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Review

Challenges and lessons learned from global coastal erosion protection strategies

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SUMMARY

Coastal erosion is a significant global threat to coastal communities, ecosystems, and infrastructure. Despite various global coastal management strategies and policies and the best efforts to combat coastal erosion, challenges persist. This study reviews global literature on coastal erosion management strategies, highlighting lessons learned and challenges encountered in implementation from past experiences. Findings indicate that global coastal erosion is increasing, with seawalls and hard engineering declining and nature-based solutions and ecological engineering being developed. However, balancing coastal protection with environmental and socioeconomic impacts remains a global challenge, as static coastal protections struggle to adapt to dynamic climate change scenarios. Thus, rising sea levels and other causes of coastal erosion should be prioritized alongside holistic coastal management approaches that consider recession, land use, infrastructure, community well-being, and resilience. This study underscores the need collaborative efforts among stakeholders to develop sustainable coastal protection solutions to address rising sea levels and coastal erosion.

INTRODUCTION

Throughout the history of coastal protection, coastal managers and regulators have been challenged to establish optimal solutions to manage coastal erosion.[1,2] Scientists, engineers and managers are still on a mission for a long-term solution to coastal erosion that has less negative consequences. Coastal erosion, defined as the net removal of sediments or bedrock from the beach, shoreline, or dune material as a result of natural coastal processes or human-induced influence, poses a significant threat to coastal communities, ecosystems, and infrastructure worldwide.[3,4] The impacts include the consequent loss of land, valuable property, and coastal ecosystems like marshes, oyster reefs, and nesting grounds,[2,5] prompting the development of diverse coastal erosion management strategies.

Various coastal management strategies have been implemented globally, including the accommodate, protect, and retreat strategies,[6–8] the United Kingdom (UK), Shoreline Management Plans (SMPs)—advance the line, hold the line, managed retreat, and no active intervention approaches,[9] and various coastal management strategies in countries like Netherlands,[10–12] and coastal erosion decrees in the United States. These coastal management strategies, however different, have the prime objective provide effective coastal protection while creating a balance between coastal development and protection, and environmental and socioeconomic sustainability. For instance, SMPs are non-statutory policy documents used for planning shoreline protection usually over short (0–20 years), medium (20–50 years), and long-term periods (50–100 years), which have been internationally considered as model coastal management strategies.[9,13] Similarly, in the United States, various coastal erosion designations such as the Florida Coastal Management Plans have been developed for beach management.[14]

Prior to the 1950s, the main purpose of coastal protection was to safeguard vulnerable structures without due consideration to the environmental aspects. This sparked a heated public discussion about whether the high cost of hard engineering and the associated environmental consequences were justified,[2] leading to the introduction of soft engineering in the 1960s as a preference over hard approaches.[2]

Common coastal protection infrastructure categories include static hard engineering (seawalls, groynes, breakwaters, and jetties), soft engineering (dredging, beach nourishment, dune rehabilitation, and wetland restoration) and managed retreat/coastal realignment such as coastal setbacks.[1,2,14] However, it must be emphasized that the implementation of coastal infrastructure typologies to protect beaches varies because of many factors such as geographic region, level of technological development, financial constraints, and governance.[7,8] Due to

Figure 1. Coastal protection structures located around the globe
(A) Breakwaters at Sally West Africa.[6]
(B) Groins at Southern California (source: Orange County Register).
(C) Seawall at Male Island, Japan (www.mofa.go.jp).
(D) Groins at Pawleys Island, USA.[32]
(E) Jetties at Columbian River mouth.
(F) Seawall in Netherlands (https://interestingengineering.com).

these differences, the implementation of coastal defenses varies greatly across the globe.

One of the significant challenges is to identify global locations where different types of coastal protection were implemented. Fortunately, this has been made possible through the dual use of artificial intelligence and websites like the Open Street Map (https://www.openstreetmap.org), where volunteers have added information on coastal protection strategies. Developing a repository of coastal protection structures will therefore be significant for stakeholders that could help to implement mitigation measures and improve the implementation of current and future coastal defenses. An interactive database of coastal protection can be an invaluable tool for stakeholders in improving future coastal protection efforts. This can be achieved by identifying best practices, learning from failures, evaluating long-term effectiveness, knowledge sharing and informing policy planning and review to make future coastal protection efforts more effective and sustainable.

