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Effectiveness of Ecosystem-Based Coastal Defenses Against Flooding

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Key Points:

- Although ecosystem-based defenses may replace hard seawalls, the latter is more stable and effective in flood protection
- Ecosystem-based coastal defenses may fail in areas with seasonal vegetation or areas experiencing coastal erosion
- Combining hard seawalls with ecosystem-based defenses to create smart, eco-friendly seawalls is an effective coastal protection strategy

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Abstract Coastal flooding is growing substantially as storms increase and sea levels rise rapidly due to climate change. It is therefore important to find safe and sustainable ways to protect coastal communities against this growing risk. However, the effectiveness of traditional coastal defenses (hard seawalls) (HS) is being questioned due to concerns about their negative ecological impacts and high economic cost. Ecosystem-Based Coastal Defenses (EBCDs) may potentially offer a more sustainable alternative. Based on a systematic literature review of >21,000 articles from 430 vulnerable areas, here we argue that EBCDs do not always provide effective protection, especially where EBCDs have seasonal vegetation cover, and in intertidal habitats in sediment-starved areas. We suggest that HS might be employed in a hybrid approach, together with EBCDs, to optimize flood protection and environmental benefits in these areas. We also consider how "intelligent HS," using adaptive materials, might be applied in future coastal flood protection systems.

Plain Language Summary Coastal areas are facing more frequent and severe flooding due to rising sea levels and stronger storms caused by climate change. Traditional methods of protection, like seawalls, have been used for thousands of years but are expensive, environmentally damaging, and may not be sufficient for future challenges. A new approach, known as Ecosystem-Based Coastal Defenses (EBCDs), uses natural environments like mangroves, salt marshes, and dunes to protect coastlines. These ecosystems can reduce wave energy, prevent erosion, and support biodiversity. However, the effectiveness of EBCDs can be limited by factors like seasonal changes in vegetation, lack of sediment, and their vulnerability to extreme storms. This review suggests that a combination of traditional seawalls and EBCDs could offer better protection. The future research into hybrid coastal protection will also likely involve smart seawalls that adapt to changing conditions. By carefully considering local conditions, we can create more sustainable and effective coastal flood defenses.

1. Introduction

In recent decades, Ecosystem-Based Coastal Defenses (EBCDs) are becoming more accepted as a potential alternative to the use of more traditional coastal defenses, such as Hard Seawalls (HS) (Morris et al., 2020; Temmerman et al., 2013; Zhu et al., 2020). EBCDs include natural habitats like mangroves, salt marshes, and dunes, which demonstrate a strong ability to reduce wave energy, prevent erosion, and adapt to changing coastal conditions (Temmerman et al., 2013). In addition to offering coastal protection, EBCDs also support biodiversity, carbon sequestration, and other essential ecosystem functions (Fluet-Chouinard et al., 2023; Macreadie et al., 2021; Vuik et al., 2016). These functions make wetlands and mangroves amongst the most valued ecosystems in the word (Fluet-Chouinard et al., 2023). The integration of EBCDs into flood defense strategies allows for a dynamic evolution between the biotic and abiotic components of coastal systems, potentially providing a long-term sustainable defense system that provides additional benefits associated with the ecosystem services so-derived (Marijnissen et al., 2021; Waryszak et al., 2021). Moreover, given the adaptive abilities of EBCDs, they can, in part, grow themselves, which potentially reduces costs (Morris et al., 2018). In contrast, HS are static features in that they do not respond to changing boundary conditions (Waryszak et al., 2021).

Furthermore, it is well known that vegetated foreshores: (a) build up sediment bodies via bio-geomorphological interactions (Mi et al., 2022); (b) stabilize sediments (Duarte et al., 2013), and; (c) attenuate waves (Zhou et al., 2022). These functions are underpinned by bio-geomorphic feedbacks whereby vegetation alters hydrodynamic flows and sediment transport to enhance sediment retention and build surface elevation, which in turn promotes further plant growth and marsh resilience (Kirwan et al., 2010; Murray, 2023). Such positive feedback

