcity as severe problems, most did not view the reduction in the quanta of mangrove cover as an alarming or even an important loss. This disconnect is of concern, given the evidence that mangroves directly mitigate these very threats (flood attenuation, salinity buffering). This lack of awareness hinders community engagement in vital conservation efforts.

These findings fundamentally shift the discourse on Sundarbans water security. Mangroves are not just biodiversity havens or surface wave buffers;

they are quantifiable, essential infrastructure for protecting the freshwater lifeline beneath the ground. The significant relationship provides actionable science for restoration. Concurrently, household ponds represent a widespread, community-owned NbS for rainwater harvesting and multiple uses, but their current vulnerability to climate impacts (drying, salinisation during storms) constitutes a major risk.

The critical disconnect between community experience of climate threats and understanding of mangrove benefits represents a significant barrier to building resilience. Therefore, effective adaptation requires an integrated NbS approach: strategically restoring mangroves as bio-shields, combined with rehabilitating ponds as climate-resilient water reservoirs (e.g., increasing depth, preventing saline inflow), all underpinned by targeted education linking mangrove conservation directly to the protection of homes, freshwater, and livelihoods. Relying solely on engineered solutions is prohibitively expensive and ignores the proven, multi-benefit potential of these synergistic natural and traditional systems. This integrated strategy offers the most sustainable and equitable pathway to safeguard the future of delta communities.

Policy and Practice Implications

The empirical evidence demands urgent integration of mangroves and ponds into the core of Sundarbans' water security and climate adaptation strategies. Policymakers, disaster management authorities, and conservation agencies must act on these findings:

A. Mandate and Implement Strategic Mangrove Buffer Zones:

Action: Enact and enforce policies designating and protecting mangrove buffers along vulnerable coastlines and estuaries adjacent to critical freshwater aquifers and settlement zones, based on the identified technical optimum. Prioritise restoration in areas with high salinity intrusion and narrow existing buffers.

Co-benefits: Mangroves provide extensive co-benefits beyond salinity reduction. They serve as crucial carbon sinks, storing up to four times more carbon per hectare than tropical rainforests, making them vital for climate change mitigation. These coastal forests act as natural buffers against storm surges, tsunamis, and coastal erosion, protecting inland communities and infrastructure from extreme weather events. Ecologically, mangroves function as nurseries for numerous marine species, supporting fisheries that millions of people depend on for their livelihoods. They filter pollutants and excess nutrients from water, improving coastal water quality. Many mangrove areas also support ecotourism, providing sustainable economic opportunities for local communities while preserving these critical ecosystems. Additionally, mangroves help stabilise shorelines through their complex root systems and contribute to subsurface water recharge in coastal areas, further enhancing their value for both environmental protection and human well-being.

B. Integrate and Upgrade Household Ponds into Climate-Resilient Water Security Systems:

Action: Launch programs for **integrated pond rehabilitation** focusing on: (a) increasing depth and storage capacity (e.g., de-silting, controlled excavation); (b) improving lining to reduce seepage; (c) constructing saline intrusion barriers (e.g., small, mangrove-reinforced berms); and (d) promoting climate-resilient aquaculture. Provide technical support and micro-finance for upgrades, prioritising ponds critical for community clusters.

Evidence Basis: The universal household reliance on ponds for diverse needs, coupled with the documented high vulnerability, necessitates investment to enhance their resilience as a vital, decentralised water source complementing. subsurface water.

Co-benefits: Improves food security (aquaculture), supports livelihoods, enhances local biodiversity, and provides supplementary irrigation, reducing pressure on subsurface water.

C. Launch Community-Led Education and Awareness Campaigns Linking Mangroves to Security:

Action: Develop and implement widespread community awareness programs co-created with local stakeholders. These must clearly communicate the direct evidence linking mangrove width to reduced subsurface water salinity (using local examples and data) and demonstrate how mangroves mitigate cyclones, flooding, and embankment breaches the very threats communities rank as severe. Integrate this into school curricula and local governance (Panchayat) initiatives.

Evidence Basis: The critical gap identified: communities suffering salinity/flooding but not linking it to mangrove loss impedes conservation support. Education is essential for fostering stewardship and ensuring the long-term success of mangrove buffer policies and NbS programs.

Co-benefits: Empowers communities with knowledge, fosters ownership of conservation efforts, builds social cohesion around environmental action, and supports sustainable livelihood development linked to healthy ecosystems.

Conclusion

This research delivers a critical scientific and practical advance for climate-vulnerable deltas: mangroves are empirically proven, quantifiable natural infrastructure for protecting subsurface water the freshwater lifeline for millions from saltwater intrusion. The identification of the significance of mangrove buffer

in reducing salinity provides a precise, science-based target for maximising salinity reduction. Concurrently, household ponds, while culturally embedded and multifunctional, face severe threats from climate change, exposing communities to water insecurity despite their presence.

The core message is clear: safeguarding freshwater in the Sundarbans, and analogous deltas globally, requires an integrated NbS approach. This must combine the strategic restoration of mangrove bioshields based on empirical thresholds with the climate-proofing of traditional pond systems, all reinforced by community education that translates scientific evidence into local understanding and action. Ignoring this integrated approach perpetuates reliance on fragmented, often unsustainable and inequitable engineering solutions. Embracing it offers a cost-effective, multi-benefit pathway to build resilience, protect biodiversity, secure livelihoods, and uphold cultural values. Future work must address temporal salinity dynamics and incorporate detailed hydrogeological data to refine models. However, the evidence presented here provides an unequivocal foundation: investing in mangroves and resilient ponds is an urgent imperative for securing the future of deltaic populations facing the escalating impacts of climate change.

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