Implementing a protection structure is however mostly dependent on what the hazard is and less on the entire ecosystem. In some areas, hybrid engineering is used to deliver protection and ecological benefits by integrating gray, natural and nature-based solutions (NbS).[15–17] Therefore, it is essential to implement coastal infrastructure options based on their value to provide protection, adapt to sea-level rise, impacts on ecosystems, and the different subtypes of adaptation to different regions.[18] By highlighting protection and ecosystem functions, researchers claim that natural habitats can complement engineered infrastructure to provide cost-effective protection while also increasing coastal resilience.[19–22]

The implementation of coastal protection is also influenced by the state of economic development, specifically the differences between developed and developing countries. Many countries require skilled human capital with the necessary engineering know-how to develop effective and efficient coastal erosion management projects. Since the decision regarding whether to implement hard or soft coastal protection or to use managed retreat is the responsibility of coastal managers and regulators,[2,14,23] it is equally essential that the human capital is equipped with the right knowledge and skills to develop and implement sustainable coastal protection solutions.

Hard-engineered coastal erosion protection structures (Figure 1) have several consequences.[24] Scholarly evidence indicates that in the endeavor to provide intended coastal protection, hard-engineered infrastructure (e.g., seawalls, jetties, and groynes), may produce unintended negative effects at different geographic scales.[6,25–28] Case examples of environmental pitfalls of hard structures include failed coastal stabilization on beaches at Kwazulu Natal, South Africa,[28] Tweed River Mouth, Gold Coast, Australia,[26] the Caribbean Coast,[25] and Suffolk

Figure 2. Some soft engineering strategies and natural solutions

(A) Dune vegetation at the Cape Cod area of Massachusetts USA (https://www.123rf.com/).

(B) Managed Retreat at Alkborough on the Humber Estuary in Eastern England (https://www.agefotostock.com/age/en/details-photo/).

(C) Sand dune rehabilitation, Mauritania.[6]

(D) Beach Nourishment at Manila Baywalk, Philippines (https://mail.pinoybuilders.ph/dolomite-sand-manila-bay/).

(E) Dune restoration, Senegal.[6]

and Norfolk in the UK,[29] impacts of the submerged breakwater in Thailand,[30] and impacts of breakwaters, jetties and groynes in Mexico,[25,31] just to mention a few examples.

Other negative setbacks for hard engineering include financial constraints due to high costs,[1,2,33] conflicts of engineering interventions and environmental conservation,[1] lack of information on stakeholder engagement,[2] difficulties in predicting the long-term effectiveness of implemented measures,[5] and impact on river, estuarine and deltaic environments.[26] In Ghana, for instance, the construction of the Ada Sea Defense Project near the mouth of the Volta Estuary[34,35] may probably be the causative factor for the drastic changes that occurred at the mouth of the Volta Estuary, which has also seen increased erosion and wave overtopping.[35] In addition, the cessation of beach nourishment at Ada likely jeopardized design performance and contributed to rapid beach deterioration.

Soft engineering strategies (e.g., Figure 2), principally beach nourishment, emerged in the 1920s and are gradually succeeding hard engineering. Beach nourishments are installed either as standalone beach nourishments[1,19,36–38] or alongside hard defenses, e.g., nourishing degraded beaches at seawalls or groyne fields.[39–42] Other soft measures include using shingles in the UK, bamboo fences as coastal protection in Vietnam,[43] or maintaining tropical beaches with seagrass and algae.[44] Nevertheless, like with gray infrastructure, solutions like beach nourishment and dredging are also bursting with many negative consequences on health, ecological diversity, and microfauna[45,46]—the materials used for nourishment could be dangerous. For instance, the dolomite sand material used for the nourishment of Manila Bay created a debate. Although no major abnormalities are noticed by tourists,[47] symptoms such as cough, phlegms, productive cough, and shortness of breath have been reported among exposed workers utilizing dolomite.

Over the past 50 years, substantial progress has been made in integrating hard and soft approaches, as well as leveraging nature and NbS (Figure 2). The goal of engineering or building with nature and nature-based infrastructure is to balance coastal protection and environmental (ecosystem) services.[1,2,16,33,48,49] Nevertheless, many problems are posed by ecological engineering. For instance, dredging and beach nourishment may disrupt ecosystems causing impacts on biodiversity.[19] In addition, building with nature is not standardized and there are many gaps in knowledge, governance, and technological and engineering know-how.[7,8] Until recently, there was very little information available on the efficacy of natural capital, which caused investor and public skepticism. In this context, understanding knowledge gaps and stakeholder preferences (e.g., Mallette et al.[50]) has become a critical global factor for coastal protection.