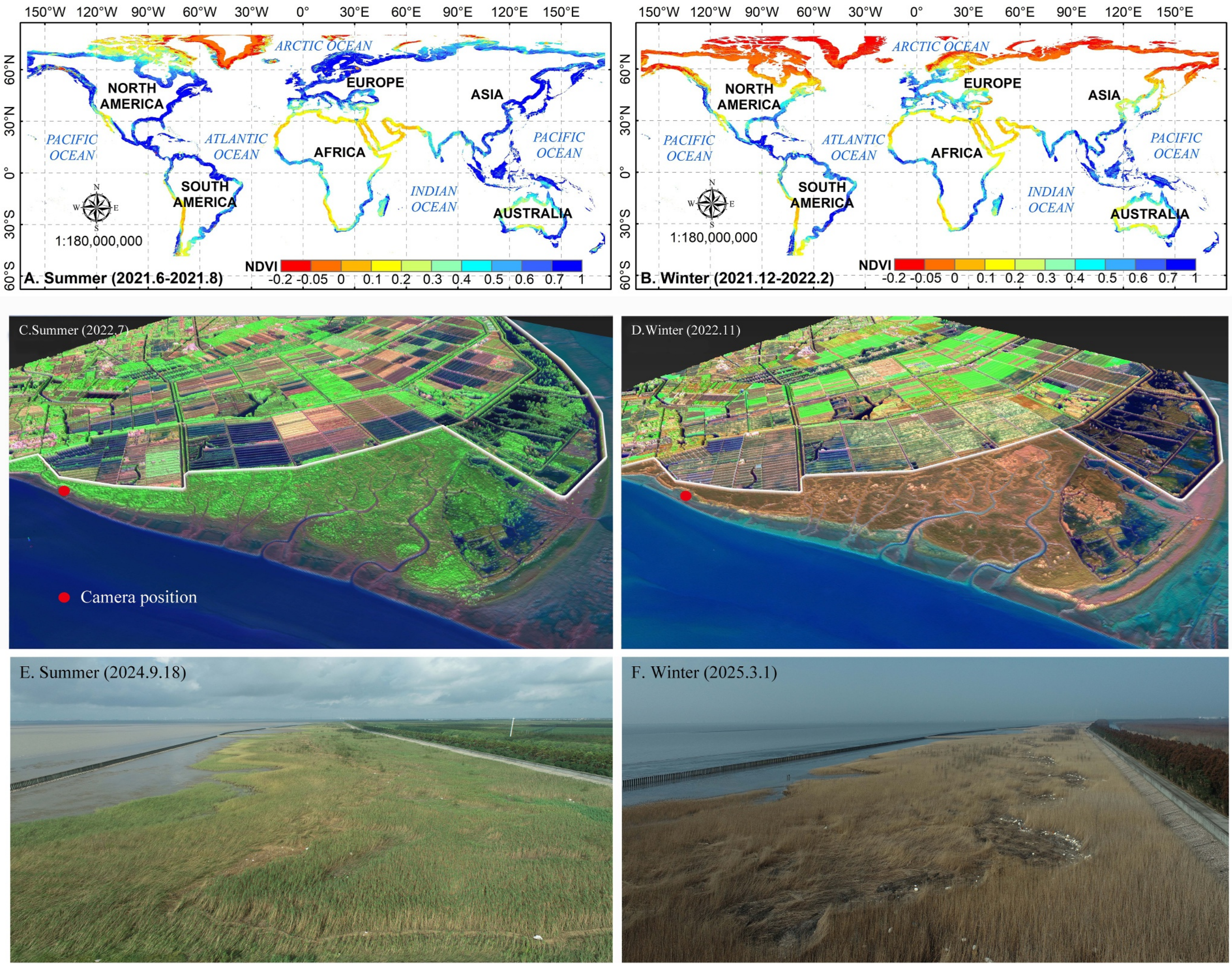

Figure 1. Subplots (a) (Summer) and (b) (Winter) illustrate seasonal changes in coastal vegetation at the global scale, as indicated by NDVI (Normalized Difference Vegetation Index) data downloaded from https://lpdaac.usgs.gov/products/mod13a1v006/. The subplots (c) (Summer) and (d) (Winter) exemplify seasonal changes at the reconstructed Bolboschoenoplectus mariqueter wetland landscape on the Chongming East Shore of the Changjiang estuary, China. The subplots (e) and (f) are photos taken during summer and winter at the same location of that site.

loops between vegetation structure, coastal hydrodynamics, and sediment dynamics are fundamental to the long-term evolution, stability, and adaptive capacity of intertidal wetlands (Fagherazzi et al., 2012; Kirwan & Megonigal, 2013). A recent meta-analysis showed that both wave attenuation and shoreline stabilization are positively correlated with vegetation density (Augustin et al., 2009), biomass production (Shepard et al., 2011), and marsh size (Waryszak et al., 2021). The wave attenuating effect largely depends on vegetation stiffness (Wilson et al., 2003), standing biomass (Feagin et al., 2011), and inundation height (Lapetina & Sheng, 2014). However, the use of vegetation within EBCDs for flood protection (such as the use of vegetated foreshores) can involve inherent challenges due to the dynamic nature of vegetation growth, especially over seasonal timescales (Mi et al., 2022). In particular, in temperate and subtropical climates, coastal wetlands may lose the majority of their aboveground vegetation structure during winter (e.g., *Spartina alterniflora*, *Salicornia spp*., *Puccinellia spp*., etc.), even if other types of vegetation (e.g., *Limonium spp*.) retain the majority of their stems (Chu et al., 2019) (Figure 1). The loss of biomass in winter means that the wave attenuation function of EBCDs becomes a seasonal phenomenon, with the loss of most function in the stormiest season, as empirically demonstrated in certain Chinese temperate marshes (Dai and Ge, 2022). So, even though EBCDs provide some flood defense value (Mi et al., 2022), there remains doubt about their overall contribution to flood protection (Vuik et al., 2018), despite the persistence of vegetation's morphodynamic effects (such as elevation and platform width) beyond the seasonal growth cycle. Meanwhile, it also remains uncertain how local and invasive vegetation (e.g., *Spartina alterniflora* and *Sonneratia apetala* in China) evolves with other ecosystem services over time and space (Marijnissen et al., 2021; Zhang et al., 2023), depending on plant growth strategies (Jiang et al., 2017), local physical conditions (Cahoon et al., 2018), and management practices (Keesstra et al., 2018). These uncertainties hamper innovation and the potential uptake of EBCDs in flood risk management around the world.

As for the eco-geomorphic processes and wetland dynamics, plant growth strategies determine the intrinsic capacity of marsh or mangrove stands to expand laterally, build root biomass, and trap sediments (Jiang et al., 2017). Whether that capacity is realized, however, depends on local physical drivers—including tidal range, wind waves, and sediment supply—which set the bio-geomorphic "envelope" within which plants can flourish (Cahoon et al., 2018). Management actions such as controlled creek excavation, coastal reclamation, or grazing exclusion can further amplify or dampen these feedbacks (Keesstra et al., 2018). Together, these biological, physical, and managerial controls generate coupled vegetation–morphology feedbacks that affect long-term platform elevation and surface roughness (Fagherazzi et al., 2012; Kirwan et al., 2010; Marani et al., 2011; Murray, 2023). Because the efficiency of EBCDs depends on those evolving biophysical properties, performance targets must account not only for present-day vegetation characteristics but also for their plausible trajectories under sea-level rise and other environmental changes (Cahoon et al., 2018; Kirwan & Megonigal, 2013).

Fundamental research over the past decades has resulted in significant insight into the ways in which HS interact with hydraulics (Morris et al., 2018; Sun et al., 2015) and offer strength (Lan & Huang, 2018) for flood defenses, which has led to the ability to determine the probability of failure of HS for events such as dike breaches, dam breaks, and breakwater collapses, considering the stochastic behavior of both loads and strength (Ahmad et al., 2019; Dang et al., 2021; Mehrabani et al., 2015). This situation contrasts with the much higher uncertainties surrounding the use of EBCDs, such as on the role of dynamic eco-engineering features, like morphology degradation and vegetation vulnerability (Rosenberger & Marsooli, 2022). Furthermore, some coastal defense schemes combine elements of EBCDs and HS together, for example, through the use of a vegetated foreshore integrated with seawalls. But for these combined features, there is as yet limited insight into their safety and no probabilistic methods are available to analyze the safety and levels of uncertainty of these systems (Marijnissen et al., 2020). An integrated treatment is, therefore, needed to assess the effectiveness of EBCDs across a range of context. In brief, the key uncertainties of EBCDs compared to HS that need to be addressed are those due to: (a) long-term dynamics of ecological and geomorphological resistance and resilience; (b) wetland stability under extreme storm conditions, and; (c) vegetational contribution to the reduction of hydraulic loads on, and failure probabilities of, flood defenses.

