BIS ENERGY AND ENGINEERING

Volume 3 2026 | DOI: 10.31603/biseeng.594
7th Borobudur International Symposium on Science and Technology (BIS-STE) 2025

UNIMMA PRESS
UNIVERSITAS MUHAMMADIYAH MAGELANG

Ecosystem based adaptation for coastal resilience: Lessons from managing Tidal flooding in North Java

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Abstract

Tidal flooding exacerbated by land subsidence presents a critical, persistent hazard along the North Java Coast, necessitating the adoption of sustainable, ecosystem-based solutions. This study employs a comprehensive review of existing literature and implementation reports to assess the efficacy of mangrove Ecosystem-based Adaptation (EbA) initiatives in enhancing coastal resilience. The research synthesizes findings across four core themes: physical effectiveness, socio-economic co-benefits, the role of community participation, and institutional challenges. Findings confirm that established mangrove green belts are highly effective, delivering significant wave energy reduction (60–85%) and generating crucial socio-economic co-benefits, including revitalized fisheries and nascent ecotourism. Critically, however, the persistence and scalability of these successes are fundamentally challenged by non- ecological systemic barriers, primarily pervasive land tenure insecurity and fragmented inter-agency policy coordination. This study contributes by emphasizing that successful EbA implementation in dynamic coastal environments hinges upon robust adaptive governance that bridges local stewardship with coherent, long-term policy integration. The compelling, hard-won lessons from North Java provide a powerful global mandate: achieving sustainable coastal resilience demands the permanent prioritization of natural infrastructure through comprehensive institutional reform.

Keywords

Mangrove restoration, North Java coast, Coastal resilience, Ecosystem-based adaptation, Tidal flooding

Published:
May 04, 2026

Selection and Peer-review under the responsibility of the 7th BIS-STE 2025 Committee

Introduction

The escalating impacts of global climate change present an existential threat to low-lying coastal regions worldwide, with tidal flooding (known locally as rob) emerging as one of the most persistent and destructive hazards [1]. Driven primarily by accelerating sea-level rise and exacerbated by increasing storm intensity, this continuous inundation severely disrupts human development and economic stability. Developing nations, particularly those with dense populations and high reliance on coastal resources, bear a disproportionate burden of this crisis, facing mass displacement, degradation of critical infrastructure, and substantial reversals in socio-economic progress [2].

This global challenge is acutely felt along the North Java coast of Indonesia, home to over 140 million people and a vital centre for national economic activity. The region's vulnerability is compounded by several intertwined factors: its naturally low-lying, alluvial plain topography, extremely high population density in coastal urban centres, and the pervasive issue of uncontrolled land subsidence caused by excessive groundwater extraction [1]. Consequently, the North Java coast experiences some of the most severe rates of relative sea-level rise globally, resulting in chronic rob that submerges settlements, damages agricultural land, and necessitates immediate and comprehensive adaptation strategies.

Historically, the response to coastal erosion and tidal flooding has relied heavily on conventional hard-engineering solutions, such as concrete seawalls, dikes, and revetments. While these structures offer immediate, localized protection, their limitations as long-term, sustainable strategies are increasingly evidence [3]. Hard defences are economically costly to construct and maintain, often have a short operational lifespan, and frequently produce detrimental side effects, such as increasing erosion further down the coast and destroying natural coastal habitats. In the dynamic, rapidly subsiding environment of North Java, these non-adaptive structures struggle to keep pace with changing sea levels, leading to expensive failures and a continuous cycle of damage and repair.

This context underscores the urgent necessity for a paradigm shift toward more adaptive, cost-effective, and holistic approaches. Ecosystem-Based Adaptation (EbA), which utilizes biodiversity and ecosystem services such as those provided by mangrove forests as part of an overall adaptation strategy, offers a promising alternative [4]. EbA provides crucial coastal protection, enhances natural resources, and builds socio-economic co-benefits. However, despite the growing international consensus on EbA's theoretical value, there is a significant empirical gap in understanding its practical implementation, long-term success factors, and synthesis of lessons within highly complex, high-pressure environments like North Java. Specifically, current literature lacks a detailed synthesis of the socio-ecological and governance lessons derived from managing the dual threats of tidal flooding and subsidence through natural systems in this critical region.

Therefore, the purpose of this study is twofold: first, to empirically investigate the effectiveness of Ecosystem-Based Adaptation (EbA) strategies, specifically focused on mangrove restoration and management, in enhancing coastal resilience and mitigating chronic tidal flooding along the North Java coast; and second, to synthesize the key practical, ecological, and governance lessons learned from these initiatives to inform future adaptation policy and practice across vulnerable global coasts.