Many lessons may be drawn from the challenges encountered in coastal erosion management globally, including successful and failed strategies. Understanding historical perspectives is crucial for avoiding past mistakes, ensuring sustainable coastal protection and creating resilient coastal zones. Based on these lessons, stakeholders can collaboratively develop sustainable solutions adapted to their geographical contexts and protect vulnerable coastal regions in the face of increasing sea-level rise and human anthropogenic activities. While coastal erosion is a well-researched topic, synthesizing data and strategies from various regions worldwide may provide fresh insights and comparative analyses contribute to the novelty of this research. In addition, research uniqueness also arises from the interdisciplinarity that emerges from integrating insights from environmental science, engineering, economics, and social sciences perspectives that could contribute to holistic solutions that consider both natural processes and human behaviors.

To guide this scoping inquiry, the central question was how to determine what challenges and lessons may be learned from the global coastal erosion protection management since the 1970s. The mid-20th century is of particular interest because it marked the diversification of shoreline protection approaches such as the transitions from shoreline armoring using hard engineering to soft engineering using beach nourishment.[2] It was also an important era during which important coastal management agencies and policies emerged. The findings will provide valuable information for coastal managers, regulators, and researchers seeking to better understand the intricacies of coastal erosion management and adapt adaptation methodologies to specific geographic settings. The idea is that in order to influence or revise coastal erosion management policies at local levels, it is necessary to understand and reference the approaches, challenges, and lessons learned from different global contexts.

The major research limitations to this study include the following. (1) Data availability and quality constraints, especially from less-studied regions or absent historical records. (2) Regional variability since coastal erosion is influenced by a myriad of factors including geomorphology, climate, and human activities, leading to significant regional variability. Therefore, generalizing findings or strategies from one region to another without considering these variations could limit the applicability of the research. (3) Technological constraints due to differences in technological gaps among different regions. (4) Temporal dynamics that dictate coastal environments to change continuously over different temporal scales. Thus, the research may not sufficiently capture long-term trends or account for future uncertainties such as climate change impacts. (5) Social and economic factors involved in implementing erosion protection strategies that are often complex. These are relevant areas that are required in the current dispensation. The research may overlook the socio-economic drivers of coastal development, such as issues of equity, governance, and stakeholder engagement.

METHODOLOGY

Literature reviews comprise different methodological approaches. The present study adopted the "describe" typology of literature reviews.[51] Descriptive reviews examine and update the existing literature based on a given research question or subject area.[51] In this regard, a "scoping review"[52,53] provided the best opportunity to establish a comprehensive body of literature and insights from global coastal erosion management.

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol.[54] PRISMA is a methodology that provides a checklist necessary to perform and report systematic reviews and meta-analyses. The process (Figure 3) helps researchers adhere to standard protocol during data search strategy, analysis, and reporting systematic reviews.[54] Documents were searched from Scopus and Journal Storage (JSTOR) databases.

It should be mentioned that although 462 documents were finally selected for the study, the study recognizes the importance of the vast literature excluded and their relevance in coastal protection literature.

Data search strategy

In this study, the Scopus database and Journal Storage (JSTOR) were searched for articles on coastal erosion management, challenges, solutions and lessons learnt from 1970 to 2023 (July 02: 15:00 GMT). In general, most of the documents from JSTOR were Scopus-indexed. However, some important documents were manually searched. The initial search identified 5,816 documents. By applying the language filters, 214 non-English documents comprising French (70), Chinese (50), Portuguese (48), Spanish (43), and Italian (3) were screened out, leaving a total of 5,602 documents. Subsequently, three Scopus database filters were applied to exclude book chapters, conference papers and conference reviews. Although book chapters and conference papers can provide valuable information, it was decided to analyze only peer-reviewed publications. The final search query was:

TITLE-ABS-KEY (coastal AND erosion AND (management OR challenges OR solutions OR lessons)) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re") AND (LIMIT-TO (LANGUAGE, "English")).

The results produced 3,919 documents, comprising 3,662 research articles (ar) and 257 review papers (re). These documents were exported to Microsoft Excel for detailed content analysis of the "title," "abstract," and "keywords" to test their eligibility for inclusion in the study. In addition, 78 documents were identified through the JSTOR to capture important documents that were not Scopus-indexed.

Additionally, geographic location data of coastal adaptation solutions like groynes, jetties/breakwaters, and dykes/seawalls were identified and retrieved from OpenStreetMap along the global coastal areas. OpenStreetMap (OSM) is a free, open geographic database updated and maintained by a community of volunteers via open collaboration. Contributors collect data from surveys, trace from aerial imagery, and also import from other freely licensed geodata sources. Therefore, the data may be unavailable in areas where the community has not uploaded such data onto the map.