Herein we undertake a systematic literature review on the historical evolution of coastal flood defense, from which we identify a clear shift from simple, isolated methods (usually based on HS) to more integrated, sustainable, and adaptive approaches (often involving EBCDs either in isolation or with HS) in response to changing environmental and societal needs (Figure 2). We show that EBCDs are now emerging as the most widely adopted nature-based solution, and are seen as the most promising option for future coastal flood defense. Our analysis critically examines the effectiveness of EBCDs in addressing coastal flood risks, while also identifying scenarios where these defenses may not succeed. Based on this analysis, we propose potential solutions to enhance the resilience of coastal areas with EBCDs. We aim for this study to serve as a milestone in the historical advancement and current application of EBCDs, offering insights into their roles in shaping the future of coastal flood protection.

2. Transfer of Coastal Flood Defenses Concepts

Humanity has a long history, spanning thousands of years, of developing coastal flood defenses (Bao et al., 2020). Given the rapid growth of coastal flood defenses research, synthesizing the vast body of literature has become increasingly challenging. In this context, big-data and bibliometric analysis techniques have proven to be effective tools for analyzing key ideas and trends (van Eck and Waltman, 2010). The development of the coastal flood defense literature from the Web of Science database is here assessed using a term-based search strategy and a bibliometric approach in VOSviewer (van Eck and Waltman, 2010). This analysis was thereby able to include 21,000 coastal flood defenses-related articles covering coastal flooding protection in approximately 400 geographic areas published between 1980 and 2025 (Figure 2). All the included articles contain the key terms "coastal protection" in their titles, abstracts, or keywords. Results show that the global volume of annual

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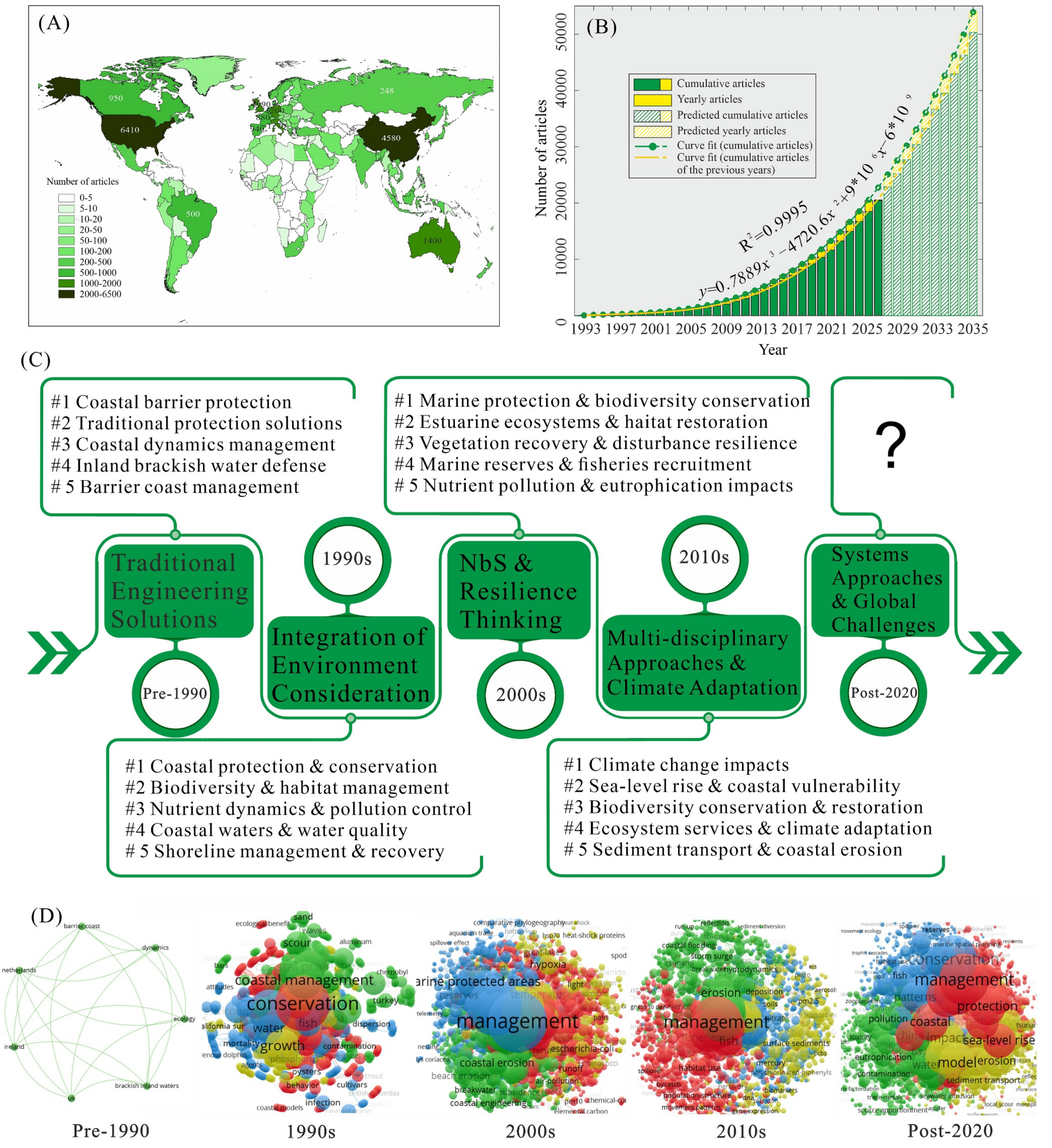

Figure 2. Evolutionary trends in coastal protection research. (a) Geographical distribution of coastal protection articles included in the literature review based on the country where the research was conducted. (b) Temporal trends of cumulative and annual number of coastal protection articles as well as their projected values for the period 2025–2035 using a third-degree polynomial curve fit equation derived from the existing data. Future trends are shown with dashed lines, omitting some nonlinear factors. (c) An infographic timeline indicating the top 5 research sub-themes with the largest number of (citing) articles during each period. (d) Clusters of frequently co-occurring terms in VOSviewer illustrating the major themes of coastal protection science during each period (the colors red, green, blue, and yellow represent the social, flood risk, ecosystem benefit, and method dimensions of the studies investigated, respectively).