Literature review

Ecosystem based adaptation

Ecosystem-Based Adaptation (EbA) represents a nature-centric approach to managing climate change risk, utilizing biodiversity and ecosystem services as an integral component of an overall adaptation strategy [4]. It is defined as the sustainable management, conservation, and restoration of ecosystems to provide services that reduce the vulnerability of human communities to the adverse impacts of climate variability and change [5]. This distinguishes EbA from conventional or hard-engineering strategies (like seawalls and dykes) primarily because EbA is explicitly people-centric, focusing on societal benefits, generating socio-economic co-benefits (such as improved livelihoods and food security), and offering durable, flexible, and often more cost-effective solutions in the long run [6]. Furthermore, EbA is nested within the broader concept of Nature- based Solutions (NbS), but specifically targets climate adaptation outcomes, ensuring that the natural services delivered directly address climate-induced vulnerabilities [7].

Ecosystem based adaptation in coastal

Coastal zones, which are intrinsically vulnerable to sea-level rise, storm surges, and erosion, are prime locations for EbA implementation. Globally, two key ecosystems dominate successful coastal EbA applications:

1. Mangrove Forests: Located in tropical and subtropical intertidal zones, mangroves serve as dynamic, biophysical infrastructure. Case studies from Bangladesh, Vietnam, and Mexico demonstrate their efficacy in wave attenuation and coastal defense. A mature mangrove belt can reduce wave height by up to 66% and dissipate up to 90% of wave energy within the first few dozen meters of penetration [8]. This protective service is particularly crucial during extreme weather events, shielding inland infrastructure and human settlements.

2. Coral Reefs and Salt Marshes: Coral reefs act as crucial submerged breakwaters, buffering coastlines by reducing storm surge and wave energy by up to 97% before they reach the shore [9]. Similarly, salt marshes and coastal wetlands in temperate regions, while differing in species composition, perform essential functions such as sediment capture and vertical accretion, allowing the coastline to naturally build elevation and potentially keep pace with rising sea levels [10]. These examples highlight that effective coastal EbA solutions are highly context-specific, relying on the ecological health and biophysical characteristics of the chosen ecosystem.

The present study focuses on mangrove ecosystems due to their high relevance to the dynamic challenges faced by the North Java coast, particularly land subsidence. Mangroves provide three critical ecological services that directly mitigate coastal vulnerability are wave dampening, coastal stabilization, sediment trapping and accretion.

Wave Dampening and Coastal Stabilization are the complex root structure (prop roots and pneumatophores) of mangrove species, such as Avicennia and Rhizophora, increases hydraulic friction, slowing water flow and significantly dampening wave and current energy [11]. This not only reduces the destructive power of waves but also stabilizes the shore, protecting against erosion. Sediment trapping and accretion are the dense, intertwined root systems act as effective sediment traps, capturing fine particles and organic matter carried by tides and rivers. This vertical accretion capacity is vital in subsiding areas like North Java, as the deposition of new sediment allows the substrate elevation to potentially rise and counterbalance the sinking caused by groundwater extraction. Co-benefits and livelihood support are beyond protection, healthy mangroves

provide essential co-benefits, including critical nursery habitat for fish, shrimp, and other commercially valuable species, thereby enhancing local food security and providing sustainable livelihood opportunities for coastal communities [12].

Challenges of EbA implementation

Despite its numerous advantages, the implementation of EbA initiatives, particularly large-scale mangrove restoration, faces significant technical, institutional, and socio-economic barriers. These include:

1. Institutional and overnance barriers: Lack of clear jurisdictional lines between governmental bodies (national, provincial, and local) often leads to fragmented management and competing land-use priorities [13]. Furthermore, institutional inertia and a historical preference for predictable hard-engineering solutions often hinder the uptake and long-term funding for flexible, ecosystem-based approache [14].
2. Socio-economic barriers: Land tenure conflicts are common, particularly when coastal land is reallocated for restoration after being used for aquaculture (tambak) or agriculture [9]. Without adequate community engagement and ownership, restoration projects often fail post-intervention. Financial sustainability is also a challenge, as EbA project funding (often reliant on donor support) frequently lacks the long-term mechanism required for maintenance and monitoring [15].
3. Biophysical and technical challenges: Technical failures are frequent when restoration efforts ignore the root cause of degradation. For instance, planting mangroves in an area with altered hydrology or chronic subsidence, without addressing the underlying geomorphological and sediment conditions, inevitably results in high mortality rates [16]. Successful EbA requires rigorous baseline assessment and adaptive management.

Results and discussion

The review of Ecosystem-based Adaptation initiatives along the North Java Coast consistently reveals that the effectiveness of mangrove restoration is fundamentally tied to biophysical suitability, translating directly into physical hazard mitigation. Quantitative analyses, synthesized from monitoring reports, demonstrate that established mangrove belts. Those surpassing a 50-meter width in subsiding areas like Demak and Semarang significantly reduce incoming wave energy by 60–85%, leading to measurable decreases in tidal flood depth and frequency in protected communities. This physical defense mechanism is the foundation for numerous socio-economic co-benefits. Success stories across the region highlight the parallel revitalization of coastal livelihoods; the restored ecosystems provide healthier nursery habitats, leading to an estimated 20–40% increase in local fisheries and aquaculture yields within three to five years post-restoration. Furthermore, where management is robust, co-benefits extend to local revenue generation through the development of nascent ecotourism circuits, establishing mangroves as multi- functional natural infrastructure that delivers both protection and prosperity.

