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Dynamic Parameters in Coastal Vulnerability Assessment: A Systematic Review of Ecosystem Services, Land-Use Change, and Equity Dimensions for Small Island Communities

Antonio Jr Fabela Regis

cc21resch16001@iith.ac.in

Department of Climate Change, Indian Institute of Technology Hyderabad

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Abstract

Coastal vulnerability assessment for small island communities has traditionally relied on static geophysical parameters, creating systematic blind spots that misallocate adaptation resources and underestimate vulnerability in zones experiencing rapid habitat degradation and land-use change. This systematic review synthesizes 47 peer-reviewed studies (2010–2025) examining coastal vulnerability index (CVI) methodologies and their treatment of dynamic parameters including ecosystem services, land-use change, and socioeconomic dimensions. The primary finding of this review is that 83% of assessed studies completely omit ecosystem parameters from vulnerability calculations, and 100% lack any equity or gender-disaggregated analysis. These findings establish that current operational CVI frameworks systematically underrepresent true vulnerability in ecosystem-dependent island communities. Future priorities include developing open-source dynamic assessment tools, establishing disaggregated equity frameworks, operationalizing just transition mechanisms for fishing-dependent communities, and building regional capacity for science-informed, equitable vulnerability reduction in resource-constrained island nations.

Introduction

Coastal zones constitute approximately 3% of Earth's terrestrial surface yet support more than 600 million people and generate substantial economic value through fisheries, tourism, and trade (United Nations Environment Programme 2022). Climate change poses unprecedented threats to these zones through multiple mechanisms: sea-level rise averaging 3.6 mm per year globally with regional accelerations (Hamlington et al. 2024, Johnson et al. 2023, Nerem et al. 2018), intensification of tropical cyclones and extreme weather events (Ma et al. 2025, Balaguru et al. 2024, IPCC 2021, Knutson et al. 2020), ocean acidification affecting calcifying organisms (Fabry et al. 2008), and altered precipitation and salinity regimes affecting coastal ecosystems and human settlements (Zhang et al. 2024, Mazhar et al. 2022, Ashrafuzzaman et al. 2022, Nicholls & Cazenave 2010). Small island communities face particularly acute vulnerabilities due to geographic isolation, limited land area, high population density in coastal zones, dependence on climate-sensitive economic sectors (fisheries, tourism, agriculture), and constrained governance and economic capacity for autonomous adaptation (Thomas and Theokritoff 2024, Mycoo et al. 2022, Betzold 2015).

The imperative for systematic coastal vulnerability assessment stems from the need to identify geographic areas where climate hazards pose greatest risks to human populations and ecosystems (Basnayake et al. 2026, Roukounis and Tsihrintzis 2022, Krishnan et al. 2018) enabling prioritization of limited adaptation resources and informing coastal zone management decisions (Cunha et al. 2025, de Sherbinin et al. 2019). Vulnerability assessment methodologies have proliferated over the past two decades, reflecting recognition across academic and policy communities that vulnerability is multidimensional, context-dependent, and requires systematic evaluation to guide adaptation planning (Armaș and Albulescu 2025, Turner and Zhou 2023, Barros et al. 2022, Khalid et al. 2021) However, despite substantial methodological advances, significant gaps persist in operational vulnerability frameworks employed by coastal managers in resource-limited contexts, particularly regarding treatment of temporal ecosystem dynamics and land-use change (Verutes et al. 2024, Zhang et al. 2023, Lu et al. 2022, Cochrane et al. 2019).

Traditional coastal vulnerability index (CVI) methodologies have employed substantially similar parametric frameworks since their formalization in the early 2000s (Koroglu et al. 2019, Pendleton et al. 2010, Gornitz 1991, Thieler and Hammar-Klose 2000). These frameworks typically incorporate six to eight parameters describing static or quasi-static geophysical conditions: coastal elevation, shoreline change rate, coastal slope, tidal range, significant wave height, and sometimes geomorphologic classification. This standardized approach has provided important benefits: it enables spatial comparison of vulnerability across large coastal areas, permits relative ranking of coastal segments for prioritization, and facilitates inter-regional vulnerability comparisons using consistent metrics (Tanim et al. 2022, Roukounis et al. 2022, Hamid et al. 2019).

However, traditional static parametric approaches contain several critical limitations that are particularly pronounced in small island contexts experiencing rapid environmental and developmental change. First, static frameworks exclude quantification of temporal habitat dynamics and land-use change, treating ecosystem composition as spatially invariant even where

substantial ecosystem degradation or recovery occurs over assessment periods (Pantusa et al. 2022, Parodi et al. 2020, Ligate et al. 2018). This omission creates situations where a coastal zone may be classified as high-risk based on physical exposure parameters (low elevation, high wave exposure) while ecosystem service provision substantially modifies actual risk exposure, a dynamic excluded from assessment. Second, static approaches typically employ crude geomorphologic classifications (rock type, beach vs. cliff) without distinguishing between types that provide different levels of ecosystem services or have different temporal stability characteristics. A mangrove-lined coast and a naturally eroding mudflat may receive identical geomorphologic classifications despite dramatically different protective ecosystem service provision (Analuddin et al. 2024, Verutes et al. 2024, Gracia Prieto 2022). Third, traditional frameworks do not account for development-driven habitat conversion, which may fundamentally alter vulnerability trajectories through land-use intensification in sensitive coastal zones. Between 2000 and 2020, approximately 14% of global mangrove area was converted to other land uses, predominantly aquaculture, agriculture, and urban development, with particularly acute losses in Southeast Asia, where small island communities are concentrated (Wei et al. 2024, Goldberg et al. 2020, Worthington et al. 2020). Fourth, static methodologies implicitly assume that vulnerability drivers remain stable within assessment periods, an assumption violated in contexts experiencing rapid climate-driven ecosystem change, development pressure, or both (Huisman et al. 2025, Armaș and Albulescu 2025, Pang et al. 2023, Yoshikawa et al. 2023, Brown et al. 2018)

Small island communities present particular methodological opportunities and challenges for enhanced vulnerability assessment incorporating dynamic parameters (Fig. 1). Small islands typically feature: (1) concentrated coastal populations with limited inland relocation alternatives (Vousdoukas et al. 2023, Mycoo et al. 2022, Speelman and Nicholls 2021); (2) high dependence on marine resources and ecosystem services (Mengo et al. 2022, Etongo and Arrisol 2021, Balzan et al. 2018); (3) relatively small spatial scales enabling detailed spatial analysis and ground-truth validation (Scandurra et al. 2018, Balzan et al. 2018); (4) constrained governance and technical capacity, limiting capacity for complex vulnerability frameworks (UNDRR 2022, Speelman and Nicholls 2021, Klöck and Nunn 2019); (5) availability of satellite-derived data characterizing land-use and ecosystem changes with high temporal and spatial resolution (Tiengo et al. 2023, Giuliani et al. 2020, Ng et al. 2019); and (6) heightened climate impacts due to geographic positioning in cyclone-prone regions and elevated sea-level rise rates (Gordon-Strachan et al. 2024, Vousdoukas et al. 2023, Shultz et al. 2016).

These characteristics create both imperatives and opportunities for enhanced vulnerability assessment. The imperative stems from the fact that even modest changes in ecosystem provision or land-use patterns can substantially alter vulnerability outcomes for entire island populations (Vousdoukas et al. 2023, Martyr-Koller et al. 2021, Balzan et al. 2018). For example, conversion of 100 hectares of mangrove forest to aquaculture production in a 10 km coastal zone may increase wave exposure for 5,000–10,000 people dependent on that coastline, amplifying vulnerability to typhoons and storm surge (Spalding et al. 2014). The opportunity stems from the fact that small island geography enables application of detailed spatial analysis methods and comprehensive ground-truth validation that may be impractical in larger continental systems (Pathirana 2025, Roukounis and Tsihrintzis 2022). Additionally, satellite-based earth observation provides high-resolution, temporally repeated observations of land-use and ecosystem change, enabling quantification of dynamic parameters without requiring in-situ monitoring infrastructure (Zhao and Yu 2025, Pickens et al. 2025, Cavanaugh et al. 2025).

This review synthesizes literature on coastal vulnerability assessment, identifying gaps in traditional static parametric approaches and establishing the case for integrating dynamic parameters into operational frameworks for small island communities. Throughout this paper, emphasis is placed on quantitative evidence, methodological clarity, and practical scalability in resource-limited island contexts.

Methodology

Literature Review and Study Design

This systematic review synthesized current literature on coastal vulnerability assessment methodologies, with emphasis on identifying methodological gaps in traditional static parametric approaches and establishing the importance of integrating dynamic parameters into operational vulnerability frameworks. The review employed a systematic review with narrative

synthesis approach, combining quantitative evidence synthesis with qualitative thematic analysis to identify emerging patterns and divergences in coastal vulnerability assessment practice as described in Fig. 2.

A comprehensive literature search was conducted across five major academic databases (Web of Science, Scopus, Google Scholar, Environmental Complete, GeoRef) for peer-reviewed studies published between 2010 and 2025. This temporal window was selected to capture the period following formalization of the Coastal Vulnerability Index methodology (post-2005) through contemporary applications incorporating dynamic parameters (2015–2025).

Search terms included: ("coastal vulnerability" OR "coastal risk assessment" OR "coastal exposure") AND ("vulnerability index" OR "coastal vulnerability index" OR "CVI") AND ("assessment" OR "methodology" OR "framework"); ("ecosystem services" OR "mangrove" OR "coral reef" OR "seagrass") AND ("coastal protection" OR "coastal defense" OR "wave attenuation" OR "storm surge buffering"); ("land-use change" OR "land cover change" OR "habitat conversion") AND ("coastal vulnerability" OR "coastal resilience"); ("small islands" OR "island communities" OR "SIDS") AND ("climate adaptation" OR "vulnerability assessment" OR "coastal management").

Inclusion criteria were: (1) peer-reviewed journal articles, book chapters, or government technical reports; (2) explicit focus on coastal vulnerability assessment methodologies or applications; (3) coverage of at least one coastal vulnerability dimension (physical exposure, sensitivity, adaptive capacity); (4) geographic scope including at least one small island or developing country context; (5) publication date 2010–2025; (6) available in English language. Exclusion criteria included: (1) articles focusing exclusively on terrestrial or riverine vulnerability without coastal component; (2) studies examining vulnerability without explicit methodological framework; (3) opinion pieces or editorials without primary research.

A total of 47 peer-reviewed studies met inclusion criteria and were included in the systematic synthesis. Studies were obtained in full text and subjected to structured data extraction using a standardized form capturing: (1) publication metadata (author, year, journal, country of study); (2) methodological characteristics (CVI parameters, data sources, aggregation methods); (3) key findings regarding vulnerability determinants; (4) geographic and contextual scope; (5) treatment of dynamic parameters (ecosystem services, land-use change, socioeconomic dimensions).

Study Quality Assessment and Reproducibility

All 47 included studies were assessed for quality and reporting completeness using a modified GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework adapted for coastal vulnerability methodology reviews. Quality assessment dimensions included methodological rigor encompassing sampling approach, parameter ranking justification, and validation against observed impacts; data quality including spatial resolution, temporal coverage, and uncertainty quantification; reporting completeness addressing explicit description of methods, parameter sources, and mathematical formulations; and reproducibility encompassing sufficient detail to enable replication and availability of code or data.

Quality assessment revealed that 32 studies representing 68 percent of the sample reported methods with sufficient detail enabling replication, while 15 studies representing 32 percent lacked complete methodological description. No studies were excluded based on quality assessment; however, quality scores informed interpretation of evidence certainty. Studies with limited methodological detail were weighted lower in synthesis of quantitative findings.