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publications exhibits a cubic polynomial growth trend, with an estimated 54,000 articles expected by 2035 (Figure 2b). The countries with the highest number of publications are the United States (6,409), China (4,579), and the United Kingdom (1,987), while the Netherlands ranks tenth with 796 publications (Figure 2a).

The historical evolution of coastal protection concepts since 1980 can be broadly categorized into five key stages (Figures 2c and 2d). Prior to 1990, studies of traditional engineering solutions were dominant. In the 1990s, there was a marked shift toward integrated management and environmental sustainability. The 2000s shifted further toward the use of EBCDs and a greater emphasis on resilience thinking, while the 2010s saw a marked rise in focus on climate change adaptation and multidisciplinary approaches. A detailed summary of the dominant concepts and methods about coastal flood defenses in each period, obtained based on the keyword frequency analysis of the Web of Science database (Figure 2c), is described as follows:

1. *Traditional engineering solutions pre-*1990: Coastal protection efforts were primarily focused on hard engineering solutions, that is HS, such as seawalls, groins, breakwaters, and dikes, designed to protect coastal areas from erosion and storm surges. The methods employed were largely reactive, aiming to control flooding through structural interventions. However, this characterization is drawn from an empirical assessment of only seven documents in our database (Figure 2b), and should therefore be interpreted with that limitation in mind.
2. *Integration of environmental considerations in* 1990s: There was an emerging recognition that over-reliance on HS could lead to ecological damage and unsustainable outcomes. During this period, concepts like Integrated Coastal Zone Management (ICZM) became popular. ICZM advocated for a more holistic approach to managing coastal areas, emphasizing the balance of environmental, social, and economic factors. This decade also saw the rise of soft engineering solutions, such as beach nourishment, dune restoration, and wetlands restoration, that aimed to work with natural processes instead of fighting them.
3. *Ecosystem-based adaptation and resilience thinking in* 2000s: The EBCDs approach became central, emphasizing restoring or mimicking natural coastal processes to enhance protection. Methods like living shorelines, mangrove restoration, and seagrass planting gained attention as alternatives to HS. There was also a growing emphasis on sustainability thinking. Coastal protection strategies expanded to include more proactive and sustainable approaches, with HS and EBCDs measures being integrated into broader frameworks for land-use planning and disaster risk reduction.
4. *Climate change adaptation and multidisciplinary approaches in* 2010s: The impacts of climate change—such as rising sea levels, increased storm intensity, and coastal flooding—became a dominant concern. As a result, coastal protection strategies evolved to incorporate climate change adaptation into long-term planning. A key development during this period was the growing emphasis on EBCDs as central strategies for reducing vulnerability. Coastal defenses began to serve multiple functions, combining flood protection with ecological and social benefits. To support these strategies, geospatial technologies such as GIS, remote sensing, big-data, and flood modeling became critical tools for understanding and managing coastal risk.
5. *Systems approach and global challenges post-*2020: The current phase has only just begun, with considerable uncertainty ahead. Based on historical trends and developments in the past 5 years, we anticipate that the future direction will embrace a systems-based approach, incorporating both natural and human systems. The focus is expected to shift from isolated protection measures to broader strategies that consider entire socio-ecological systems, placing a greater emphasis on human well-being in coastal protection planning. This shift will drive a more holistic and inclusive approach to managing flood risks and other coastal challenges.

3. Profiling of Ecosystem-Based Coastal Defenses

EBCDs have emerged as a significant approach to coastal flood defense in response to evolving human needs and the increasing recognition of the role of natural systems in enhancing social resilience and sustainability. The concept was first introduced by Danielsen et al. (2005) and later expanded by Costanza et al. (2008). Since the particularly influential publication by Temmerman et al. (2013), EBCDs have gained widespread recognition as a viable and increasingly favored strategy for coastal protection. The adoption of EBCDs has accelerated in the past decade, with a sharp rise in research and practical applications, with the number of related publications increasing rapidly each year, totaling nearly 1,276 publications by 2025, as visualized in the VOSviewer cluster in Figure 3. Based on the frequency of occurrence of the terms "wetlands" and "coastal protection" in the titles and abstracts of the EBCD-related articles analyzed, four major themes have emerged: (a) Social Dimensions and Community Benefits (b) Flood Defense and Risk Indicators, (c) Ecosystem and Habitat Values, and (d) Methods and Approaches. In Figure 3, VOSviewer shows that terms mutually appear in multiple articles are displayed adjacent,

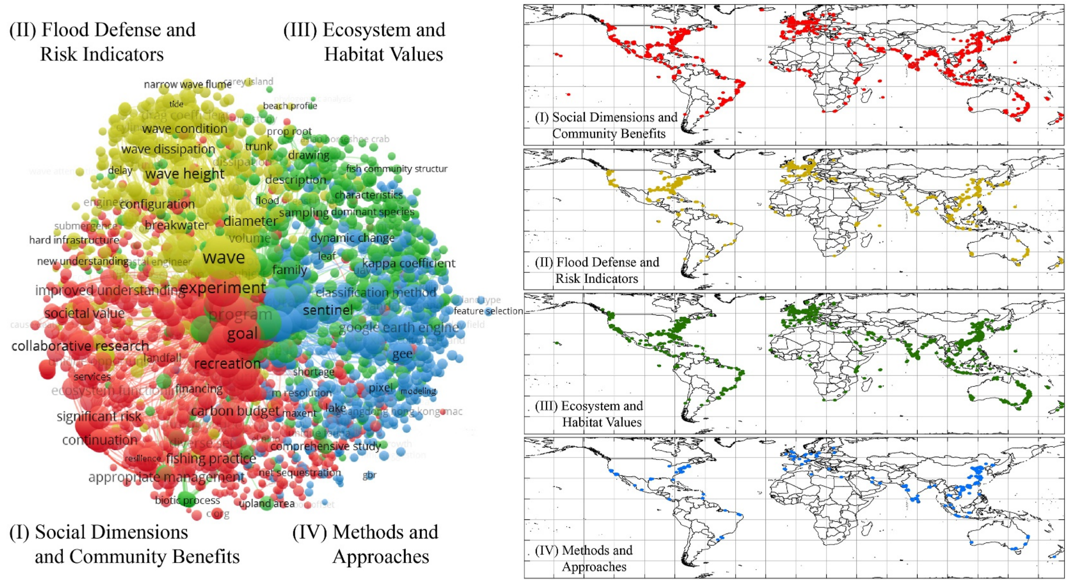

Figure 3. Major research clusters (themes) of Ecosystem-Based Coastal Defense (EBCD) science in VOSviewer and their spatial distribution of case study locations: (I) Social Dimensions and Community Benefits (red symbols), (II) Flood Defense and Risk Indicators (yellow symbols), (III) Ecosystem and Habitat Values (green symbols), and (IV) Methods and Approaches (blue symbols).

forming a research theme (or cluster) at an aggregate level. The nodes represent terms, with their size proportional to the number of occurrences within each research theme.

