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Study on the Effectiveness of Environmentally Friendly Breakwater Development in High Erosion Coastal Areas

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ABSTRACT

Purpose: *This study investigates the effectiveness of environmentally friendly breakwaters as a sustainable solution to mitigate severe coastal erosion. The research aims to evaluate not only the engineering performance of the structure but also its ecological impacts and community acceptance, thereby addressing the multidimensional nature of coastal protection.*

Subjects and Methods: *A Before–After–Control–Impact (BACI) design was employed to compare shoreline conditions at intervention and control sites. Hydrodynamic data were collected using Acoustic Doppler Current Profilers (ADCPs), while shoreline changes were monitored with UAV-based photogrammetry and analyzed in DSAS. Sediment samples, ecological indicators (benthic diversity, vegetation cover, water quality), and socio-economic perceptions (n = 64 respondents) were assessed. Numerical modeling with SWAN and XBeach complemented field observations.*

Results: *The breakwater reduced significant wave height by 42%, with an average transmission coefficient (Kt) of 0.58. Shoreline trajectories shifted from net retreat (–1.1 m/year) to modest accretion (+0.4 m/year), and the sediment budget indicated a net gain of +6,250 m³. Ecological responses included increased benthic diversity (H' rising from 1.62 to 2.05), expanded vegetation cover (+12.5%), and improved water clarity (turbidity reduced from 12.5 NTU to 7.9 NTU). Community surveys revealed strong acceptance, with 78% perceiving reduced coastal risk and 65% reporting improved fishing conditions, though concerns regarding maintenance costs persisted.*

Conclusions: *nvironmentally friendly breakwaters proved effective in reducing erosion, enhancing ecological functions, and gaining community support. These findings highlight their potential as viable alternatives to conventional hard defenses, particularly when integrated with broader nature-based solutions.*

INTRODUCTION

Coastal erosion has emerged as one of the most pressing environmental challenges in the twenty-first century, driven by a combination of natural processes and anthropogenic pressures (Owens, 2020; Vousdoukas et al., 2020; Spiridonov et al., 2025). Rising sea levels, increasing storm intensity, and altered sediment dynamics associated with climate change exacerbate erosion risks, particularly in low-lying coastal regions. At the same time, human activities such as sand mining, land reclamation, and poorly planned coastal development further destabilize shorelines, placing communities, infrastructure, and ecosystems at heightened risk. It is estimated that nearly 70% of the world's sandy shorelines are experiencing measurable retreat, underscoring the urgency of effective and sustainable interventions (Sarker, 2024; Tsekouropoulos et al., 2024; Saiz et al., 2024).

Conventional hard-engineering solutions such as seawalls, groins, and conventional breakwaters have long been the dominant response to shoreline retreat (Morris et al., 2018; Vieira, 2022; Williams et al., 2016; Romão et al., 2024). While these structures can provide short-term protection, they are often associated with significant ecological degradation, including habitat loss, disruption of sediment transport, and reduced biodiversity. Moreover, rigid infrastructure tends to transfer erosion problems downstream, creating a cycle of dependence on ever-expanding protective measures. This paradigm has been increasingly criticized as unsustainable, both environmentally and economically (Kopnina, 2016; Castro, 2004; Sanders et al., 2016).

In response, the past two decades have witnessed growing interest in environmentally friendly and nature-based coastal defenses, which seek to balance engineering performance with ecological integrity (Jordan & Fröhle, 2022; Perricone et al., 2023). These approaches range from fully nature-based solutions, such as mangrove or seagrass restoration, to hybrid or eco-engineered structures that incorporate ecological functions into conventional designs. Among them, the development of environmentally friendly breakwaters designed with porous, modular, or biogenic elements has emerged as a promising innovation. Such structures aim not only to dissipate wave energy and reduce erosion but also to provide habitat complexity, improve water quality, and support social acceptance (Gracia et al., 2018; Suedel et al., 2022; Jordan & Fröhle, 2022).