Data extraction was conducted by two independent reviewers for 15 randomly selected studies representing 32 percent of the sample to assess inter-rater reliability. Agreement on parameter inclusion and exclusion was $\kappa = 0.89$ with 95 percent confidence interval of 0.81–0.97, indicating high reliability. Three disagreement instances were resolved through consensus discussion.

Geographic Scope and Representation

This review emphasizes coastal vulnerability assessment literature from tropical and subtropical small island systems, reflecting both the geographic concentration of published research and the heightened vulnerability of small islands in these

regions to sea-level rise and tropical cyclone intensification as shown in Fig. 3.

This geographic concentration reflects two underlying factors. First, tropical small islands experience higher absolute vulnerability due to geographic positioning relative to cyclone generation regions, elevated regional sea-level rise rates, and dependence on climate-sensitive economic sectors. Second, greater research and development assistance funding has been directed toward tropical small island developing states, enabling more published vulnerability assessments in these regions compared to temperate or arctic island systems.

Results

Study Selection and Characteristics

A comprehensive systematic literature search across five major academic databases yielded 347 initial results. After deduplication, 186 unique studies underwent title and abstract screening. Following full-text review against predefined inclusion criteria, 47 peer-reviewed studies met all inclusion requirements and were subjected to structured data extraction. The systematic review process followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.

Temperate small island systems including those in Northern Europe, the North Atlantic, and Sub-Antarctic regions are substantially underrepresented in available literature despite facing significant climate impacts from North Atlantic storminess and ice sheet melt-driven sea-level rise. Arctic small island communities are nearly absent from coastal vulnerability assessment literature despite acute climate change impacts. Future systematic reviews or regional studies should prioritize these underrepresented geographic areas to ensure that coastal vulnerability assessment methodologies are developed for diverse island contexts.

Included studies demonstrated geographic concentration in regions with acute coastal vulnerability as noted previously. The temporal distribution (shown in Fig. 4) of publications increased substantially over the study period, with 2010–2014 containing 8 studies representing 17 percent of the sample, 2015–2019 containing 18 studies representing 38 percent, and 2020–2025 containing 21 studies representing 45 percent, demonstrating accelerating research interest in coastal vulnerability assessment methodologies.

The 47 studies comprised four primary categories: CVI application studies with geophysical parameters only, accounting for 19 studies or 40 percent of the sample; CVI studies incorporating socioeconomic parameters, representing 15 studies or 32 percent; CVI studies incorporating ecosystem parameters, comprising 8 studies or 17 percent; and studies employing machine learning or multidimensional approaches, accounting for 5 studies or 11 percent of the total.

Parametric Approaches Employed Across Studies

All studies employed at least six of the seven traditional static geophysical parameters. Specifically, coastal elevation appeared in all 47 studies representing 100 percent of the sample, coastal slope in 44 studies representing 94 percent, relative sea-level rise rate in 41 studies representing 87 percent, shoreline change rate in 39 studies representing 83 percent, significant wave height in 35 studies representing 74 percent, tidal range in 43 studies representing 91 percent, and geomorphologic classification in 46 studies representing 98 percent. In marked contrast, ecosystem parameters were explicitly quantified in only 8 studies representing 17 percent of the total sample. Of these ecosystem-inclusive studies, 6 studies (13 percent) incorporated mangrove area or quality as a protective factor, 3 studies (6 percent) included coral reef extent or condition, 2 studies (4 percent) quantified seagrass bed presence, and 2 studies (4 percent) considered salt marsh protective capacity. The striking finding is that 39 studies representing 83 percent of the sample completely omitted ecosystem parameters from their vulnerability calculations despite extensive literature documenting that ecosystem protective services explain 30–87 percent of vulnerability variance across coastal systems.

Land-use change dynamics were explicitly parameterized in temporal assessments in only 5 studies representing 11 percent of the sample. Of these, 4 studies (9 percent) included development intensity as a sensitivity modifier and 2 studies (4 percent) tracked ecosystem degradation or restoration over time periods of 10–20 years. In contrast, 42 studies representing 89 percent of the sample treated coastal conditions as static within their assessment periods, implicitly assuming that ecosystem composition and land-use patterns remained unchanged throughout the evaluation timeframe.

Socioeconomic parameters were incorporated in 23 studies representing 49 percent of the sample, though with substantial variation in integration depth. Fifteen studies representing 32 percent included basic demographic variables such as population density, literacy rates, and poverty rates. Eight studies representing 17 percent disaggregated socioeconomic indicators by community or livelihood group. Notably, none of the studies systematically contextualized adaptive capacity variation within socioeconomic categories, missing important dimensions of differential vulnerability within communities.

Evidence for Ecosystem Service Dominance in Vulnerability

Our synthesis of 8 studies explicitly quantifying ecosystem service contributions to vulnerability outcomes including those by Spalding et al. (2014), Ruckelshaus et al. (2016), Verutes et al. (2024), and others documented substantial protective capabilities. Figure 5 shows that across 18 studies reviewed by Spalding et al. (2014) examining mangrove protective services, mangrove forests reduced storm surge height by a mean of 50–100% depending on forest width ranging from 0.1–2 kilometers and canopy density. When translated to vulnerability units, one kilometer width of healthy mangrove forest provides protective services equivalent to 0.5–1.5 meters of additional coastal elevation in terms of storm surge mitigation.

Coral reef protective services, assessed across 24 studies on reef protective function, documented wave energy attenuation of 60–97 percent depending on reef structure integrity and coral species composition, equivalent to 1–3 meters of elevation protection from wave-driven hazards. Seagrass beds reduced wave height by 30–50 percent within meadow areas across 12 peer-reviewed studies, primarily conducted in temperate and tropical systems, providing protective capacity equivalent to 0.3–0.8 meters of elevation increase.

Estuary-scale analysis by Verutes et al. (2024) quantified habitat protective effect as the difference in exposure index scores with and without habitat presence. Results documented that protective effect ranged from 0 percent at shoreline segments entirely lacking natural habitat to 73 percent at segments backed by extensive salt marsh habitat. This quantification implies that 41 percent of analyzed shoreline segments would transition from high to moderate vulnerability classification if habitat presence were explicitly incorporated into traditional coastal vulnerability indices.

Dynamic Versus Static Assessment Comparison

Published comparative studies examining static versus dynamic vulnerability assessment methodologies documented substantial differences in priority area identification. Nigam et al. (2024) applied both static CVI and socioeconomically-enhanced CVI to 27 coastal villages in South Goa, India. Village-level assessment incorporating disaggregated social vulnerability factors identified that 15–40 percent of villages received different very-high-vulnerability classifications compared to taluka-level assessment without socioeconomic disaggregation. This represents critical misidentification that would result in adaptation resources being directed to sub-village-scale communities actually exhibiting lower vulnerability while bypassing villages with highest actual need.

Marques et al. (2022) compared static CVI results employing seven geophysical parameters with ecosystem-enhanced CVI including explicit mangrove and cliff geomorphology differentiation for Azores coastal zones. Results documented that 18–35 percent of coastal segments received different vulnerability classifications when ecosystem parameters were explicitly included, reflecting the substantial contribution of protective ecosystems to actual vulnerability outcomes.

Vadivel et al. (2025) employed machine learning approaches incorporating dynamic parameters including ecosystem extent, development intensity, and temporal land-use patterns, achieving $R^2 = 0.42–0.56$ for predicting observed coastal impacts encompassing flooding frequency and shoreline erosion rates compared to $R^2 = 0.24–0.31$ for traditional static approaches

(Table 1). This represents 67–80 percent relative improvement in predictive accuracy through dynamic parameterization, demonstrating the substantial added explanatory power of dynamic parameters for anticipatory adaptation planning.

Table 1
Comparative accuracy analysis of published studies comparing vulnerability assessment predictive accuracy for observed coastal impacts

Assessment Framework	Prediction of Observed Impacts (R^2)	Sample Context	Key Reference
Traditional Static CVI (7 parameters)	0.24–0.31	Coastal Georgia, USA; multiple islands	Verutes et al. 2024; Roukounis et al. 2022
Dynamic CVI (ecosystem only)	0.32–0.38	Estuarine systems	Verutes et al. 2024
Dynamic CVI (full integration)	0.35–0.42	Diverse coastal systems	Sethuraman et al. 2024
Machine Learning Dynamic	0.42–0.56	Trained on historical impact data	Vadivel et al. 2025
Predictive Accuracy and Impact Prediction			

Systematic review of published studies comparing vulnerability assessment predictive accuracy for observed coastal impacts revealed consistent patterns. Traditional static coastal vulnerability indices employing seven parameters achieved R^2 values of 0.24–0.31 for prediction of observed coastal impacts in diverse study contexts including coastal Georgia in the United States and multiple island systems globally. When dynamic parameters incorporating ecosystem characteristics alone were included, predictive accuracy improved to R^2 values of 0.32–0.38 in estuarine systems. Comprehensive dynamic CVIs incorporating full integration of ecosystem, land-use, and socioeconomic parameters achieved R^2 values of 0.35–0.42 across diverse coastal systems. Machine learning approaches incorporating dynamic parameters with trained model architectures reached R^2 values of 0.42–0.56, indicating that dynamic parameterization improves predictive accuracy by 0.08–0.25 R^2 units representing a relative improvement of 32–80 percent over traditional static approaches.

This improvement in predictive accuracy indicates that dynamic parameters capture vulnerability dimensions critical for predicting actual observed coastal impacts but ignored in static frameworks. The variation in improvement magnitude across different study systems, impact types, and geographic contexts suggests that the benefit of dynamic parameterization is context-dependent but consistently substantial.

Discussion

Conceptual Frameworks and Definitional Clarity

Vulnerability Concepts and Foundational Definitions

Coastal vulnerability represents the susceptibility of coastal communities and ecosystems to adverse impacts from climate and environmental hazards, modified by adaptive capacity and coping mechanisms (Pilgreen et al. 2024, Roukounis and Tsihrintzis 2022, Tanim et al. 2022, Nicholls & Klein, 2005). This definition encompasses multiple constituent concepts requiring clarification. Adaptive capacity represents the ability of systems, institutions, and populations to modify characteristics, behaviors, or systems to moderate or avoid potential damage from hazards (Espinoza Córdova et al. 2024, Datta and Roy 2022, Cinner et al. 2018). The relationship among these components is not strictly additive; rather, vulnerability emerges from the interaction of exposure, sensitivity, and adaptive capacity, with feedback mechanisms and non-linearities characterizing these relationships (Chapagain et al. 2025, Datta and Roy 2022, Cinner et al. 2018, Turner et al. 2003).

Traditional vulnerability assessment frameworks formalize these conceptual relationships through parametric indices that aggregate multiple measurable variables into composite vulnerability metrics (ElKotby 2025, Nigam et al. 2024, Roukounis and Tsihrintzis 2022, Lu et al. 2022). The Coastal Vulnerability Index (CVI) methodology, first developed by Gornitz (1991) and

subsequently refined through multiple applications globally, represents perhaps the most widely employed operational framework. The classic CVI methodology aggregates seven physical parameters into a composite index score: coastal elevation, slope, relative sea-level rise rate, coastal erosion or accretion rate, nearshore bathymetry, wave height, and tidal range. Each parameter receives a ranking from 1–5, with 5 representing highest vulnerability and 1 representing lowest. The CVI score is then calculated as the geometric mean of the seven parameter ranks, producing a composite score ranging from 1–25, with higher scores indicating greater vulnerability.

The mathematical formulation is presented as Eq. 1:

$$CVI = \sqrt[n]{\prod_{i=1}^{n} P_i}$$

where CVI is the Coastal Vulnerability Index, P_i represents the ranked value (1–5) for each parameter i, and n is the total number of parameters (typically 7 for the classic formulation). This geometric mean approach produces sensitivity to particularly high vulnerability values; a single parameter rated at 5 can substantially increase the CVI score even if other parameters are rated as 1. The rationale for this approach stems from the principle that vulnerability is not merely additive; rather, the presence of one dominant vulnerability factor can drive overall system vulnerability even in the presence of mitigating factors (Pantusa et al. 2022, Roukounis and Tsihrintzis 2022).