In general, EBCD articles in Cluster (I) focus on the social benefits, emphasizing enhanced community resilience, improved public health, and greater social cohesion of EBCDs. In particular, restored coastal ecosystems offer recreational opportunities that can boost mental health and well-being for coastal communities. Cluster (II) highlights the role of wetlands in reducing wave energy and serving as natural barriers against storm surges and tsunamis, as well as their functions to attenuate wave energy, trap sediment, and stabilize shorelines. Cluster (III) explores the broader ecological and economic benefits of EBCDs in terms of their potential to provide multiple co-benefits, such as enhancing biodiversity, improving water quality, and supporting carbon sequestration, in addition to protecting human settlements from coastal hazards. Cluster (IV) discusses the methods and technologies used for advanced processing and real-time monitoring. However, despite their promise, challenges remain in terms of the scalability and effectiveness of EBCDs under extreme climate change scenarios. Moreover, there remains a need for additional research to better understand the long-term performance and uncertainty of EBCD use in flood mitigation.

4. The Challenge of Protecting Against Coastal Flooding

Anthropogenic climate change is driving rising mean sea levels and increasing the frequency and intensity of extreme weather events, such as tropical cyclones (IPCC, 2021; Zhang et al., 2025). As a result, the coastal zone, home to some 60% of the world's population, will experience increased flooding in the future. HS, including levees, culverts, bulkheads, and seawalls, have long provided protection against coastal flooding. For example, Hangzhou Bay, China, is prone to tidal flooding and storms (Best et al., 2022) (Figures 4a and 4b). Without the ancient “fish-scale” seawall, constructed over 1700 years ago, the low-lying northern Hangzhou Bay plain would experience frequent inundation (Figures 4a and 4b). But the sustainability of conventional flood defenses such as HS is increasingly being challenged (Morris et al., 2020; Sutton-Grier et al., 2015). A key issue is that HS are recognized as inhibiting the connectivity between water, sediment, and biology (Temmerman et al., 2013), contributing to ecosystem degradation. Furthermore, existing HS need to be heightened and reinforced to cope with the increased risk of coastal flooding due to climate change (Syvitski et al., 2009). Finally, the financial cost of the HS required to maintain even current standards of protection is very high (Karim & Mimura, 2008; Tessler et al., 2015; Welch et al., 2017). For example, to date, China has built 14,500 km of seawalls, but only 58% of