Despite the growing theoretical and experimental interest in eco-engineered breakwaters, empirical evidence on their long-term effectiveness in high-erosion coastal settings remains limited. Most studies to date have focused either on small-scale laboratory flume tests or on short-term pilot installations, often neglecting multidimensional outcomes such as ecological co-benefits and community perceptions. There remains a critical need for integrated, field-based assessments that rigorously evaluate the performance of environmentally friendly breakwaters across physical, ecological, and socio-economic dimensions.

The present study addresses this gap by assessing the effectiveness of an environmentally friendly breakwater in a high-erosion coastal area using a Before After Control Impact (BACI) framework. Specifically, it evaluates: (i) the hydrodynamic performance of the breakwater in reducing wave energy; (ii) its influence on shoreline change and sediment dynamics; (iii) associated ecological responses in benthic communities and water quality; and (iv) local community perceptions regarding its benefits and challenges. By adopting a multidimensional perspective, this study not only provides empirical evidence on the viability of environmentally friendly breakwaters but also contributes to the broader discourse on sustainable and socially acceptable coastal management strategies.

METHODOLOGY

Research Design and Analytical Framework

This study adopted a Before After Control Impact (BACI) research design to rigorously evaluate the effectiveness of an environmentally friendly breakwater in high-erosion coastal settings. The BACI framework was selected because it integrates temporal comparison (conditions before and after intervention) with spatial comparison (impact sites versus control sites), thereby enabling a clearer attribution of observed changes to the intervention itself rather than to background environmental variability or long-term natural trends. Within this design, coastal segments where the breakwater was installed were systematically compared with morphologically similar, non-intervened sites over two observation phases, ensuring a robust basis for causal inference.

Study Area Selection and Baseline Characterization

Study locations were chosen using a set of clearly defined criteria to ensure comparability and relevance. These criteria included historically high shoreline retreat rates exceeding one meter per year, similarity in geomorphological and sedimentary characteristics between impact and control sites, and logistical feasibility for sustained field monitoring. Baseline shoreline conditions were reconstructed using multi-temporal satellite imagery spanning approximately two decades. Landsat and Sentinel-2 datasets were processed using the Digital Shoreline Analysis

System (DSAS) to quantify historical erosion and accretion patterns, establishing a rigorous reference point against which post-installation changes could be evaluated.

Dimensions of Effectiveness Assessment

The effectiveness of the breakwater was assessed through an integrated, multi-dimensional framework encompassing hydrodynamic, morphological, ecological, and socio-economic aspects. Hydrodynamic performance focused on wave characteristics such as significant wave height, peak wave period, dominant wave direction, and wave transmission coefficients (Koraim & Rageh, 2013). Morphological effectiveness was evaluated through changes in shoreline position, beach profile evolution, and sediment volume dynamics. Ecological assessment emphasized benthic biodiversity, vegetation cover, and key water quality parameters, while socio-economic evaluation addressed community perceptions, coastal safety, and impacts on fisheries and local livelihoods. This comprehensive framework ensured that the intervention was evaluated not only in technical terms but also in relation to environmental sustainability and social acceptance.

Data Collection Procedures

Data collection combined field-based measurements, remote sensing analysis, and social research methods. Hydrodynamic data were obtained using Acoustic Doppler Current Profilers deployed at both impact and control sites, recording wave and current conditions at high temporal resolution over a six-month period. Shoreline position and beach morphology were monitored through quarterly UAV surveys, corrected with RTK-GNSS and processed using structure-from-motion photogrammetry. Semi-annual beach profile surveys were conducted using a total station to estimate sediment budgets, complemented by sediment sampling across swash, surf, and offshore zones for laboratory grain-size analysis. Ecological data were collected seasonally using transect–quadrat methods, while water quality parameters were measured in situ with multiparameter sondes. Socio-economic information was gathered through structured questionnaires and semi-formal interviews with key stakeholder groups, ensuring adequate representation of coastal communities.

Numerical Modeling and Scenario Analysis

To complement empirical observations, numerical modeling was employed to explore hydrodynamic and morphological responses under different conditions. The SWAN model was used to simulate wave transformation and energy dissipation, while XBeach was applied to assess sediment transport and shoreline change during storm events. Both models were calibrated using field measurements and validated against observed post-installation shoreline and profile changes, strengthening confidence in the interpretation of field results and enabling exploration of alternative design scenarios.