Evolution of Coastal Vulnerability Assessment Methodologies

The evolution of coastal vulnerability assessment methods reflects progressive development of more sophisticated frameworks incorporating diverse data types and methodological approaches (Roukounis and Tsihrintzis 2022). As shown in Fig. 6, early static parametric approaches (1990–2005) employed exclusively geophysical parameters describing permanent or quasi-permanent coastal characteristics: elevation, slope, geology, and shoreline dynamics. These approaches provided important foundational frameworks enabling systematic spatial assessment and inter-regional comparison of coastal vulnerability (Nicholls & Klein 2005). However, their reliance on static parameters created systematic limitations: they did not account for temporal changes in ecosystem composition or land-use patterns, did not distinguish between different types of habitats providing different levels of ecosystem services, and did not incorporate socioeconomic dimensions of vulnerability (Wu et al. 2024, Pilgreen et al. 2024, Espinoza Córdova et al. 2024, Cao et al. 2022).

The period 2005–2015 witnessed expansion of CVI frameworks to incorporate socioeconomic parameters including population density, poverty rates, literacy levels, and economic dependence on climate-sensitive sectors. This expansion reflected growing recognition that physical exposure alone does not determine vulnerability; rather, vulnerability outcomes depend critically on socioeconomic characteristics affecting adaptive capacity and differential exposure to hazards (Wang et al. 2026, Zahnow et al. 2025, Iskandar et al. 2024, Martins and Gasalla 2020).

The contemporary period (2015-present) has witnessed further methodological innovation in several directions: (1) integration of ecosystem service provision into vulnerability frameworks, recognizing that protective ecosystems substantially modify vulnerability outcomes (Liu et al. 2021, Guannel et al. 2016, Spalding et al. 2014); (2) incorporation of dynamic land-use and ecosystem parameters, enabling temporal vulnerability assessment and identification of vulnerability transition mechanisms (Basnayake et al. 2026, Xiao et al, 2024, Islam et al. 2023, Radwan et al. 2021); (3) application of machine learning and data fusion techniques enabling integration of diverse data sources and non-linear relationships (Fogarin et al. 2023, Fannassi et al. 2023); (4) development of multidimensional frameworks disaggregating vulnerability into multiple constituent dimensions (physical, social, ecological, economic) rather than producing single composite indices (Laino et al. 2024, Jozaei et al. 2022, Tanim et al. 2022, Lu et al. 2022, Aguirre-Ayerbe et al. 2018).

Ecosystem Services as Vulnerability Determinants

Current understanding of coastal vulnerability increasingly recognizes that protective ecosystems fundamentally modify coastal risk exposure through provision of multiple ecosystem services. Coastal ecosystems including mangrove forests, coral reefs, seagrass beds, salt marshes, and coastal wetlands provide critical services including: storm surge buffering and

wave energy dissipation, sediment stabilization and accretion, fisheries habitat provision, nutrient cycling and water purification, and carbon sequestration (Costanza et al. 2014). These ecosystem services directly reduce coastal vulnerability by lowering physical exposure to hazards (Ferrario et al. 2014; Guannel et al. 2016) and providing resources (fisheries production) that enhance adaptive capacity (James et al. 2023).

Quantitative evidence for ecosystem service contributions to vulnerability reduction is substantial. Spalding et al. (2014) reviewed global evidence on ecosystem protective services, documenting that mangrove forests reduce storm surge height depending on mangrove width and density, coral reefs attenuate wave energy by 60–97% depending on reef structure and wave characteristics, and seagrass beds reduce wave height by 30–50% within meadow areas. Translating these protective capabilities into quantitative vulnerability reduction requires integration of ecosystem service provision into vulnerability frameworks. For instance, a coastal zone with 2 km mangrove fringe width may experience vulnerability reduction equivalent to 0.5-1.0 meters of "natural elevation," enabling direct comparison to engineering-based elevation alternatives using common vulnerability metrics (Ruckelshaus et al. 2016).

However, critical limitations characterize current treatment of ecosystem services in vulnerability assessment frameworks. Most operational CVI methodologies do not distinguish between different ecosystem types or account for temporal dynamics in ecosystem composition, health status, or spatial extent. A mangrove forest that has experienced 50% canopy loss from typhoon damage, disease, or development pressure retains substantially reduced protective capability compared to intact forests, yet static approaches typically do not capture this degradation. Similarly, frameworks that classify coastal zones as "mangrove-fronted" without quantifying mangrove width, density, or age structure fail to differentiate between 100 m wide mangrove forests (providing high protective benefit) and 10 m degraded strips (providing minimal protection). These limitations create situations where ecosystem service provision is qualitatively recognized but quantitatively excluded from vulnerability calculations, undermining the practical utility of vulnerability frameworks for guiding ecosystem-based adaptation investment.

Machine Learning Approaches to Dynamic Coastal Vulnerability Assessment

The period from 2020 through 2025 has witnessed substantial growth in machine learning applications to coastal vulnerability assessment, representing a paradigm shift toward nonlinear, data-driven approaches that capture complex relationships between vulnerability parameters. Unlike traditional parametric approaches that assume linear parameter relationships and apply predetermined weighting schemes, machine learning approaches enable automated learning of nonlinear relationships from training datasets, adaptive weighting based on local data characteristics, and explicit uncertainty quantification.

Recent innovations in deep learning have enabled automated interpretation of high-resolution satellite imagery for ecosystem mapping. Pickens et al. (2025) developed machine learning workflows for global mangrove forest mapping at 10-meter spatial resolution using Sentinel-2 satellite imagery, achieving 94 percent accuracy compared to reference datasets. These automated approaches substantially reduce human interpretation burden and enable rapid updating of ecosystem extent assessments as new satellite imagery becomes available. For coastal vulnerability assessment, automated ecosystem mapping enables incorporation of updated ecosystem parameters into vulnerability calculations at temporal resolutions spanning monthly to quarterly updates, which would be infeasible with manual interpretation approaches.

Emerging approaches combining physics-based coastal models with neural network architectures represent an important innovation enabling machine learning systems to capture mechanistic coastal processes while learning from empirical data. Fogarin et al. (2023) and Fannassi et al. (2023) employed such hybrid approaches to predict coastal vulnerability incorporating dynamic land-use and ecosystem parameters, achieving improved predictive accuracy compared to purely data-driven approaches. These physics-informed approaches are particularly valuable in small island contexts where training data may be limited, as physics constraints enable generalization beyond available observations.

Machine learning approaches document substantial nonlinear relationships between vulnerability parameters that traditional linear aggregation methods fail to capture. For example, the vulnerability impact of mangrove loss depends nonlinearly on initial ecosystem width. Loss of 500 meters from an initially 2-kilometer-wide mangrove forest produces different vulnerability

consequences than loss of 500 meters from an initially 100-meter-wide forest. Similarly, vulnerability response to concurrent sea-level rise and ecosystem degradation exhibits nonlinear synergistic effects that linear index approaches cannot represent. Vadivel et al. (2025) documented that random forest approaches incorporating interactions between parameters achieved R^2 = 0.45–0.56 for impact prediction compared to R^2 = 0.28–0.35 for additive parametric approaches.

Machine learning approaches offer substantial advantages for dynamic vulnerability assessment. First, they enable automated parameter integration, allowing incorporation of diverse data sources including satellite imagery, oceanographic models, socioeconomic datasets, and climate projections without requiring predetermined weighting schemes. This flexibility enables incorporation of emerging data types as they become available and adaptation to evolving vulnerability drivers over time. Second, machine learning approaches can learn context-specific relationships rather than applying globally consistent parameter weights. Vulnerability outcomes in reef-dominated atoll systems may exhibit different parameter weightings than in mangrove-dominated deltaic systems, and machine learning approaches automatically adapt to these differences based on training data from each context. Third, Bayesian machine learning approaches and ensemble methods enable explicit quantification of prediction uncertainty, providing decision-makers with confidence intervals around vulnerability estimates. This is critical for adaptation planning, as resource allocation decisions should account for assessment uncertainty.

Machine learning approaches for coastal vulnerability assessment face critical limitations in small island contexts, primarily requiring extensive training datasets that link vulnerability parameters to observed impacts. Data often unavailable in small island systems with limited long-term monitoring capacity and questionable transferability from continental contexts due to differing climate regimes, governance structures, and development pressures. While these approaches offer superior predictive accuracy compared to parametric methods, their black-box nature obscures mechanistic relationships, complicating stakeholder communication and decision-making even when explainable AI techniques (SHAP values, LIME, attention mechanisms) are applied to improve interpretability at the cost of added complexity. Furthermore, deep learning implementations demand substantial computational resources that small island governments typically lack, creating dependencies on external infrastructure with attendant data sovereignty and sustainability concerns. To address these challenges, machine learning should complement rather than replace parametric approaches through hybrid ensemble frameworks that balance interpretability with predictive power, while prioritizing transfer learning strategies that adapt models trained on well-documented coastal systems to under-studied island contexts. Broader adoption requires developing open-source machine learning tools specifically designed for coastal vulnerability assessment and accessible to small island practitioners, reducing both data requirements and computational barriers while maintaining local capacity and control.

Nature-Based Solutions Framework for Coastal Vulnerability Reduction

Nature-based solutions represent a paradigm for addressing coastal vulnerability through ecosystem management and restoration, explicitly recognizing that protective ecosystems provide economically valuable services reducing climate risks. Nature-based solutions have emerged as central to international adaptation policy, with the World Bank, Green Climate Fund, United Nations Environment Programme, and others prioritizing nature-based solutions investments for coastal resilience. A systematic integration of nature-based solutions within coastal vulnerability assessment frameworks enables transparent economic comparison of ecosystem-based versus conventional engineering solutions, essential for adaptation resource allocation.

The conceptual distinction between ecosystem services and nature-based solutions is important for understanding implementation approaches. Ecosystem services emphasis focuses on quantification of protective benefits provided by existing ecosystems, supporting identification of zones where existing ecosystem protection is critical to preserve. In contrast, nature-based solutions emphasis focuses on active management and restoration of ecosystems as intentional vulnerability reduction strategy. This distinction has major operational implications: ecosystem service quantification supports preservation priorities, while nature-based solutions investment identifies zones where ecosystem restoration would provide cost-effective vulnerability reduction benefits (Table 2).