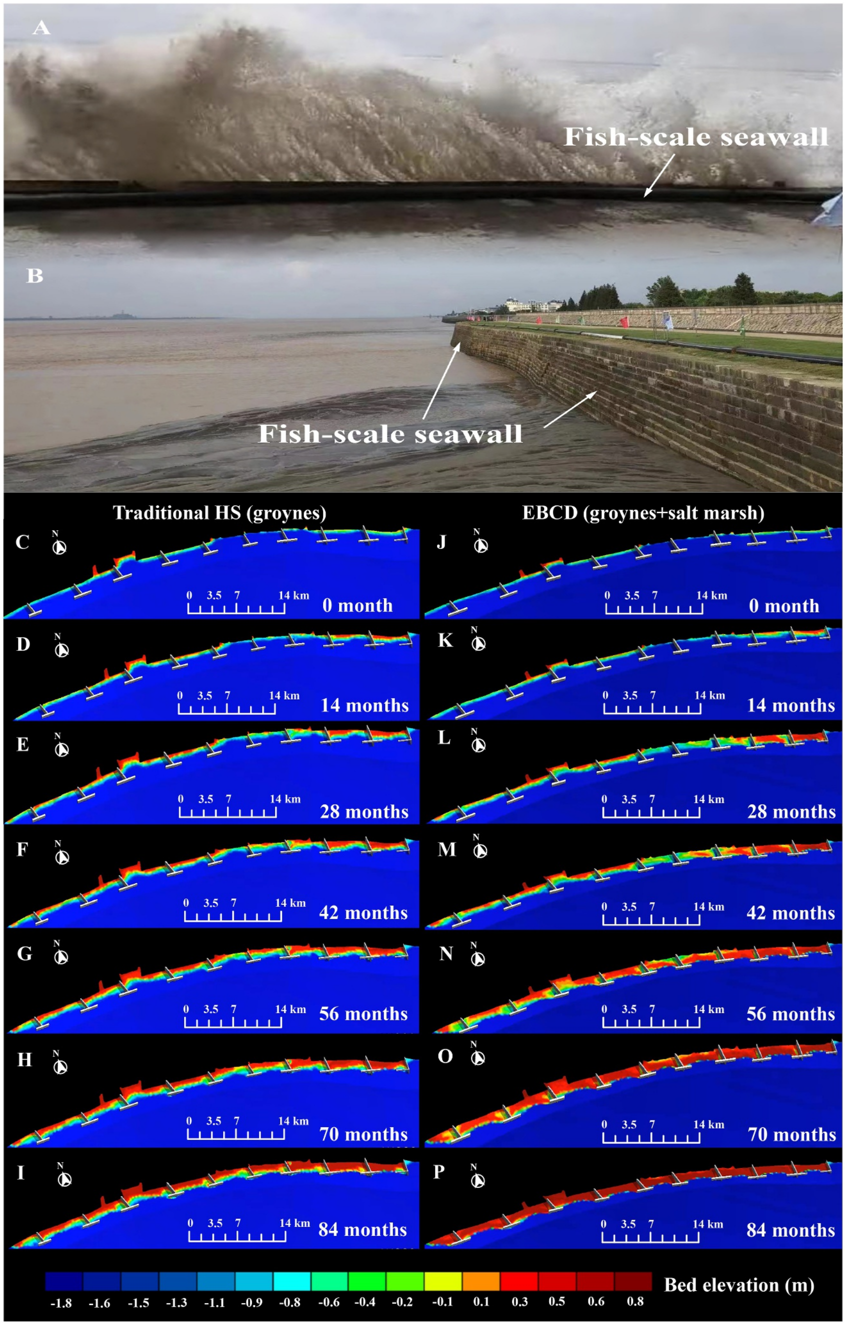

Figure 4. Erosional tidal flat and EBCD-based tidal flat restoration on the northern shore of Hangzhou Bay in China. Subplots (a and b) show typical tidal bore waves during astronomical spring high tide and the ancient fish-scale seawall constructed over 1,700 years ago. Subplots (c-i) and (j-p) display modeling results of tidal flat morphology restoration over 14-month intervals, with subplots (c-i) illustrating restoration using traditional HS T-groynes (arms 1,500 m) and subplots J-P showing restoration through a hybrid approach combining T-groynes and attached salt marsh. For details about the modelling setups please refer to Mi et al. (2025).

these provide protection against storm surge floods of greater than a 20-year return period (MWR, 2017). Increasing the level of protection to defend against 50–100 years return interval events would require another $2.4 billion of investment in the next 10 years (MWR, 2017). In the United States, more than $400 billion of investment is needed to reinforce key seawalls and dikes by 2040 (Chinowsky & Helman, 2021), and in the Netherlands, up to €1.6 billion per year is required to maintain coastal protection against the risk of increased flooding by 2050 (Welch et al., 2017).

5. Working With Nature: An Alternative Approach?

In the face of the above pressures, EBCDs have been proposed as a potential lower-cost alternative to conventional engineering approaches (Temmerman et al., 2013). The term EBCD covers a wide variety of specific defense measures, including the use of salt-marsh vegetated wetlands in front of dikes (Mi et al., 2022; Temmerman et al., 2013), the pond-mangrove aquaculture model (Morris et al., 2020), and using salt marshes to immobilize dunes (Stoorvogel et al., 2024). While vegetation friction attenuating storm energy is a foundational mechanism in many EBCDs (Temmerman et al., 2013), their long-term performance, however, is governed by bio-geomorphic feedbacks in which vegetation slows flow, traps sediment, and progressively raises the marsh surface, thereby reinforcing plant growth and platform stability (Fagherazzi et al., 2012; Kirwan et al., 2010; Kirwan & Megonigal, 2013; Marani et al., 2011; Murray, 2023). These positive feedbacks enable restored marshes to keep pace with moderate sea-level rise and to recover after storm disturbance, making them integral to the resilience of EBCDs. Therefore, EBCDs are typically created by restoring tidal marshes or mangroves between the protected assets and the sea (Kirwan & Megonigal, 2013; Mi et al., 2025; Temmerman et al., 2013; Zhu et al., 2020), with substantial ecological benefits (Figures 4c–4p), and they are also lower in cost compared with HS (Ferrario et al., 2014). Some prior studies have shown that EBCDs can succeed in defending against coastal flooding when wide bands of vegetation are grown in the intertidal zone (Figures 4c–4p) (Mi et al., 2025; Möller et al., 2014). In such cases, EBCDs may be effective in (a) resisting typhoon-storm flooding, and (b) trapping sediments that promote salt-marsh elevation—an effect that, through the above-mentioned bio-geomorphic feedbacks, further increases coastline resilience to rising sea levels (Kirwan & Megonigal, 2013).

Using a calibrated MIKE21 hydro-sediment-dynamics model for northern shore of Hangzhou Bay, Shanghai, Mi et al. (2025) tested how groyne design influences sediment capture and marsh formation, as shown in Figures 4c–4p (Mi et al., 2025). They compared three configurations—(a) the existing seawall plus short-armed, open T-groynes ("gray"), (b) the same seawall plus long-armed, closing T-groynes ("green-gray"), and (c) a traditional hard defense with no groyne structure—and found that extending the T-arms creates a semi-enclosed cell that fostered bio-geomorphic feedbacks of intertidal salt-marsh vegetation, boosting sediment deposition by about 30%, accelerating intertidal landforms recovery by roughly 50% along northern shore of Hangzhou Bay, and transforming a conventional barrier into a novel hybrid system that delivers both reliable flood protection and rapid habitat growth.

6. When EBCDs Fail

However, despite their undoubted potential, there appear to be constraints that may prevent EBCDs from being effective in certain circumstances:

1. *Sediment-starved environments*: Global riverine sediment supplies have fallen sharply in recent decades (≈60%–70% from 1985 to 2008), largely due to upstream dam construction that has more than halved sediment delivery to the sea in major systems such as the Yellow, Nile, Yangtze, and Mississippi (Syvitski et al., 2009). For saltmarshes, this reduction constrains suspended-sediment availability and lowers vertical accretion rates, increasing the risk that relative sea-level rise outpaces platform building, with consequent edge erosion and eventual marsh drowning. Ongoing losses of adjacent intertidal flats further diminish sediment exchange and wave attenuation, compounding marsh sediment deficits; globally, intertidal area has been shrinking by about 0.55% per year and could decline by up to 77% over the next century (Murray et al., 2019). Together, these trends indicate that in persistently sediment-starved settings, salt-marsh EBCDs may not sustain their protective function over the long term without active sediment augmentation or other adaptive measures.
2. *Salt marsh squeeze*: The expansion of salt marsh seaward is restricted by erosion associated with typhoon-induced storm surges and sea level rise (Spencer et al., 2016; Syvitski et al., 2009). Moreover, marsh-edge retreat rates scale linearly with incoming wind-wave power, as first demonstrated by Marani et al. (2011) and subsequently confirmed by Leonardi et al. (2016). Meanwhile, 35,000 km of the world's coastlines are constructed with artificial seawalls and built structures, which stop salt marsh migration landward under sea level rise. The limited flexibility of HS reduces the space available for intertidal area, leading to squeezed salt marshes. The consequences are already plain: around Blackwater National Wildlife Refuge on the U.S. Atlantic coast, ~20 km^2 of high marsh have converted to open water since the 1930s (Schepers et al., 2017); in the heavily armored estuaries of south-east England roughly 4,000 m^2 of marsh vanish each year because seawalls block retreat (Hughes & Paramor, 2004); and along China's Yangtze estuary thousands of kms of

seawalls prevent landward migration, with modeling projecting a further 6%–25% loss of marsh area by 2,100 (Ge et al., 2016).