Synthesis of title, abstract, and keywords

A mechanism was developed to test the "title," "abstract," and "keywords" columns for the terms "coastal erosion," "coastal management strategy," "coastal protection," or "nature-based

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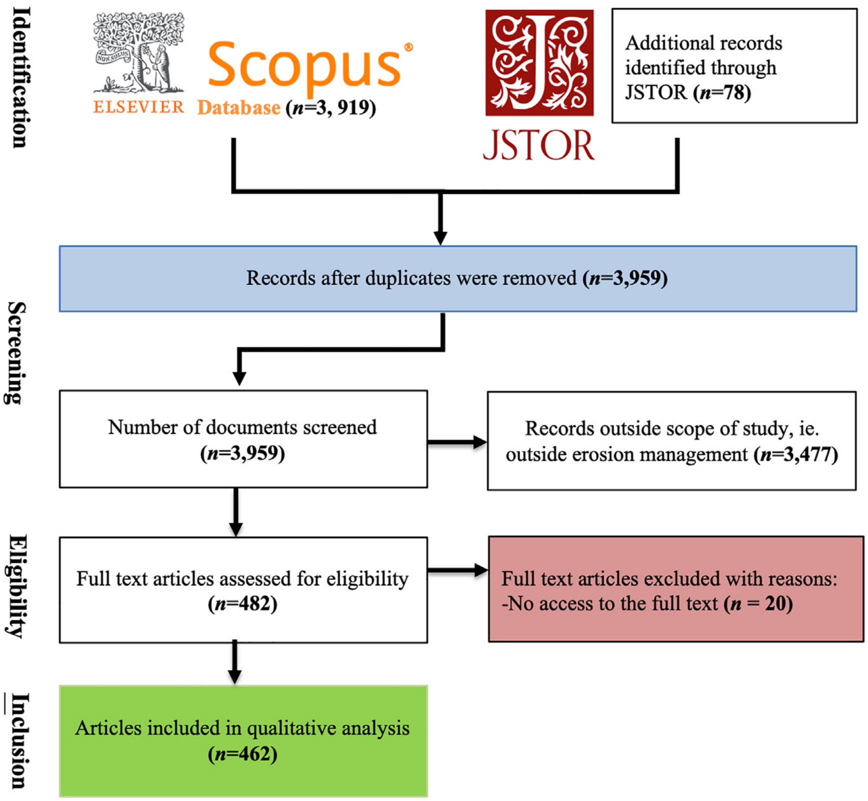

Figure 3. PRISMA workflow showing the stages followed in the literature inclusion

solutions," "green infrastructure," "gray infrastructure," or "hybrid infrastructure" with the objective as follows: (1) include papers only focusing on "coastal erosion management" approaches or "coastal infrastructure" typologies and their subtypes; (2) subclass the findings into "management approaches," "challenges," or "lessons learnt"; and (3) assign additional categorization for each document like country, subtype of infrastructure, e.g., hard or soft engineering, or further classify challenges and lessons learned. Finally, 572 documents passed the eligibility test. However, 370 documents were subsequently excluded from the final analysis with valid reasons such as no access to full text and similar studies. In total, 462 documents were analyzed and used in the final qualitative assessment. A conscious effort was made to ensure that the documents captured all the key issues to satisfy the objective of the study.

Data quality assessment: Inclusion-exclusion criteria

To guarantee the quality, the abstracts from the identified literature were exhaustively synthesized for relevance to the topic, following the identification, screening, eligibility, and inclusion of phrases consistent with the PRISMA framework. Furthermore, the inclusion criteria meant papers were peer-reviewed papers written in the English language. Articles that fell outside the scope of the study were excluded.

Validation of literature

In this study, expert input was sought from six experts in coastal management and engineering to provide their expert opinions on the relevance of a scoping review of this nature to global coastal erosion management. Expert input enriches the quality, depth, and credibility of identified literature, ensuring accuracy, relevance, and up-to-dateness. It also served to minimize bias and misinterpretation in the review process. Overall, this served to improve the robustness of the data and methodology used in the study and its usefulness in influencing policy at different global scales.

Classification of documents by source

Most published literature was obtained from four journals. The journal-wise classification (Figure 4), indicates that the Journal of Coastal Research leads other journals in terms of coastal protection literature followed by the Journals of Coastal Engineering and Journal of Ocean and Coastal Management.

Resource availability

The data used in this manuscript have been deposited at https://doi.org/10.5281/zenodo.10574878 and are publicly available as of the date of publication.