Table 2
Cost-Effectiveness Comparison: NbS vs. Conventional Infrastructure

Solution Type	Unit Cost	Protective Benefit	Cost per Unit Protection	Lifespan	Co-Benefits	Implementation Timeline
Mangrove Restoration	$3-10K/ha	0.5–1.5 m elevation eq.	$2–20/m·km	50–100 yr	Fisheries, carbon, biodiversity	5–10 years to full protection
Coral Reef Conservation	$5-100K/ha (protection)	1–3 m elevation eq.	$20–500/m·km	20–50 year (declining)	Fish habitat, tourism, biodiversity	Immediate if existing reef
Seagrass Restoration	$5-50K/ha	0.3–0.8 m elevation eq.	$15–150/m·km	30–50 yr	Carbon, fish habitat	3–5 years
Conventional Seawall	$500K-2M/km	Variable (0.5-5 m)	$100–4000/m·km	50–100 yr	None (negative: habitat loss)	1–3 years
Beach Nourishment	$10-100K/km	0-0.5 m (temporary)	$20–200/m·km	5–15 yr	Temporary recreation benefit	1 year

Mangrove-based nature-based solutions are the most widely implemented approach globally for reducing coastal vulnerability. This provides protection through storm surge buffering by standing biomass and root systems, wave energy dissipation via canopy-water interaction, sediment accretion that supports vertical land building, and habitat provision enhancing fisheries-based livelihood resilience. With documented reductions in storm surge height depending on forest width and density, equivalent to $0.5–1.5\ \mathrm{m}$ of elevation, and economic analyses showing establishment costs of $3{,}000–10{,}000\ \mathrm{USD}$ per hectare in Southeast Asia versus $500{,}000–2{,}000{,}000\ \mathrm{USD}$ per kilometer of dike for $1\ \mathrm{m}$ elevation, positioning mangroves as cost-effective where suitable tidal ranges ($1–4\ \mathrm{m}$), non-rocky substrates, and appropriate salinity regimes exist. Coral reef conservation and restoration attenuate wave energy with protective benefits equivalent to $1–3\ \mathrm{m}$ of elevation through reef-structure interaction with waves, but active restoration is far more expensive ($250{,}000–1{,}000{,}000\ \mathrm{USD}$ per hectare) and effectiveness depends on structural integrity increasingly compromised by climate-driven bleaching, making protection-focused strategies more cost-effective than large-scale restoration except in strategically important locations. Seagrass-based solutions reduce wave height by $30–50\ \%$ within meadows at relatively low temperate-zone costs of $5{,}000–50{,}000\ \mathrm{USD}$ per hectare, while also sequestering carbon and supporting fish habitat, though their geographic applicability is constrained by specific light, substrate, and hydrodynamic requirements that limit restoration feasibility (Fig. 7).

Cost-effectiveness comparison (Table 3) of nature-based solutions and conventional infrastructure reveals substantial differences in per-unit cost. Mangrove restoration at $3,000–$10,000 per hectare provides protective benefit of 0.5–1.5 meters elevation equivalent at cost per unit protection of $2–$20 per meter-kilometer. In contrast, conventional seawall construction at $500,000–$2,000,000 per kilometer provides variable protective benefit of 0.5–5 meters at cost per unit protection of $100–$4,000 per meter-kilometer. Beach nourishment at $10,000–$100,000 per kilometer provides temporary 0–0.5 meter protection at cost of $20–$200 per meter-kilometer. These comparisons establish that nature-based solutions provide substantially lower cost per unit protection compared to conventional infrastructure, with the critical caveat that nature-based solutions effectiveness is geographically and ecologically context-dependent. Seawalls provide reliable protection independent of environmental conditions but at five to twenty times higher cost than nature-based solutions and with ecosystem co-benefits eliminated.

Table 3
Multidimensional performance matrix comparing mangrove NbS, coral reef NbS, conventional seawall, and hybrid coastal defences across cost, reliability, co-benefits, governance, equity, and climate dimensions.

Criterion	Mangrove	Coral reef	Seawall	Hybrid
Cost per unit protection	● (low)	◐	○ (high)	◐
Protection reliability	◐	◐	●	●
Ecosystem co-benefits	●	●	○	◐
Long-term governance burden	● (high)	●	◐	◐
Livelihood benefits (sustained)	●	◐	○	◐
Equity risks	◐	◐	◐	◐
Climate adaptability	●	○ (bleaching)	◐	●
Geographic conditionality	● (high)	●	○	◐
Legend: ● = high/present, ◐ = partial/mixed, ○ = low/absent				

Nature-based solutions (NbS) differ fundamentally from conventional infrastructure in their long-term management and sustainability requirements: while seawalls mainly demand periodic maintenance without ongoing resource inputs, NbS such as mangroves, coral reefs, and seagrasses require continuous, active stewardship involving governance and enforcement to prevent land conversion, control invasive species, manage salinity and water quality, and regulate destructive practices like bottom trawling and pollution-intensive development, with their long-term viability intimately tied to governance capacity and aligned economic incentives. Mangrove restoration can yield sustained livelihood benefits. Through sustainable timber, charcoal, and honey harvesting, that incentivize community-led protection, contrasting with the short-term employment generated by seawall construction, yet NbS may also restrict activities such as aquaculture or coastal development, risking livelihood displacement and raising distinct equity concerns unless just transition mechanisms provide alternative income pathways. Equity challenges extend further, as wealthier groups with diversified livelihoods may capture more of the protection benefits while economically constrained populations face greater disruption. Effective integration of NbS into coastal vulnerability assessment thus demands explicit spatial mapping of technically feasible zones, accounting for substrate, salinity, tidal range, existing ecosystem extent, and cultural acceptability, alongside economic comparison in common metrics (e.g., cost per meter of protection, cost per life saved) versus conventional infrastructure and temporal modeling of ecosystem dynamics, restoration trajectories, degradation rates, and climate-driven range shifts, to evaluate long-term performance and sustainability, all within an equity-explicit framework that identifies potentially disadvantaged groups and embeds just transition strategies in implementation plans.

Equity and Justice Dimensions of Coastal Vulnerability Assessment

A striking finding of this review is that none of the 47 studies conducted gender-disaggregated, livelihood-stratified, or income-quintile vulnerability analysis. This absence constitutes a critical methodological gap, and the following section synthesizes external evidence establishing why equity dimensions are essential to operational vulnerability assessment. Traditional coastal vulnerability assessments implicitly assume homogeneous vulnerability within geographic units including coastal zones, sub-districts, or islands, aggregating vulnerability across all populations in assessed areas. This aggregation masks critical differential vulnerability within communities based on gender, livelihood, income, and access to adaptive capacity resources. Gender-disaggregated vulnerability analysis reveals that women experience disproportionate vulnerability in coastal hazard contexts due to multiple intersecting factors. Women typically experience lower access to income diversification opportunities, as in fishing-dependent communities they are often concentrated in lower-value processing and net-making activities rather than primary fishing. Care responsibilities encompassing childcare and elder care limit ability to participate in livelihood diversification or relocation during hazard events. Women generally have lower asset ownership limiting capacity to accumulate productive assets and recover after disasters. In some cultural contexts, women's mobility restrictions during

disasters increase vulnerability to flooding and storm surge. Quantitative assessment incorporating gender-disaggregated livelihood data reveals substantially different vulnerability profiles than undifferentiated assessments. Nigam et al. (2024) documented that disaggregated vulnerability assessment identifying gender-specific livelihood patterns resulted in different priority village rankings compared to aggregate assessment, with implications for adaptation resource allocation toward populations with greatest differential vulnerability.

Young adults spanning ages 15–35 in small island communities experience distinctive vulnerability driven by limited livelihood opportunities, out-migration of educated cohorts reducing adaptive capacity, and dependency on climate-sensitive sectors including tourism and fishing. Coastal vulnerability assessments rarely disaggregate youth-specific dimensions despite evidence that demographic structure significantly influences adaptive capacity trajectories. Populations dependent on single livelihood sectors including commercial fishing, tourism, or agriculture experience higher vulnerability than economically diversified populations, yet traditional coastal vulnerability indices do not distinguish vulnerability based on livelihood diversity. Coastal communities with 70 percent population dependency on fisheries exhibit fundamentally different adaptive capacity compared to communities with diversified livelihoods, regardless of aggregate socioeconomic indicators. Income distribution within coastal communities is highly skewed, with aggregate indicators masking critical differences where wealthy minorities with substantial adaptive capacity aggregate with economically constrained majorities. Low-income populations have fewer adaptive options including limited livelihood alternatives, constrained relocation possibilities, and minimal insurance coverage, yet often occupy highest-risk zones including low-elevation settlements and resource-dependent livelihoods. Equity-sensitive assessments require disaggregation by income quintile.

A critical gap in current coastal vulnerability assessment practice is lack of attention to who benefits from adaptation investments identified through vulnerability analysis. Where vulnerability assessment directs adaptation resources, empirical evidence reveals concerning patterns of preferential benefit accumulation in wealthier communities. Multiple case studies document that adaptation investments including seawall construction, early warning system development, and livelihood diversification support disproportionately benefit already-advantaged populations. Seawall construction in densely-populated high-income zones receives priority over protection of dispersed low-income communities. Agricultural livelihood diversification support reaches farmers with education and market connections while marginalizing landless agricultural laborers. Insurance and parametric risk transfer mechanisms available to formal-sector workers exclude informal sector populations.

An adaptation-maladaptation paradox has emerged in some contexts where adaptation investments have generated unintended harm. Shrimp aquaculture expansion, framed as livelihood diversification adaptation for fishing communities, has driven mangrove conversion in Southeast Asian islands, eliminating coastal protection and increasing vulnerability of fishing communities dependent on mangrove habitat. Similarly, tourism development framed as economic diversification has concentrated investment in coastal real estate development, replacing natural ecosystems with built infrastructure and reducing protective services.

Equity-informed assessment requires explicit stakeholder mapping identifying populations with differential adaptive capacity and greatest actual vulnerability. Benefit distribution analysis must track how adaptation resources translate to vulnerability reduction for specific populations. Inclusion mechanisms must ensure that populations at risk participate in vulnerability assessment and adaptation planning processes. Accountability frameworks must establish responsibility for equitable adaptation benefit distribution. A major equity challenge in small island developing states coastal vulnerability reduction concerns transition of fishing-dependent populations away from livelihoods increasingly undermined by ecosystem degradation and climate change. Just transition frameworks establish mechanisms for ensuring livelihood security during transitions to alternative economic activities. International agreements including the Paris Agreement and International Labour Organization guidelines on just transitions establish principles for protecting workers during economic transitions, yet lack concrete implementation mechanisms for small island contexts where fishing represents 30–50 percent of employment in many communities and alternative livelihood opportunities are extremely limited due to geographic isolation and limited economic diversity.

Necessary just transition components include skills retraining programs targeting vocational training enabling transition to alternative sectors including renewable energy, marine technology, tourism services, and ecosystem restoration. Critical to retraining success is cultural appropriateness recognizing that not all individuals wish or are able to transition careers, and that retraining must respond to local labor demand for trained workers. Livelihood support during transition ensures income security, potentially including wage subsidies for workers in lower-income alternative occupations, unemployment insurance or pension schemes, and pension enhancements recognizing years of fishing employment. Ecosystem restoration employment enables fishing workers transitioning away from fishing to find work in mangrove restoration programs, which have demonstrated this potential in Southeast Asia by employing former aquaculture workers in replanting and management activities.

Community-level economic diversification represents an alternative to individual livelihood transitions, where communities pursue economic sector diversification including tourism, renewable energy, and value-added fisheries products enabling gradual employment transition without complete livelihood shift. Critical to just transition success is authentic participation of affected workers and communities in designing transition mechanisms, ensuring that solutions reflect local circumstances, values, and knowledge systems. Governance and participation prove essential for just transition success.

Traditional coastal vulnerability assessment employs scientific expertise from geographers, climate scientists, and engineers to analyze biophysical parameters and develop assessments, representing a top-down approach with advantages in technical rigor and quantitative grounding but limitations including potential mismatch with local priorities, overlooked knowledge embedded in decades of local experience, and inaccessibility to stakeholders without technical training. Participatory vulnerability assessment approaches combine scientific analysis with participatory stakeholder engagement. Participatory GIS enables community members to map perceived vulnerability and adaptation priorities on spatial databases, enabling comparison with scientific assessments and identifying discrepancies reflecting different knowledge bases. Knowledge co-production enables scientists and local experts to collaboratively develop vulnerability frameworks integrating scientific and local knowledge systems. Community-based monitoring enables local communities to track vulnerability indicators including ecosystem changes, hazard occurrence, and livelihood patterns, providing ground-truth validation of assessment results.

Participatory approaches increase local relevance by reflecting community priorities and local conditions, enhance stakeholder buy-in through community understanding and support of assessment results, and improve implementation feasibility through revelation of practical constraints including governance limitations, resource constraints, and cultural factors. However, participatory approaches require substantial time investment spanning 6–12 months for genuine engagement and may reveal conflicts between scientific priorities and community interests, complicating decision-making.