Data Analysis and Statistical Techniques

Data analysis followed both descriptive and inferential approaches to capture patterns and test intervention effects. Hydrodynamic performance was quantified through changes in wave transmission, while morphological trends were expressed using indicators such as end point rate, net shoreline movement, and sediment volume change. Ecological data were analyzed using diversity indices and appropriate statistical tests to detect differences between impact and control sites. Socio-economic data were examined descriptively and integrated through Multi-Criteria Decision Analysis to synthesize technical, ecological, and social dimensions. A Difference-in-Differences approach was applied to isolate the effect of the breakwater by comparing temporal changes across sites.

Ethical Considerations and Methodological Limitations

Methodological rigor was reinforced through careful matching of control and impact sites, replication across multiple locations, and adherence to ethical standards. Social data collection followed informed consent procedures, ensured anonymity, and respected participant confidentiality, while ecological sampling was conducted with minimal habitat disturbance. Despite the strengths of the BACI framework and complementary modeling, limitations remain, particularly the relatively short post-installation monitoring period and the potential influence of extreme storm events. Nonetheless, the integrated mixed-methods approach provides a holistic and credible assessment of the breakwater's performance across physical, ecological, and social dimensions.

RESULTS AND DISCUSSION

Hydrodynamic Performance of the Breakwater

Deployment of the environmentally friendly breakwater led to a marked reduction in wave energy at the impact site compared to the control. Prior to installation, mean significant wave height (Hs) at both sites was statistically indistinguishable (~1.25 m). Post-installation, Hs behind the breakwater decreased by 42%, while at the control site no significant reduction was observed. The calculated wave transmission coefficient (Kt) averaged 0.58, well within the range reported for semi-permeable or nature-based breakwaters (Kt = 0.5–0.7).

Table 1. Changes in Hydrodynamic Parameters (Before vs. After Intervention)

Parameter	Control Site (Before)	Control Site (After)	Impact Site (Before)	Impact Site (After)	% Change (Impact)
Significant Wave Height (Hs, m)	1.26 ± 0.15	1.29 ± 0.12	1.24 ± 0.14	0.72 ± 0.10	−42.0%
Peak Wave Period (Tp, s)	7.1 ± 0.6	7.3 ± 0.5	7.2 ± 0.7	6.9 ± 0.5	−4.2%
Wave Transmission Coefficient (Kt)	–	–	–	0.58 ± 0.06	–

Table 1 illustrates the contrasting hydrodynamic responses observed at the control and impact sites following the intervention. While conditions at the control site remained broadly stable over time, the impact site exhibited a clear attenuation of wave energy after the installation of the environmentally friendly breakwater. This pattern indicates that the observed changes are attributable to the intervention rather than to background temporal variability or regional wave climate fluctuations.

The reduction in wave energy at the impact site reflects the breakwater's capacity to dissipate incoming wave forces and alter nearshore hydrodynamic conditions. The modification of wave characteristics suggests a transition toward a more sheltered coastal environment, which is consistent with the intended function of nature-based or low-impact coastal protection structures. By limiting the transmission of wave energy toward the shoreline, the structure creates conditions that are more favorable for sediment retention and shoreline stabilization.

Importantly, the presence of a measurable wave transmission coefficient at the impact site provides further evidence that the breakwater does not completely block wave action but instead allows partial energy passage. This controlled transmission is ecologically and morphodynamically significant, as it reduces erosive forces while still maintaining natural water circulation and sediment dynamics. Overall, the hydrodynamic patterns summarized in the table demonstrate that the intervention achieved its primary objective of wave attenuation without inducing abrupt or artificial alterations to the coastal system.

Morphological Adjustments of the Shoreline

Analysis of UAV and DSAS data revealed divergent shoreline trajectories between impact and control sites. At the control site, the shoreline continued to retreat at an average of 1.2 m/year. In contrast, the impact site shifted from a retreat rate of –1.1 m/year (before) to a modest accretion of +0.4 m/year (after). Sediment budget calculations showed a net gain of +6,250 m^3 over 12 months behind the breakwater, compared to a net loss of –4,800 m^3 at the control site.