3. *Seasonal succession*: The stems of living salt marsh vegetation are effective in dissipating wave energy, even during storms (Vuik et al., 2018). However, seasonal die-back can create gaps in protection. In subtropical and temperate regions, salt marsh canopies thrive in the summer but wither in the winter, leaving minimal above-ground biomass to reduce wave impact. This seasonal vegetation loss also increases the risk of intertidal morphology erosion. For example, surveys of Cape Cod marshes (Massachusetts, USA) showed that winter die-off exposed bare sediment along 10%–90% of creek-bank edges (Holdredge et al., 2009). The loss of vegetation can be particularly damaging if storms occur during this period. The Fritchie Marsh Restoration Project in southeastern Louisiana provides the example: between 2004 and 2010, the marsh lost 3.7 km^2 (14.6%) due to Hurricane Katrina's surge, which stripped away vegetation and eroded underlying peat (Monica et al., 2013). Without the protective canopy, the shoreline became more vulnerable to subsequent flooding, accelerating erosion of the exposed intertidal morphology. While this event exceeded design expectations, it highlights the importance of two aspects of EBCDs: (a) the immediate hydraulic resistance provided by vegetation, and (b) the long-term morphological stability resulting from past bio-geomorphic interactions.
4. *Storm surge condition*: Salt marsh and mangrove belts in the intertidal zone often have large gaps between the plants, even for the densest *Spartina alterniflora* in summer. When storm-surge or spring-tide water levels rise several meters above the marsh platform, vegetation—particularly a sparse winter canopy—offers only limited wave attenuation. Under such high-water conditions, the elevation of the marsh platform itself becomes the dominant control on energy dissipation and flood prevention. Consequently, while EBCDs reduce wave energy, they cannot fully block tides and surges that exceed platform height, allowing water to penetrate the marsh and inundate the ostensibly protected hinterland. Hurricane Isabel (18–19 September 2003) demonstrated this limitation, when the surge moved up Chesapeake Bay and into tributaries such as the Chester River, funneling 2–2.5 m of water through tidal creeks, inundating freshwater marshes on Maryland's Eastern Shore, and overwhelming both natural wetlands and engineered defenses (Li et al., 2006).

In brief, salt marshes can still contribute to wave reduction in winter through the elevated tidal-flat morphology they gradually develop over time, but the effectiveness of protection is inevitably weakened when seasonal die-back leaves little above-ground vegetation. This seasonal loss matters because it reduces the system's overall buffering capacity, particularly when repeated storms occur during low-biomass periods that break stems at scale or even trigger intertidal morphology erosion, leaving fewer natural barriers to absorb wave energy. Looking ahead, continued sea-level rise and declining sediment supply raise a central uncertainty: whether salt marshes can keep building upward fast enough to avoid long-term drowning and retreat. Recognizing these changing limits is essential for designing robust EBCDs that remain reliable under both seasonal variability and escalating extremes.

7. Future Solutions Against Coastal Flooding

It is evident that some questions remain over whether EBCDs can effectively deliver reliable coastal protection at scale: Can EBCDs replace traditional engineering works? Can EBCDs be applied widely? And can dormant vegetation in the intertidal zone resist intensive winter storms? The answers to these questions have not yet been addressed, either theoretically or empirically. Especially in subtropical and/or temperate zones in winter, there may be substantial risks of replacing hard seawalls with untested EBCDs.

For example, Shanghai, China, a megacity located in the Yangtze River delta, is subject to typhoons and storms in summer and winter, respectively. While EBCDs can dissipate the wave energy generated by summer typhoons to some extent (Figures 1a, 1c, and 1e), they cannot defend against winter storm waves due to seasonal vegetation withering (Figures 1b, 1d, and 1f). Further evidences of flooding intensification attributable to the loss of ground vegetation include the catastrophic floods of Hurricane Sandy on the U.S. East Coast in October 2012 (Epiphan et al., 2025) and the North Sea flood in the Netherlands in January 1953 (Zhu et al., 2020). The wave-attenuating function of EBCDs depends on interaction with the lower water column, so when deeply submerged, vegetation becomes far less effective and wave energy can propagate inland beyond the marsh buffer. Prolonged inundation and strong wave action may even erode the marsh substrate, undermining both structural integrity and long-term resilience. Thus, although EBCDs are valuable as part of an integrated coastal defense system—especially for frequent, low-to-moderate events—they should not be relied upon as standalone barriers in extreme conditions. For example, during Typhoon Winnie in 1997 the maximum water level reached 5.99 m (MWR, 2017), which

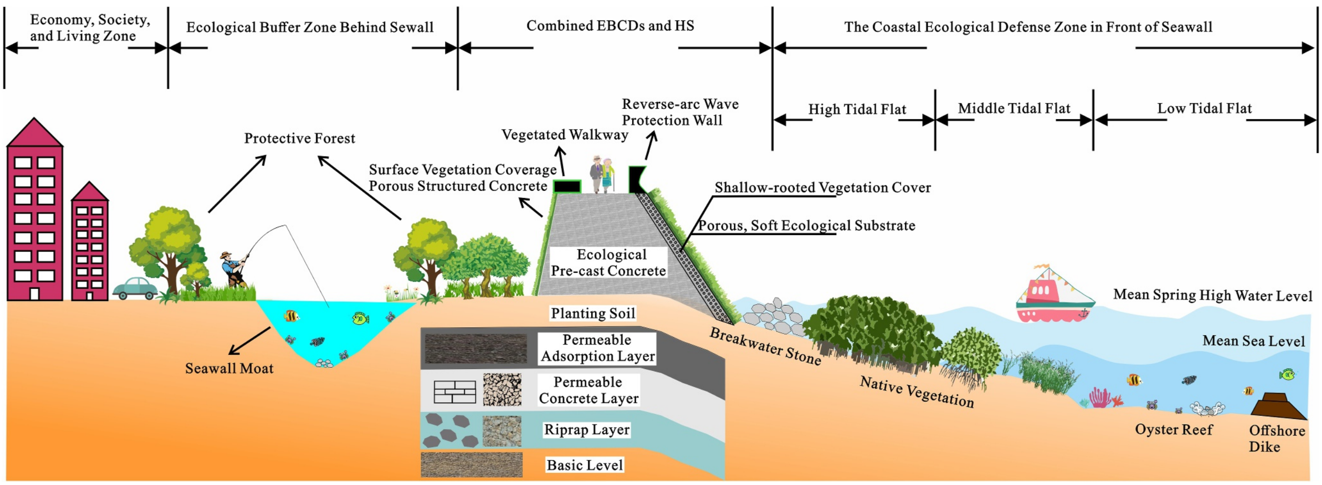

Figure 5. Combined ecological defense and tidal coastal hazard system (HS) and ecosystem-based coastal defense (EBCDs) design, illustrating the integration of various ecological and structural measures for coastal protection (Revision after Dai and Ge, 2022). Note that the illustration of oyster reef, coral reef, salt marsh, and mangrove should be combined based on various adapted climate zones.