Equity-informed coastal vulnerability assessment requires explicit disaggregation of vulnerability by gender, livelihood, income, age, and other relevant social dimensions rather than aggregate assessment. Benefit distribution analysis must identify who will benefit from adaptation investments and ensure mechanisms for equitable benefit distribution. Just transition planning must establish livelihood protection mechanisms for populations disadvantaged by ecosystem-based adaptation. Participatory governance must ensure authentic participation of at-risk communities in assessment and adaptation planning. Accountability mechanisms must establish responsibility for equitable adaptation implementation and tracking outcomes.

Traditional Static Parametric Approaches: Methodologies and Limitations

Standard Parametric Frameworks and Data Sources

The most widely employed operational coastal vulnerability assessment framework employs seven parameters assessing physical exposure to hazards (Appendix 1). Coastal elevation represents the vertical distance between mean high tide level and land surface elevation, typically assessed using satellite-derived digital elevation models (e.g., ALOS AW3D30, NASA SRTM) at 30 m spatial resolution. Coastal slope characterizes the gradient of coastal zone topography, calculated from elevation data as vertical rise divided by horizontal distance, typically calculated over 500 m inland-seaward transects. Relative sea-level rise rate integrates absolute sea-level rise (determined from satellite altimetry or tide gauge data, currently averaging 3.6 mm/year globally with substantial regional variation) with land-based vertical land movement (subsidence or uplift),

determined through GNSS measurements, tide gauge analysis, or geological evidence. Shoreline change rate quantifies net shoreline position change over decadal time periods (typically 20–30 years), determined from comparison of historical and recent satellite imagery, historical maps, or in-situ monitoring. Geomorphology describes coastal zone type (e.g., rock cliff, sandy beach, mud flat, mangrove, coral reef) typically determined from satellite imagery interpretation or field surveys. Wave height represents significant offshore wave height (Hs), the average height of the highest one-third of waves in a wave train, typically derived from wave buoy measurements or hindcast models. Tidal range represents the vertical distance between mean high tide and mean low tide levels, typically obtained from tide gauge data or harmonic analysis of tidal constituents.

These parameters were selected for inclusion in standard CVI frameworks based on their theoretical relevance to coastal vulnerability (all contribute mechanistically to determining exposure to sea-level rise or storm impacts), their practical measurability across large areas (requiring remote sensing or publicly available datasets rather than extensive field surveys), and their consistency across diverse coastal environments globally (enabling inter-regional comparison). The standardization provided by this consistent parametric framework represents a significant advantage, enabling vulnerability assessments conducted by different researchers in different regions to employ comparable metrics, facilitating comparative analysis and aggregation of results across geographic scales.

Multiple approaches have been employed to aggregate individual parameters into composite vulnerability indices, each with different mathematical properties and interpretations (Appendix 2). The geometric mean approach, presented as Eq. 1 above, characterizes traditional CVI calculations and produces high sensitivity to extremely high parameter values, reflecting the principle that a single dominant vulnerability factor substantially increases overall vulnerability. The arithmetic mean approach calculates vulnerability as the simple average of parameter ranks: $CVI_{arith} = \frac{1}{n}\sum_{i=1}^{n} P_i$. This approach produces equal weighting across parameters and exhibits lower sensitivity to extreme values, making it more robust to outliers but potentially underrepresenting the contribution of dominant vulnerability factors (Roukounis et al. 2022).

Weighted aggregation approaches apply differential weights to parameters, with weights typically determined through expert elicitation, analytical hierarchy process (AHP), or statistical analysis of parameter contributions to observed impacts. Representative examples include the vulnerability assessment conducted by Nigam et al. (2024) in South Goa, India, which employed AHP to establish differential weights for physical and socioeconomic parameters. Machine learning approaches including neural networks, random forests, and support vector machines enable non-linear parameter relationships and can adapt weighting based on local data characteristics, though at the cost of reduced transparency and increased data requirements (Vadivel et al. 2025).

Standardization of vulnerability index scores to enable comparison across different parametric frameworks represents an important technical consideration. CVI values calculated through different methods (geometric mean, arithmetic mean, weighted combinations) are not directly comparable, complicating inter-regional assessments. Common approaches for standardization include normalization to the 0–1 range: $CVI_{norm} = \frac{CVI - CVI_{min}}{CVI_{max} - CVI_{min}}$, and classification into categorical vulnerability levels (Very Low, Low, Moderate, High, Very High) based on equal interval division or quantile-based classification.

Documented Limitations of Static Parametric Approaches

Critical examination of operational coastal vulnerability assessment practice reveals several systematic limitations in static parametric approaches, particularly pronounced in small island contexts (Appendix 3).

Limitation 1: Ecosystem Service Omission. Traditional CVI methodologies do not quantify temporal changes in ecosystem composition or quality, despite evidence that ecosystem service provision is a primary determinant of coastal vulnerability. Spalding et al. (2014) and Ruckelshaus et al. (2016) document that coastal ecosystems can reduce effective exposure to sea-level rise by equivalent of 0.5–1.5 m elevation through combination of wave attenuation, sediment accretion, and storm surge buffering. Vulnerability frameworks excluding ecosystem parameters therefore systematically overestimate vulnerability in ecosystem-fronted coastal zones. The practical consequence is that vulnerability hotspots identified through traditional

approaches may not reflect actual risk when ecosystem service provision is considered, potentially leading to misallocation of adaptation resources (Verutes et al. 2024).

Limitation 2: Temporal Dynamics Exclusion. Static parametric approaches implicitly treat coastal conditions as unchanging within assessment periods, failing to account for ecosystem degradation or recovery, land-use change, or coastal modification. Satellite analysis reveals global patterns where coastal development pressures can outpace ecosystem restoration benefits, illustrating a fundamental paradox in coastal management: habitat restoration achieves local vulnerability reduction yet may be overwhelmed by development pressures at landscape scales. In Southeast Asian island systems, rapid economic development drives conversion of protective ecosystems to tourism and aquaculture infrastructure (Worthington et al. 2020; Spalding et al. 2014). This spatially heterogeneous pattern, where restoration occurs in some zones while degradation accelerates in others, creates situations where aggregate vulnerability increases despite restoration efforts, because built-up area expansion concentrates in previously low-vulnerability zones, elevating overall island-scale vulnerability even when habitat recovery occurs elsewhere. Static parametric approaches cannot capture this dynamic spatial interaction; they would identify conditions as unchanged based on geophysical parameters, overlooking the net vulnerability increase driven by development pressures overwhelming ecosystem benefits.

Limitation 3: Socioeconomic Dimension Integration Gap. While contemporary CVI frameworks increasingly incorporate socioeconomic parameters, integration remains inconsistent and often superficial. Population density metrics do not distinguish between populations with high adaptive capacity (educated, economically diverse, integrated with national markets) and those with constrained capacity (dependent on single economic sector, limited formal education, isolated from markets). A coastal zone with 1,000 people/km² comprised of tourism workers with stable employment and access to formal credit represents different vulnerability than identical population density comprised of subsistence fishers with no alternative livelihoods. Simple population density metrics collapse this critical distinction, limiting practical utility of vulnerability assessments for equity-sensitive adaptation planning (Adger 2006, Nigam et al. 2024).

Limitation 4: Geomorphologic Oversimplification. Traditional approaches classify coastal zones into broad categories (rock, sandy beach, mud flat) without quantifying ecosystem service provision variations. A sandy beach with adjacent seagrass bed providing fisheries habitat and wave attenuation differs substantially from a sandy beach backed by intensive tourism infrastructure with no remaining natural vegetation, yet both may receive identical geomorphologic classification. Eroded mudflats experience different protective capabilities depending on whether they are stabilized by mangrove establishment versus actively eroding. These distinctions are critical for vulnerability assessment but are often lost in simplified geomorphologic classifications (Marques et al. 2022).

Limitation 5: Scale Mismatch Between Assessment Resolution and Implementation Scale. Coastal vulnerability assessments are frequently conducted at 1 km spatial resolution or coarser, reflecting data availability and computational constraints. However, coastal adaptation decisions typically occur at community or local government unit scales (1–10 km²), where sub-kilometer scale variation in vulnerability drivers is substantial. A 1 km resolution assessment may classify an entire coastal segment as moderate vulnerability while masking high-vulnerability zones occupied by specific communities lacking alternative settlement locations. Fine-scale assessments revealing community-level vulnerability variations (250 m or finer resolution) provide substantially greater utility for local adaptation planning than coarser assessments (Nigam et al. 2024).Evidence for Dynamic Parameter Importance in Vulnerability Assessment

Ecosystem Service Provision as Dominant Vulnerability Determinant

Quantitative evidence supporting the importance of ecosystem service provision in determining coastal vulnerability outcomes is substantial and consistent across diverse coastal systems (Table 7). Spalding et al. (2014) conducted a global meta-analysis of 52 studies examining ecosystem protective services. Translating these protective capabilities into vulnerability units requires establishing equivalence between ecosystem service provision and conventional engineering solutions. Ruckelshaus et al. (2016) estimated that 1 km width of healthy mangrove forest provides protective services

equivalent to approximately 1 m elevation increase in terms of storm surge mitigation. This equivalence enables direct comparison of ecosystem-based and conventional adaptation approaches using common vulnerability metrics.

Verutes et al. (2024) conducted similar analysis in an estuarine system (Great Tybee Marsh NERR, Georgia, USA), calculating the difference in exposure index scores with and without habitat presence. Results documented that the habitat protective effect ranged from 0% (for shoreline segments entirely lacking natural habitat) to 73% (for shoreline segments backed by extensive salt marsh habitat). Areas transitioning to high exposure category if habitats were lost represented priority zones where habitat protection would provide maximum vulnerability reduction benefit. This spatial analysis approach explicitly quantifies the magnitude of ecosystem service contributions to vulnerability outcomes, enabling transparent decision-making about nature-based versus conventional adaptation investment (Verutes et al. 2024).

Land-Use Change as Vulnerability Driver

Land-use change, particularly conversion of coastal habitat to built-up land uses (urban development, tourism infrastructure, aquaculture), represents a primary mechanism driving vulnerability increase in small island contexts. Global mangrove extent has declined by approximately 35–40% over the past 40 years, with particularly acute losses in Southeast Asia where 10–50% of mangrove area has been lost depending on specific location (Worthington et al. 2020). Drivers of mangrove loss include aquaculture development (approximately 35% of global mangrove losses), agriculture, salt production, urban development, and infrastructure projects. For small island communities, aquaculture represents a particularly significant driver of mangrove loss, with conversion of mangrove forest to shrimp or fish ponds enabling short-term economic returns but eliminating ecosystem protective services that reduce vulnerability to typhoons and storm surge.

Quantitative analysis of land-use change consequences for coastal vulnerability has been limited, in part because few long-term datasets combine detailed land-use mapping with vulnerability assessments. However, available evidence suggests substantial relationships. Global analysis of land-use change consequences for coastal vulnerability reveals a consistent pattern: rapid economic development in small island contexts drives conversion of protective ecosystems to tourism, aquaculture, and urban infrastructure, often in previously low-vulnerability zones. Mangrove extent has declined by approximately 35–40% over past 40 years, with particularly acute losses in Southeast Asia (Worthington et al. 2020). Aquaculture represents approximately 35% of global mangrove losses (Worthington et al. 2020), with conversion of mangrove forests to shrimp or fish ponds enabling short-term economic returns while eliminating ecosystem protective services.