Table 2. Shoreline and Sediment Budget Analysis

Indicator	Control (Before)	Control (After)	Impact (Before)	Impact (After)
Shoreline Change Rate (m/year)	−1.3	−1.2	−1.1	+0.4

Net Shoreline Movement (NSM, m)	−12.4	−11.8	−10.7	+3.9
Sediment Budget (m^3, 12 months)	−5,100	−4,800	−5,300	+6,250

Table 2 highlights a clear divergence in shoreline behavior between the control and impact sites following the intervention. While the control site continued to exhibit a persistent erosional trend with only marginal improvement over time, the impact site underwent a marked transition toward shoreline stabilization and advancement. This contrast reinforces the interpretation that the observed changes are driven by the breakwater rather than by broader coastal processes or natural recovery.

The reversal from erosional dominance to accretion at the impact site indicates a fundamental reconfiguration of nearshore sediment processes. By attenuating wave energy, the breakwater reduced the capacity of waves to mobilize and transport sediments offshore, thereby promoting sediment retention within the protected zone. This facilitated the accumulation of material along the shoreline, signaling an improvement in coastal resilience.

Furthermore, the positive sediment balance observed after the intervention suggests that the structure not only limited sediment loss but also enhanced the trapping and redistribution of sediments within the system. Such conditions are essential for long-term shoreline stability, as they create a feedback mechanism in which reduced hydrodynamic stress supports sustained deposition. Overall, the patterns summarized in the table demonstrate that the breakwater effectively shifted the coastal system from a state of chronic erosion toward one of morphological recovery and sediment equilibrium.

Ecological Responses

Ecological monitoring revealed that the breakwater provided new habitat niches, supporting increased biodiversity. Shannon–Wiener diversity index (H’) for benthic assemblages rose from 1.62 to 2.05 at the impact site, while the control site remained relatively stable (1.58 to 1.61). Water turbidity declined significantly (from 12.5 NTU to 7.9 NTU), indicating reduced sediment resuspension.

Table 3. Ecological Indicators

Indicator	Control (Before)	Control (After)	Impact (Before)	Impact (After)
Shannon Diversity (H’)	1.58	1.61	1.62	2.05
Vegetation Cover (%)	32.4	33.1	34.2	46.7
Turbidity (NTU)	12.8	12.5	12.5	7.9

Table 3 indicates that the installation of the environmentally friendly breakwater was associated with a general improvement in ecological conditions at the impact site compared to the control area. The post-intervention patterns suggest that the reduction in hydrodynamic stress created a more stable nearshore environment, which is conducive to higher biological diversity and improved habitat quality. Increased structural complexity and calmer water conditions likely facilitated the recolonization of benthic organisms and supported the expansion of coastal vegetation within the protected zone.

The observed improvement in water clarity further reflects the ecological benefits of wave attenuation, as lower energy conditions reduce sediment resuspension and create more favorable conditions for photosynthetic organisms. Together, these changes indicate that the breakwater functioned not only as a physical protection measure but also as a catalyst for ecological recovery, reinforcing the role of eco-engineered structures in supporting coastal ecosystem functions.

These ecological trends are consistent with community perceptions gathered through local surveys, which emphasized enhanced environmental quality and improved nearshore conditions for small-scale fisheries. At the same time, the concerns expressed by residents highlight the importance of long-term maintenance and the integration of complementary nature-based solutions, such as mangrove restoration, to ensure that ecological gains are sustained and equitably distributed.

Socio-Economic Perceptions

Community surveys (n = 64) demonstrated strong local acceptance of the intervention. A majority (78%) perceived reduced coastal risk, and 65% reported improved conditions for small-scale fisheries due to calmer nearshore waters. Concerns included maintenance costs and the need for integration with mangrove replanting programs.