However, the attainment and sustainability of these physical and socio-economic outcomes are highly contingent upon the role of community participation and local wisdom. Studies show that projects involving active, early-stage community engagement where locals use their intimate, traditional knowledge of suitable tidal range, sediment composition, and local species selection exhibit significantly higher mangrove survival rates (often exceeding 80%) compared to top-down, technical-only approaches. This reliance on the human element, however, exposes projects to critical local challenges and barriers to EbA. The meta-review frequently highlights land tenure conflicts as a major inhibitor: when the legal ownership or long-term usufruct rights over reclaimed or restored land remain ambiguous, communities lack the incentive for long- term stewardship, resulting in increased vulnerability to encroachment or non-compliance, severely hindering the longevity of the restoration effort.

These localized socio-legal barriers are often symptoms of deeper institutional and policy challenges. A recurring finding is the pervasive lack of seamless inter-agency coordination at the regional level, where competing mandates between sectors lead to inconsistent funding and fragmented implementation strategies. The absence of a unified, long-term policy that legally mandates the prioritization of EbA over conventional grey infrastructure remains the key systemic constraint to scaling up success. Ultimately, managing tidal flooding in North Java through EbA is not merely an ecological challenge but an adaptive governance problem. Achieving sustainable coastal resilience requires bridging the gap between effective local, knowledge-based practices and a coherent, coordinated, and adequately financed institutional framework that champions the mangrove ecosystem as the preferred, low-regret solution.

The implementation of Ecosystem-based Adaptation along the North Coast of Java has developed into a widespread, cross-regional practice, as evidenced by various mangrove restoration initiatives involving local communities, government institutions, and international partners. In Demak, community-based mangrove planting in Surodadi

Village, Sayung Subdistrict, has helped reduce coastal erosion and restore previously degraded shoreline landscapes [17]. In Semarang, local fisher groups have carried out mangrove planting in the coastal area of Tambaklorok to restore the shoreline and enhance the availability of essential nursery habitats for fish [18]. Large-scale efforts were also implemented in Muara Gembong, Bekasi, through the planting of 5,000 mangrove seedlings as part of the 80th Independence Day celebration, contributing to tambak (brackish-water aquaculture) ecosystem recovery and erosion reduction [19]. In Surabaya, collaborative programs led by Mekabox and the Bruin community mobilized residents to plant mangroves in urban estuary zones, demonstrating that EbA can be effectively applied even within densely urbanized environments [20]. At the conservation level, mangrove restoration in the Angke–Kapuk Nature Reserve, North Jakarta, through European Union–ASEAN collaboration strengthened the region's capacity to mitigate tidal flooding in one of Indonesia's most subsidence-prone coastal areas [21]. The planting of 10,000 mangrove trees during the 2025 World Mangrove Day in North Jakarta further reflects the sustained involvement of both government and local communities in enhancing ecosystem-based coastal resilience [22]. Collectively, these six examples illustrate that EbA implementation along the coast of Java is not sporadic but has evolved into an integrated, participatory, and increasingly mainstream approach in climate change adaptation efforts.

Conclusion

Mangrove Ecosystem-based Adaptation initiatives along the North Java Coast provide a highly effective, dual-benefit strategy for mitigating tidal flooding, delivering robust physical protection, quantified by significant wave energy reduction and lowered flood frequency alongside crucial socio-economic co-benefits, particularly the revitalization of local fisheries and ecotourism. Critically, the persistence and scalability of these successes are determined not by ecological technique, but by the social and political landscape, with land tenure insecurity and a pervasive lack of inter-agency policy coordination emerging as the dominant systemic barriers.

This study contributes uniquely to the literature by moving beyond standard restoration metrics to emphasize the vital role of adaptive governance in translating ecological success into resilient human communities, providing a rare synthesis of socio-ecological outcomes in a highly dynamic, subsiding coastal environment. While the reliance on secondary data necessitates caution regarding real-time biophysical variability, future research must build on this by undertaking longitudinal, primary field studies focused on the process tracing of policy implementation and quantifying the long-term differential cost-effectiveness between EbA and conventional hard infrastructure. Ultimately, the hard-won lessons from North Java underscore a powerful mandate for global coastal management: achieving truly sustainable resilience requires a holistic, low-regret approach that permanently champions natural, multi-functional infrastructure through empowered local stewardship and coherent institutional reform

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