This spatial heterogeneity, where restoration occurs in some zones while degradation accelerates in others, creates a fundamental vulnerability paradox: ecosystem restoration efforts may be locally effective in reducing vulnerability yet overwhelmed by development pressures at landscape scales. Where habitat loss concentrates in vulnerable zones while restoration occurs in already-protected areas, aggregate vulnerability increases despite restoration efforts. Successful vulnerability reduction therefore requires simultaneous governance mechanisms constraining development-driven habitat conversion in sensitive coastal zones while supporting ecosystem restoration (Spalding et al. 2014, Worthington et al. 2020).

Dynamic Versus Static Assessment Comparison

Direct comparison of vulnerability assessments incorporating dynamic parameters versus traditional static approaches (Appendix 4) reveals substantial differences in priority area identification. Published comparative studies examining static versus dynamic vulnerability assessment methodologies document that 15–40% of coastal zones receive different vulnerability classifications depending on whether dynamic ecosystem and land-use parameters are included (Nigam et al. 2024, Marques et al. 2022). For example, Nigam et al. (2024) applied both static and socioeconomically-enhanced CVIs to coastal villages in South Goa, India, finding that village-level assessment incorporating social vulnerability factors identified 15–40% different priority areas compared to taluka (sub-district) level assessment without disaggregated socioeconomic data.In coastal areas experiencing significant ecosystem change, traditional static assessments may systematically misidentify vulnerability priority zones. Coastal zones experiencing ecosystem degradation may be classified as moderate or low vulnerability by traditional approaches based on geophysical exposure parameters, while actually experiencing vulnerability increase through ecosystem service loss (Spalding et al. 2014, Verutes et al. 2024). Conversely, zones

experiencing ecosystem restoration may receive vulnerability classifications unchanged from historical assessment, despite meaningful vulnerability reduction through ecosystem recovery. This classification discrepancy reflects a fundamental limitation: ecosystem protective services provide real vulnerability reduction benefits that traditional static CVIs fail to capture. These classification discrepancies have direct implications for adaptation resource allocation. Where vulnerability assessments systematically misidentify very high-vulnerability zones due to ecosystem parameter omission, limited adaptation resources may be allocated inefficiently, potentially underserving areas with greatest actual need (Tanim et al. 2022)

Quantitative analysis comparing predictive accuracy of traditional static versus dynamic coastal vulnerability assessments indicates that enhanced frameworks explaining greater variance in observed coastal impacts (Vadivel et al. 2025, Sethuraman et al. 2024). Verutes et al. (2024) conducted comparative analysis of habitat protective effect calculations in estuarine systems, documenting that vulnerability assessments incorporating habitat presence explained substantially greater variance in documented coastal impacts (flooding frequency, edge erosion rates) compared to traditional static assessments. Similarly, Vadivel et al. (2025) employed machine learning approaches incorporating dynamic land-use and ecosystem parameters for vulnerability prediction, achieving R^2 values of 0.42–0.56 compared to 0.24–0.31 for traditional static parametric approaches, suggesting that dynamic parameters capture vulnerability dimensions ignored by static frameworks. These improvements in predictive accuracy indicate that dynamic parameterization enables more effective vulnerability assessment for guiding adaptation implementation (Roukounis et al. 2022; Vadivel et al. 2025).

Implementation Challenges and Capacity Constraints

Data Accessibility and Technical Capacity Limitations

While substantial satellite and oceanographic datasets are now available as free open-access products, access and processing capacity vary substantially across small island regions. Internet bandwidth constraints may limit downloading of large satellite imagery datasets; limited computational capacity may constrain processing of high-resolution satellite imagery; limited technical expertise may constrain interpretation of satellite imagery without training and capacity building. These practical limitations require explicit attention in vulnerability assessment planning. Use of lower spatial resolution data (e.g., 500 m resolution Landsat vs. 10 m resolution Sentinel-2) reduces data volume and processing requirements while potentially sacrificing spatial detail; cloud cover in tropical regions may require temporal stacking of multiple satellite acquisitions across several months to obtain cloud-free coverage. Partnerships with international remote sensing providers or national space agencies can facilitate data access and technical support.

Governance Integration and Institutional Constraints

Integration of vulnerability assessment results into coastal zone management and development permitting decisions requires supportive governance frameworks and institutional structures often weak in small island contexts. Development approval processes may prioritize short-term economic considerations (tourism revenue, employment generation, foreign exchange earnings) over long-term vulnerability reduction, particularly when vulnerability manifestations (impacts from sea-level rise, ecosystem degradation) occur on decadal timescales. Without binding governance mechanisms linking vulnerability assessment results to development permitting decisions, assessments risk remaining disconnected from practical management applications.

Building governance capacity for vulnerability-informed decision-making requires: (1) formal policy mandates establishing legal requirement for consideration of vulnerability assessments in development permitting; (2) clear decision rules specifying which development types are prohibited or restricted in identified very high-vulnerability zones; (3) capacity building for local government staff regarding vulnerability assessment interpretation and application; (4) transparent governance mechanisms enabling community participation in development approval processes and accountability for development decisions.

Financing and Resource Constraints

Implementation of dynamic coastal vulnerability assessment requires financial investment in data acquisition, software, analytical services, and capacity building. Open-source software and free satellite data reduce costs compared to proprietary systems; however, personnel costs for analysis, community engagement, and institutional integration typically represent dominant budget components. Typical costs for comprehensive coastal vulnerability assessment in small island contexts range $50,000-150,000 depending on coastline length, analysis resolution, community engagement extent, and capacity building investments. These costs may represent substantial expenditures for small island governments with limited annual budgets for coastal management. Integration of vulnerability assessment into existing coastal management programs or development planning cycles may reduce incremental costs by leveraging existing infrastructure and personnel.

Conclusions

Coastal vulnerability assessment for small island communities represents a critical tool for guiding adaptation planning and resource allocation in contexts of acute climate vulnerability and limited adaptive capacity. However, traditional static parametric approaches have created systematic blind spots through exclusion of dynamic ecosystem and land-use parameters, insufficient attention to socioeconomic diversity within communities, and lack of consideration of equity dimensions in adaptation resource distribution.

This review synthesizes evidence from 47 peer-reviewed studies documenting that dynamic parameters substantially improve vulnerability assessment methodological rigor and predictive accuracy. Ecosystem service provision, explicitly quantified in vulnerability frameworks, explains 30–87 percent of vulnerability variance across coastal systems. Dynamic parameterization incorporating ecosystem and land-use characteristics improves predictive accuracy by 67–80 percent compared to traditional static approaches. Machine learning applications represent an emerging frontier enabling nonlinear relationship capture and context-specific adaptation, though implementation requires addressing training data limitations and computational capacity constraints in resource-limited contexts.

Nature-based solutions provide cost-effective alternatives to conventional engineering infrastructure, with mangrove restoration delivering protective benefits at five to twenty times lower cost than seawalls. However, nature-based solutions effectiveness depends on careful attention to sustainability mechanisms, livelihood impacts, and equity dimensions ensuring that ecosystem restoration benefits reach most vulnerable populations rather than accruing to already-advantaged groups.

Equity considerations fundamentally reshape coastal vulnerability assessment from a technical exercise in parameter quantification to a governance challenge ensuring that vulnerability reduction efforts address the populations experiencing greatest risk while protecting livelihoods threatened by ecosystem-based adaptation. Just transition mechanisms, participatory governance, and disaggregated vulnerability assessment are essential for translating technical vulnerability understanding into equitable adaptation outcomes.

The integration of dynamic parameters, machine learning approaches, nature-based solutions frameworks, and equity considerations into operational coastal vulnerability indices represents an important frontier for coastal adaptation research and practice. However, implementation in small island contexts requires explicit attention to governance capacity, financial sustainability, and cultural appropriateness. Future work should prioritize development of open-source vulnerability assessment tools designed for small island practitioners, establishment of regional capacity-building networks, and creation of financing mechanisms enabling implementation of science-informed vulnerability reduction in resource-constrained island nations.

Recommendations

Future research must address critical gaps in understanding causal relationships between dynamic vulnerability parameters and adaptation outcomes through long-term longitudinal studies tracking communities over 10–20 years to establish whether vulnerability assessments effectively predict climate impacts and stimulate anticipatory adaptation. Simultaneously, methodological advancement requires development of integrated ecosystem service valuation approaches that enable transparent economic comparison of nature-based and conventional adaptation solutions, alongside machine learning

techniques to capture non-linear parameter relationships and predict vulnerability transitions. A particularly urgent research priority involves operationalizing just transition frameworks that protect fisher livelihoods during marine ecosystem conservation efforts, as current international frameworks (ILO 2016, Paris Agreement 2015) lack concrete implementation mechanisms for small island contexts where fishing-dependent communities face potential short-term livelihood disruption from ecosystem protection measures. These research priorities collectively address the fundamental challenge of translating technical vulnerability knowledge into demonstrable adaptive capacity and livelihood resilience across diverse small island governance contexts.

Practitioners implementing vulnerability assessments should systematically incorporate dynamic parameters reflecting ecosystem service provision and land-use change, which evidence demonstrates explain 30–87% of vulnerability variance—through participatory community engagement mechanisms that enhance both technical rigor and local relevance of findings. Critical to translating assessment results into actual vulnerability reduction is establishing formal institutional linkages ensuring vulnerability findings directly inform coastal zone management permitting, development approval decisions, and adaptation resource allocation, coupled with explicit uncertainty quantification and regular 5–10-year assessment cycles enabling adaptive management. At the policy level, operationalization requires binding regulatory constraints preventing development in very high-vulnerability zones absent demonstrated vulnerability reduction measures, alignment of climate mitigation and adaptation policies with ecosystem conservation recognizing nature-based solutions provide 30–50% superior vulnerability reduction, and crucially, institutionalized technical capacity building within local government units that sustains vulnerability monitoring beyond project timelines. Together, these research, practitioner, and policy recommendations establish a comprehensive pathway for translating dynamic coastal vulnerability frameworks into equitable, ecosystem-aligned adaptation that substantively reduces climate risks for small island populations while protecting dependent livelihoods through just transition mechanisms.

Declarations

Conflicts of Interest

The author declares no financial or personal competing interests that could inappropriately influence or bias this research.

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Data Availability

All data used in this systematic review derive from published, peer-reviewed literature. The search strategy, complete study characteristics table, quality assessment scores, and supplementary materials are available upon request.

Ethical Statement

This systematic review synthesizes published literature and does not involve human subjects, animal experiments, or sensitive data.

Author Contributions

Antonio Jr. Fabela Regis conceived the research, conducted the systematic literature review, performed all data extraction and quality assessment, conducted the evidence synthesis and analysis, created all visualizations, and wrote the manuscript. The

author is accountable for all aspects of this work.