Table 4. Community Perceptions (n = 64 Respondents)

Perception Category	% Positive Response
Reduced risk of coastal erosion/flooding	78%
Improved fishing conditions	65%
Enhanced aesthetic value	54%
Concerns over maintenance costs	42%
Support for integration with mangroves	71%

The community perception survey (n = 64) revealed that local stakeholders largely viewed the environmentally friendly breakwater as a beneficial intervention. The most prominent response was a sense of reduced coastal risk, with 78% of respondents affirming that the structure lessened the threats of erosion and flooding. This perception is consistent with the measured physical outcomes, namely the reduction in wave height and the stabilization of the shoreline, which were directly visible to coastal residents.

A second notable outcome was related to fishing conditions. Approximately 65% of respondents reported improved opportunities for small-scale fisheries, particularly because the calmer nearshore environment facilitated safer boat operations and created new microhabitats that may enhance fish abundance. While these effects require longer-term ecological validation, they demonstrate the socio-economic relevance of eco-engineered interventions. Perceptions of aesthetic value were more mixed: 54% of respondents felt the breakwater contributed positively to the coastal landscape, while others remained neutral, suggesting that the structure's visual integration with the natural setting is important to local acceptance.

However, concerns were also voiced. Notably, 42% of respondents expressed worries about maintenance costs, highlighting the importance of governance and long-term financing strategies. This finding points to the need for clear institutional responsibility and possible community-based management schemes to ensure sustainability. Finally, a strong majority (71%) supported the integration of the breakwater with mangrove restoration programs, underscoring community interest in hybrid approaches that combine hard–soft protection. Such preferences align with global trends emphasizing *Nature-Based Solutions* that not only defend shorelines but also enhance ecological resilience and provide co-benefits such as carbon sequestration and fisheries support.

Taken together, the survey suggests that the environmentally friendly breakwater was not only effective from a technical standpoint but also resonated positively with the community. Importantly, the responses underline that social acceptance hinges not only on physical effectiveness but also on perceived ecological harmony, economic feasibility, and integration with broader coastal management initiatives. The findings clearly demonstrate that environmentally friendly breakwaters can significantly reduce hydrodynamic energy and promote sediment accretion in high-erosion coastal environments. The observed wave transmission coefficient (~0.58) falls within the efficiency range of semi-permeable and nature-based structures, confirming their functionality in dissipating wave energy without fully obstructing coastal processes.

From a geomorphic perspective, the shift from net erosion (–1.1 m/year) to net accretion (+0.4 m/year) at the impact site is a critical outcome, as it suggests that the breakwater not only mitigated shoreline retreat but actively promoted stabilization. This aligns with modeling predictions (XBeach, SWAN) and corroborates prior empirical evidence from hybrid coastal protection projects in Southeast Asia. Ecologically, the enhancement of benthic diversity and vegetation cover provides evidence that the structure acted as an artificial reef-like habitat, contrasting with conventional concrete breakwaters that often degrade ecological conditions. The decline in turbidity further indicates improved water clarity, which may favor seagrass and juvenile fish habitats.

Socially, the intervention was positively received, highlighting the importance of aligning engineering design with community needs. However, concerns over long-term maintenance emphasize the need for adaptive management strategies and cost-sharing mechanisms. Integrating the breakwater with nature-based solutions such as mangrove restoration could enhance both ecological resilience and social acceptance. Overall, the results suggest that environmentally friendly breakwaters represent a viable compromise between hard engineering and purely nature-based solutions. They are effective in reducing erosion while supporting ecological functions and garnering community support, though careful consideration of design optimization and long-term governance remains crucial.

Discussion

Integrated Hydrodynamic Implications

The intervention fundamentally reshaped nearshore wave dynamics by moderating energy transfer toward the coastline. Rather than functioning as a rigid barrier, the breakwater operated as a regulator of hydrodynamic forces, allowing sufficient circulation while dampening destructive wave action. This balance is critical in high-energy coastal environments, as it reduces erosive stress without disrupting natural coastal processes. The contrast with the control site strengthens the interpretation that the observed hydrodynamic moderation was driven by the intervention itself, underscoring the suitability of environmentally friendly breakwaters as adaptive coastal protection measures (Bhattacharya & Sachdev, 2024).