would have inundated the entire Shanghai urban area (average elevation 2–4 m above mean sea level) without the support of engineered seawalls and other hard structures. Similarly, tropical mangroves play an important role in defending against super-cyclone and cyclone-induced wind waves in the Ganges-Brahmaputra-Meghna delta (Karim & Mimura, 2008). Nevertheless, high water levels generated by high tide and storm surges will penetrate the gaps between tree stems and cause flooding of the hinterland, as occurred during the super-cyclone Sidr in 2007, which claimed 3,500 lives (Karim & Mimura, 2008).

In summary, all relevant factors, including local economic conditions, sediment supply, space availability, local salt marsh species, and future flooding risks, must be considered comprehensively and with great care to scientifically design hard seawalls, softer EBCDs, and a combination thereof. Unfortunately, the current state-of-the-art is not yet sufficiently developed to enable strong advocation of EBCDs as an outright replacement for HS, especially in subtropical and temperate coastal zones. In tropical areas, coastal protection employing only EBCD is especially unfavorable for low-lying areas that experience elevated water levels through tidal and/or tropical cyclone-induced storm surges. By contrast, HS can effectively protect against flooding, albeit at the risk of harming local ecosystem health and at a substantial economic cost. Nevertheless, HS are essential for adequate flood defense when: (a) the coastline is affected by high wave energy where vegetation cannot grow, such as in the north bank of Hangzhou Bay (Figure 4) and the coastal area of Japan (Figures 1a and 1b); (b) the lasting recession of estuarine and coastal area with limited sediment supply, such as in the southern Mekong delta (Welch et al., 2017), and (c) in locations where there are extensive infrastructure and other high-value assets.

It follows that using EBCDs as a supplemental measure to HS in a hybrid approach may offer an attractive proposition (Sutton-Grier et al., 2015). Examples of this kind of approach include the Dutch "double dike system," which seeks to nourish salt marsh in polder lands by opening a gap in the outer dike, which allows the benefits of developing the foreshore vegetation while including a second dike to defend against extreme coastal flooding (Zhu et al., 2020). In a similar vein, combining engineering and ecological measures, including the use of salt marshes or mangrove in front of the seawall to promote sedimentation and reduce wave energy, and the planting of shrubbery behind the seawall to stabilize the seawall, maximizes the protective capacity of HS (Figure 5). Furthermore, there is potential to reduce the negative ecological impacts of HS by adopting more environment-friendly innovative HS that apply new technology. For example, advanced seawalls that adjust automatically according to the predicted storm intensity by adapting their materials from concrete during storms to porous materials after the storm recedes would help to restore intertidal ecosystem connectivity (Hosseinzadeh et al., 2022).

Overall, there is an urgent need to develop new intelligent HS and incorporate these together with EBCDs in more sophisticated designs that are based on local climate and vegetation characteristics. There is need for a greater focus on nature-positive solutions that not only protect against floods and erosion, but also enhance biodiversity and ecosystem services. Moreover, the integration of smart technologies—including digital twins that produce dynamic virtual replicas of both living-shoreline habitats and engineered structures, together with real-time IoT sensor networks, machine-learning algorithms, and predictive analytics—is rapidly transforming how we design, monitoring, and adaptive management of EBCD and hybrid coastal-defense solutions (Cavanaugh et al., 2025). In this context, coastal protection must be viewed as a shared responsibility across stakeholders, with more emphasis on governance frameworks that effectively integrate science, policy, and local knowledge. There should be also a growing recognition of the need for global cooperation in addressing transboundary coastal risks, particularly in the face of global climate challenges.

8. Conclusions

This study reviewed the historical transition from traditional HS to EBCDs, reflecting a global shift toward sustainable and adaptive flood protection strategies coping with rising sea levels and intensifying storms. Our findings highlight that while EBCDs offer numerous ecological and social benefits, such as biodiversity conservation and carbon sequestration, their effectiveness as flood defenses is subject to several limitations. EBCDs, particularly those relying on vegetation such as salt marshes and mangroves, demonstrate wave attenuation and sediment stabilization, but their capacity to withstand extreme storm conditions, especially during winter or in sediment-starved environments, remains uncertain. Furthermore, seasonal changes in vegetation biomass and the limitations imposed by coastal infrastructure further constrain the flood defense potential of EBCDs in highly urbanized regions. This study offers valuable insights into the dynamic interaction between ecological and engineering flood defenses, proposing that EBCDs, while promising, are not universally applicable as replacements for HS, particularly in subtropical and temperate regions vulnerable to seasonal and extreme storm surges. Our analysis suggests that the most effective flood defense systems may involve hybrid approaches, combining the benefits of EBCDs with the robustness of HS, thereby integrating both nature-based solutions and traditional engineering to enhance coastal resilience. However, significant research gaps remain in understanding the long-term stability and performance of EBCDs under extreme climate conditions. Future research should focus on improving the predictability and scalability of EBCDs, particularly in areas with variable sediment supply and high storm surge risks. Additionally, the development of advanced technologies, such as smart seawalls and integrated monitoring systems, could provide innovative solutions to enhance the synergy between natural and engineered systems.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

This study did not use or generate new data or code. Literature statistics sourced from the Web of Science database are available in Zhang (2026), and the analysis was conducted using VOSviewer software (van Eck and Waltman, 2010). For the numerical simulation method and scenario setup of coastal tidal flat erosion and deposition in Figure 4, refer to Mi et al. (2025). The global seasonal coastal NDVI (Normalized Difference Vegetation Index) calculations used data referenced to Didan (2015).

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