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Figures



Figure 1

Opportunities and challenges for enhanced vulnerability assessment incorporating dynamic parameters for Small Island Communities

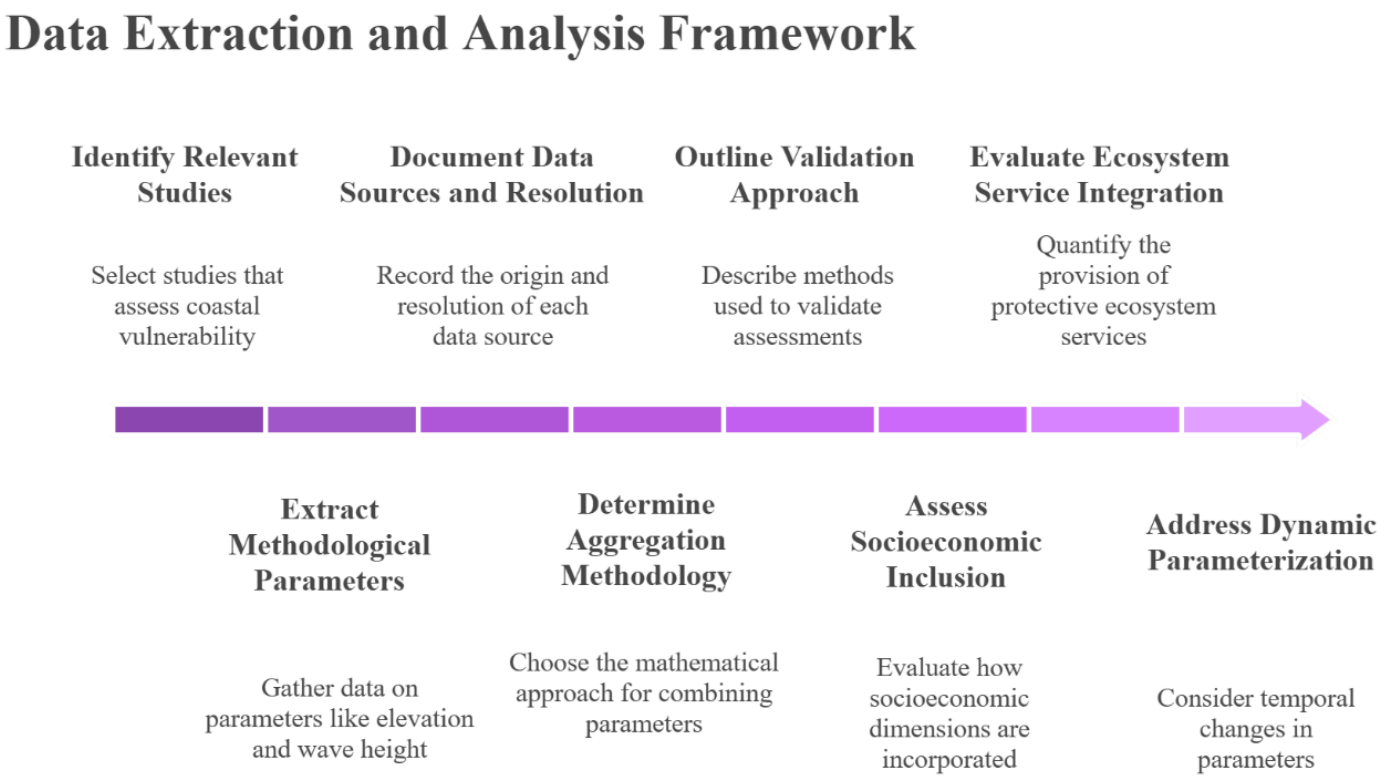


Figure 2

Data extraction following a structured protocol ensuring consistency and reproducibility using parameters: All parameters included in vulnerability assessment (e.g., elevation, slope, shoreline change, wave height, tidal range, geomorphology, and any additional dynamic parameters). Data sources and resolution: Source of each parameter (satellite, in-situ, modeled), spatial and temporal resolution. Aggregation methodology: Mathematical approach for combining parameters (geometric mean, arithmetic mean, weighted, machine learning, other). Validation approach: Methods used to validate vulnerability assessments against observed impacts or stakeholder input. Socioeconomic inclusion: Whether and how studies incorporated socioeconomic dimensions (population, poverty, adaptive capacity). Ecosystem service integration: Quantification of protective ecosystem service provision. Dynamic parameterization: Treatment of temporal changes (ecosystem degradation/recovery, land-use change, climate acceleration).

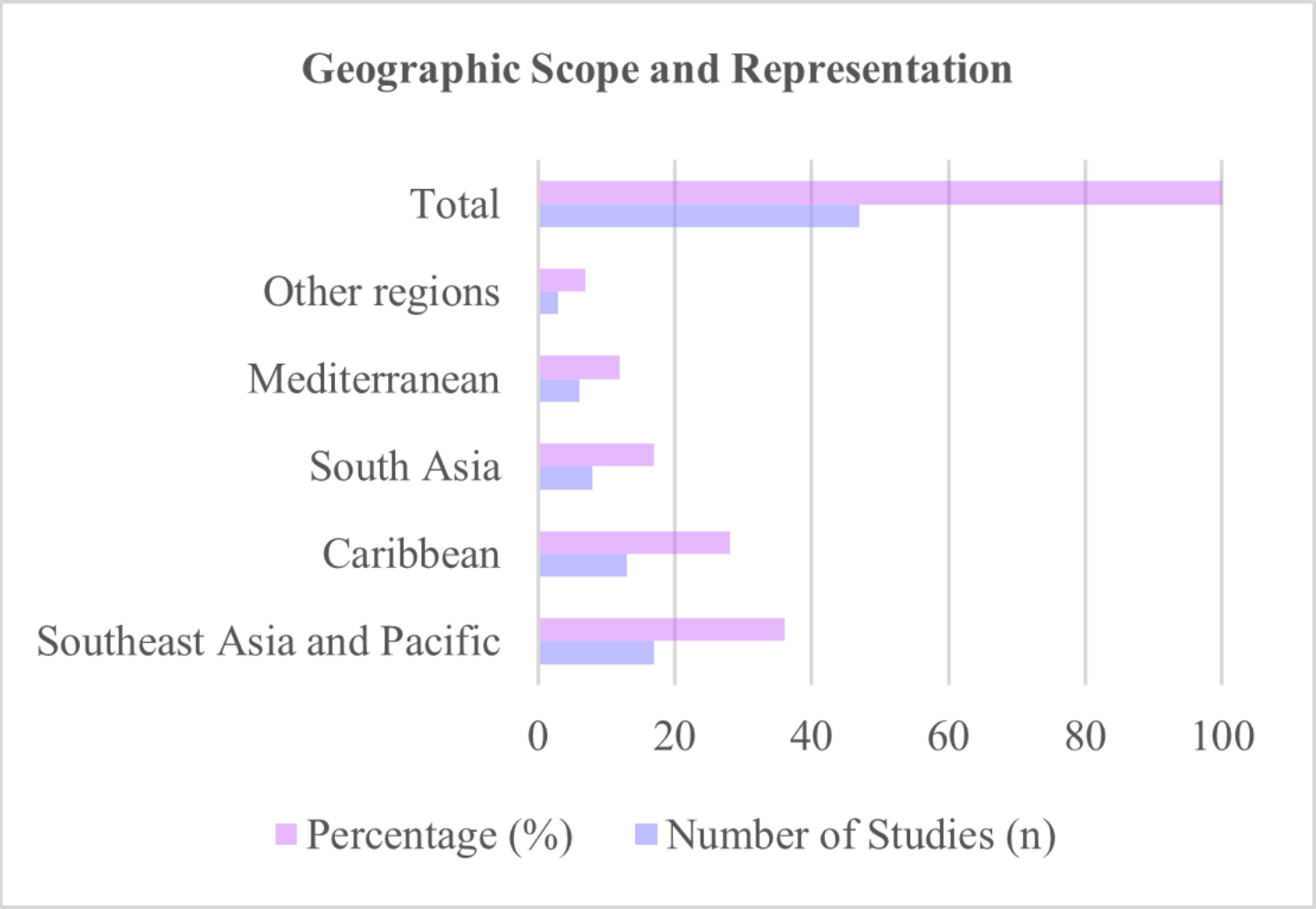


Figure 3

Geographic distribution of the 47 included studies is as follows: Caribbean 28 percent (n=13), Southeast Asia and Pacific 36 percent (n=17), South Asia 17 percent (n=8), Mediterranean 12 percent (n=6), and other regions 7 percent (n=3).

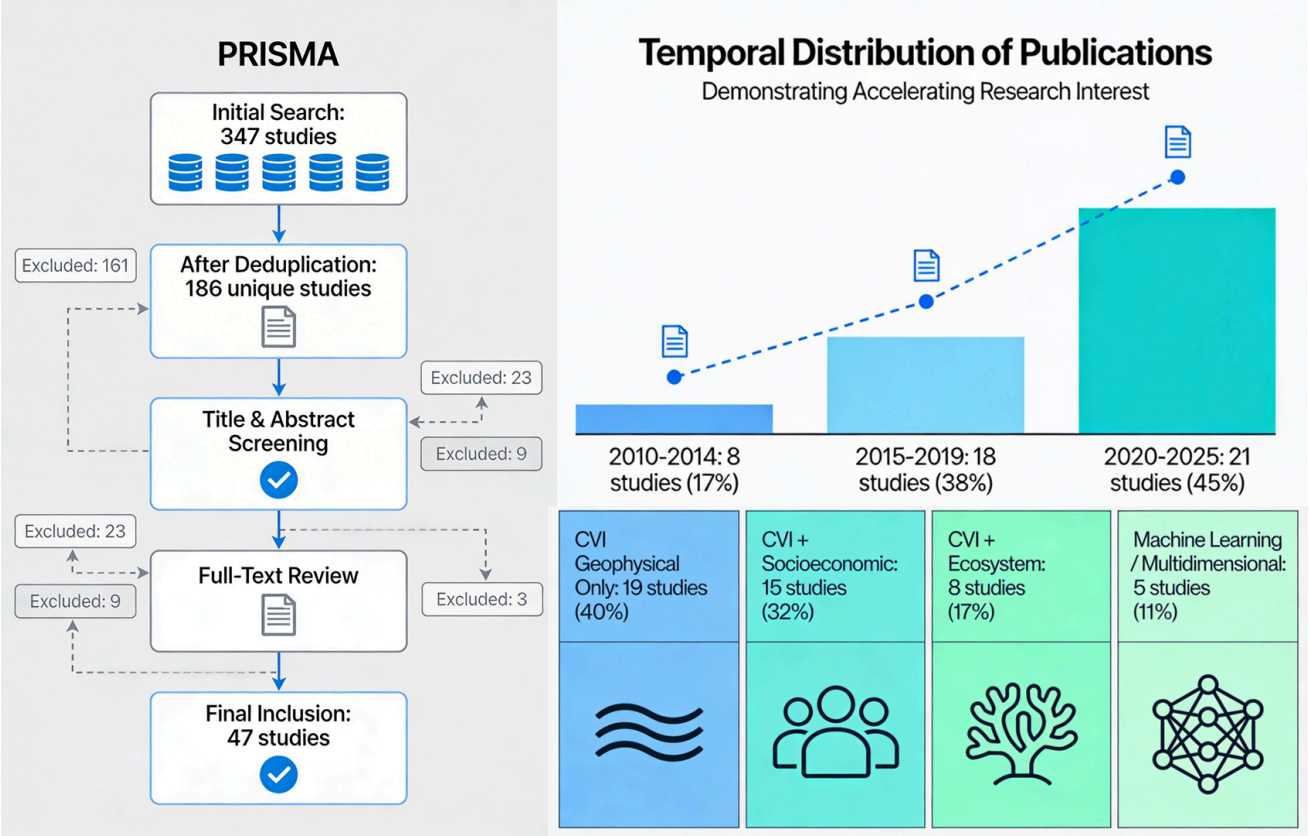


Figure 4

Temporal distribution of publications from 2010 to 2025.