Shoreline Stability and Sediment Reconfiguration

The morphological response of the coastline demonstrates that hydrodynamic attenuation translated directly into physical stabilization. The post-intervention shoreline behavior reflects a systemic shift in sediment pathways, where material previously lost to offshore transport was retained and redistributed along the protected coast. This reconfiguration suggests the emergence of a new morphodynamic equilibrium in which sediment deposition reinforces shoreline resilience. Importantly, the divergence between impact and control sites indicates that the changes cannot be attributed to regional sediment supply or seasonal variability alone, but rather to the localized influence of the breakwater.

Ecological Enhancement and Habitat Function

Beyond physical protection, the structure played a substantive ecological role by fostering conditions conducive to biological recovery. Reduced turbulence and improved water clarity created a more hospitable environment for benthic communities and coastal vegetation, allowing ecological processes to reassert themselves. The breakwater effectively functioned as a hybrid habitat, combining protective engineering with ecological opportunity (Morris et al., 2018). This outcome contrasts with conventional hard infrastructure, which often simplifies habitats, and highlights the potential of eco-engineered designs to support biodiversity alongside coastal defense objectives.

Social Meaning and Community Valuation

Community responses reveal that the intervention's success cannot be evaluated solely through physical or ecological metrics. Perceptions of safety, livelihood support, and environmental quality shaped local acceptance of the project (Harvey et al., 2018; Lyakurwa et al., 2025). The sense of reduced risk and improved fishing conditions indicates that residents interpreted the calmer nearshore environment as both practically and economically beneficial. At the same time, concerns regarding maintenance emphasize that long-term legitimacy depends on governance arrangements, financial clarity, and ongoing engagement with local stakeholders.

Toward Hybrid and Adaptive Coastal Management

The convergence of hydrodynamic moderation, sediment stabilization, ecological recovery, and social approval points to the broader relevance of environmentally friendly breakwaters within integrated coastal management frameworks (Pincetti, 2023). Rather than replacing nature-based solutions, the findings suggest that such structures are most effective when combined with complementary measures, such as mangrove restoration. This hybrid approach aligns engineering performance with ecological resilience and social expectations, offering a pragmatic pathway for managing erosion in vulnerable coastal settings.

Synthesis of Outcomes

Overall, the results demonstrate that environmentally friendly breakwaters can achieve multiple objectives simultaneously: reducing wave energy, stabilizing shorelines, enhancing ecological conditions, and earning community support. Their effectiveness lies not in eliminating natural dynamics, but in recalibrating them toward more resilient states. However, the findings also highlight that technical success must be matched with adaptive management and long-term stewardship to ensure durability and equity. In this sense, the intervention represents not a final solution, but a flexible component within a broader, socially informed coastal resilience strategy.

CONCLUSION

This study demonstrates that environmentally friendly breakwaters can serve as an effective and multifunctional solution for addressing severe coastal erosion. By integrating hydrodynamic measurements, shoreline and sediment analyses, ecological monitoring, and community perceptions within a BACI framework, the research provides robust evidence that such structures significantly reduce wave energy, stabilize eroding shorelines, and enhance sediment deposition. Beyond their engineering function, the breakwaters also generated ecological co-benefits, including increased benthic biodiversity, improved water clarity, and expanded vegetation cover. These outcomes suggest that eco-engineered coastal defenses can bridge the longstanding trade-off between shoreline protection and ecosystem integrity, moving toward genuinely sustainable coastal management. Equally important, the strong level of community acceptance underscores that technical effectiveness alone is insufficient without social legitimacy. Local stakeholders valued the reduced erosion risk and improved fishing conditions, but also raised concerns about long-term maintenance. Their expressed support for integrating the breakwater with mangrove restoration indicates that future designs should adopt hybrid approaches that combine structural and nature-based elements. Taken together, the findings affirm that environmentally friendly breakwaters represent a viable alternative to conventional hard infrastructure in high-erosion settings. They not only mitigate physical risks but also promote ecological resilience and social acceptance. For policymakers and coastal managers, this suggests that investment in eco-engineered solutions can deliver long-term benefits that extend well beyond erosion control. Future research should focus on optimizing design configurations under different wave climates, assessing long-term cost–benefit performance, and developing governance models that ensure equitable maintenance and adaptive management.

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