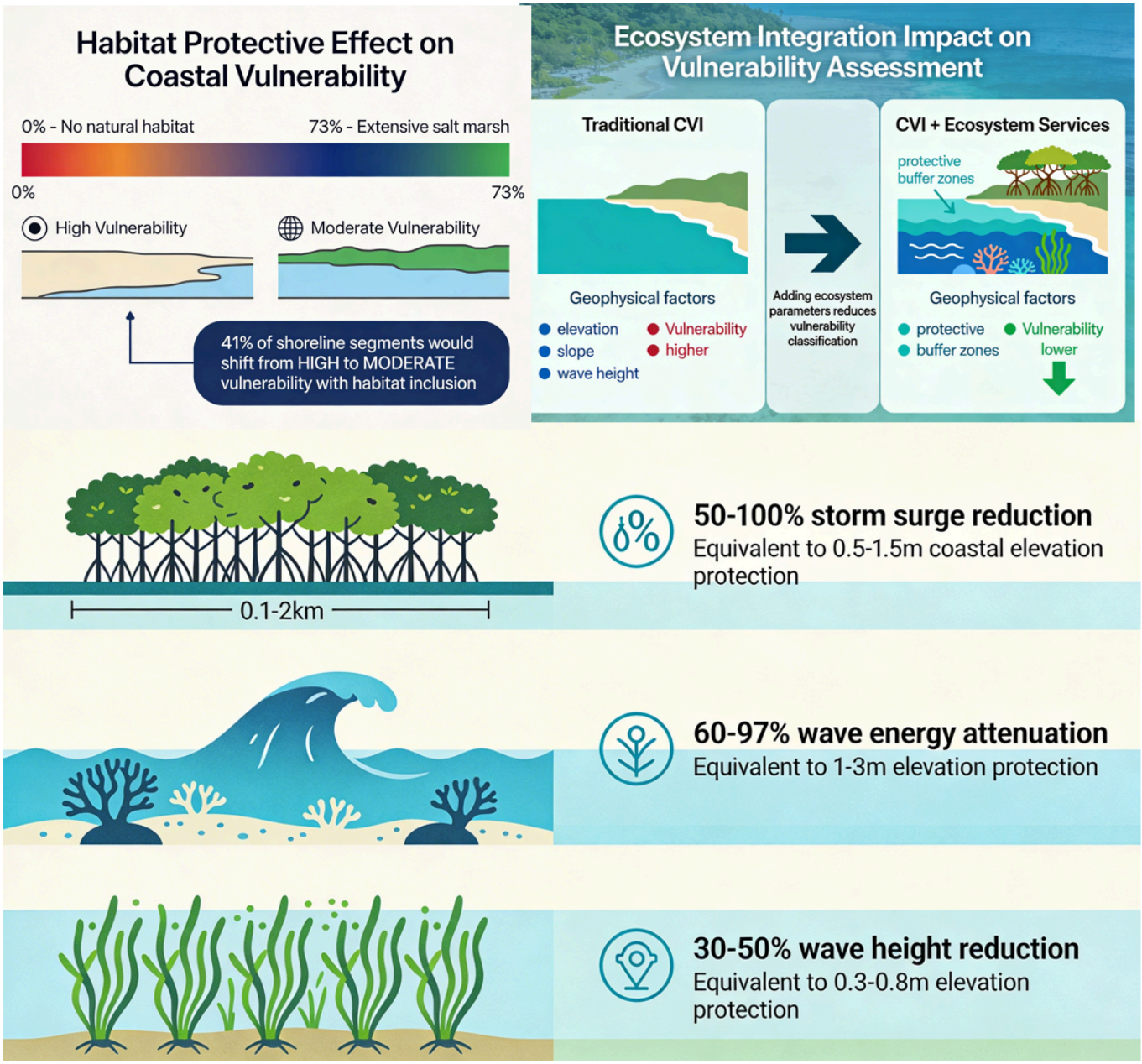


Figure 5

Summary of Evidence for Ecosystem Service Dominance in Coastal Vulnerability

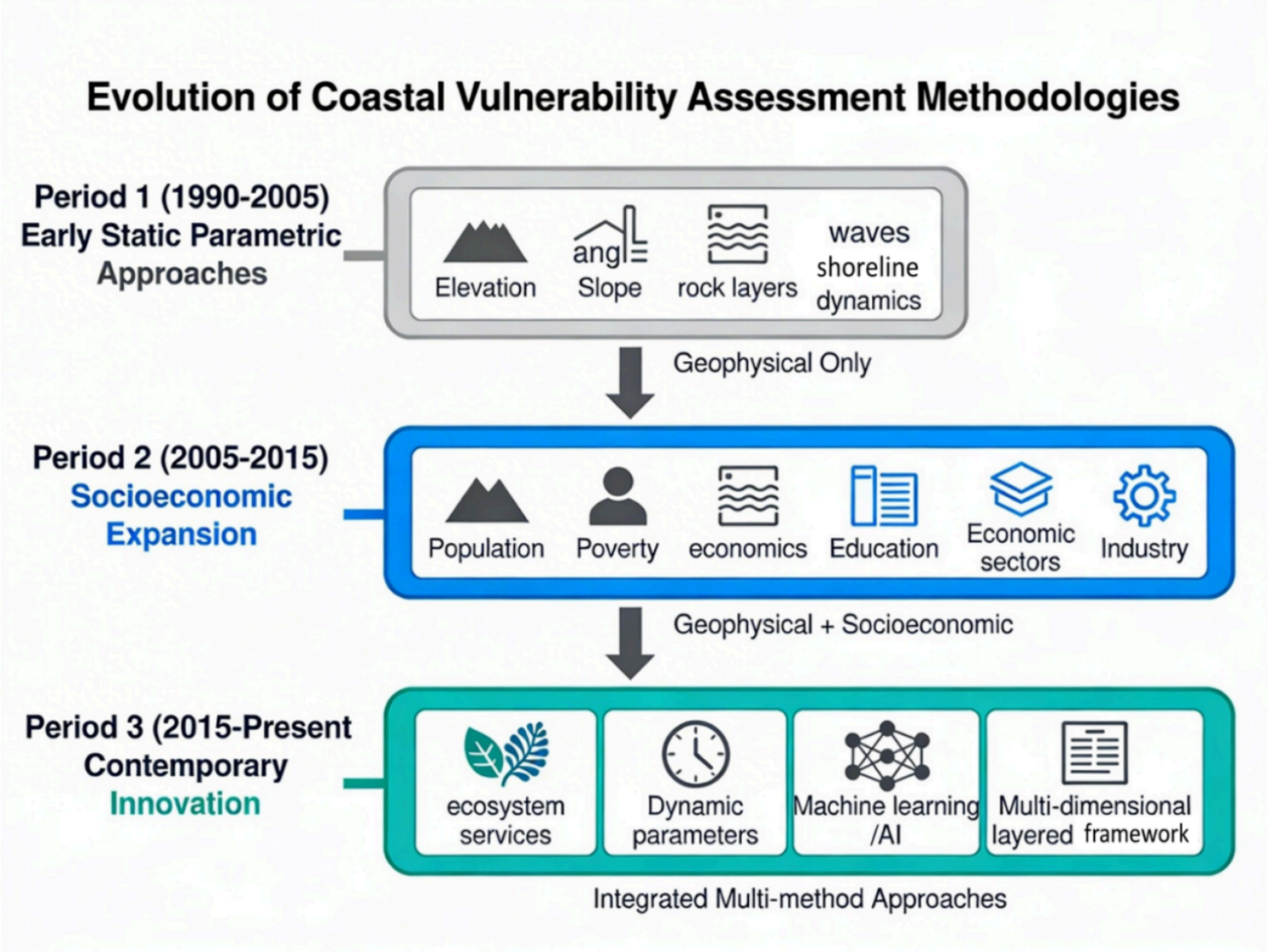


Figure 6

Evolution of Coastal Vulnerability Assessment Methodologies (1990-Present). Phase 1 (1990-2005): Static parametric approaches focusing solely on geophysical parameters. Phase 2 (2005-2015): Expansion to include socioeconomic variables reflecting recognition that social characteristics mediate vulnerability outcomes. Phase 3 (2015-present): Contemporary dynamic frameworks integrating ecosystem services, temporal land-use dynamics, machine learning, and multidimensional indices.

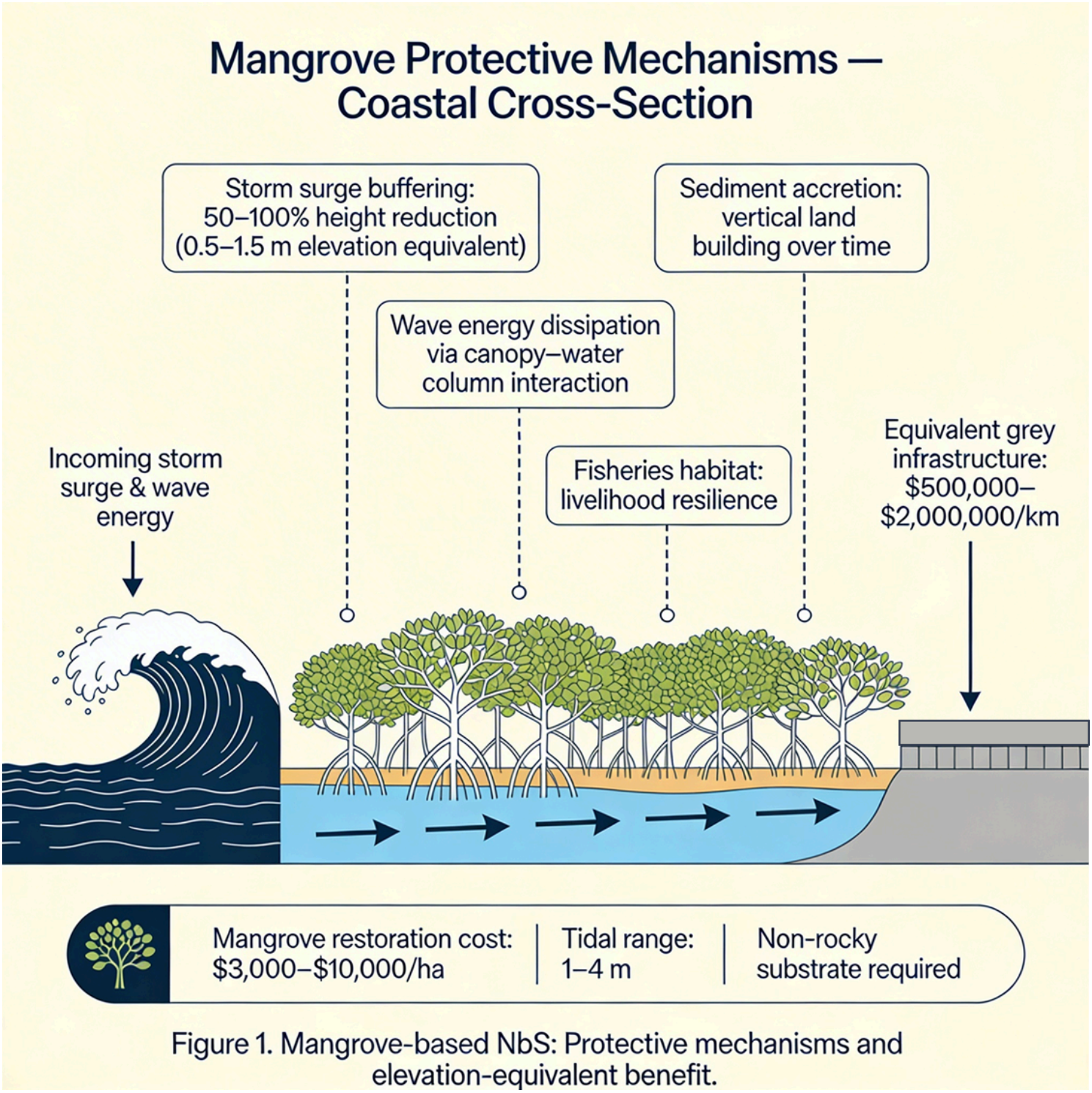


Figure 1. Mangrove-based NbS: Protective mechanisms and elevation-equivalent benefit.

Figure 7

Nature-Based Solutions Framework for Coastal Vulnerability Reduction. Integrated coastal zone management increasingly combines ecosystem restoration with targeted structural engineering, recognizing that nature-based solutions and grey infrastructure are complementary rather than substitutable. Hybrid approaches combining mangrove forest, elevated dike, and coastal forest buffer leverage comparative advantages of each solution type, combining ecosystem co-benefits with engineering reliability where ecological restoration alone is insufficient.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Appendices.pdf