RESULTS

Coastal management literature and implementation concentrated in the global north countries

The global literature production (Figure 5) is greatly skewed to the global north. Based on the analysis, the United States dominate the global coastal management literature production followed by the UK, Australia, and the European States like Portugal, Italy, and Netherlands, as well as China and India. These countries lead coastal management literature in terms of hard, soft, hybrid, and managed realignment approaches. They also trend in terms of coastal governance, research innovations, and subclassification of coastal infrastructure categories. For instance, managed realignment has been used extensively to accommodate salt marshes in the UK[55] and beach nourishment has been used extensively to improve the stability of the Portuguese coastline.[56,57]

The dominant gray infrastructure was seawalls, breakwaters, and groynes. The major green infrastructure is mangroves, salt marshes, and coral reefs. The major hybrid infrastructure is living shorelines, groynes with nourishment, and vegetated revetments and rock sills. Several studies have been conducted to review NbS, particularly those that appraised the effectiveness of NbS at different spatial scales. For instance, the performance of NbS for coastal protection in shallow, biogenic ecosystems[58] and local perceptions of their effectiveness.[59]

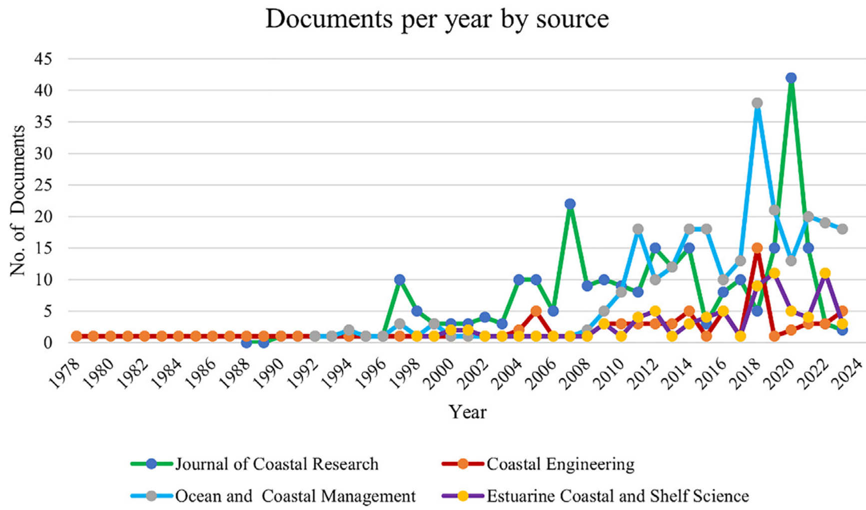

Figure 4. Journal-wise classification of literature

Articles that are based on monitoring of coastal defenses mostly originated from the United States (n = 88), UK (n = 80), Australia (n = 38), Netherlands (n = 26), and Italy (n = 27). Despite this presentation, it should be noted that, while some regions have coastal defenses installed, this information has not been published through peer review processes. In West Africa, for instance, while sea defenses were installed, the information on coastal protection structure has not been published in research journals. In most cases (Figure 3), the information is mostly available in reports that are not published in peer-reviewed journals. Figure 4 represents hard coastal infrastructures protections from OSM, such as groynes, dykes as well as breakwaters along the coastlines of the globe. The results of total structures (Figure 4) reveal that most of the defense structures are located in Western Europe (France ~1,048; Italy~1,055; Netherlands~3,319; UK~3,576, and Germany~4,157) east Asia (Japan~3,047 and the Philippines ~1,117), and US of America (4,679). Our assessment reveals that many countries do not have their coastal protection structures on the map that creates a research gap in getting this information. Among the various defenses, groynes are predominantly used.

The results of this study indicate that the most popular coastal protection structures used globally for erosion adaptation purposes are the groynes, sea walls/dykes and breakwaters/jetties. The top 5 countries with the highest number of dyke structures include North Korea (200), India (356), Germany (661), USA (821), and the Philippines (1,031). Dykes/sea walls are found in over 52 countries. The global south has the lowest structures while Europe and North America have the highest quantities of infrastructure. The distribution of groynes by country on the other hand reveals the dominance of these structures in Europe compared to the rest of the world. Over 60 countries use this type of structure for coastal protection and the top six countries include Italy (with 579), Denmark (622), France (769), USA (1,452), UK (3,027), Netherlands (3,084), and Germany (3,201 groyne structures). Breakwaters or jetties by country are the most widely used adaptation strategy within over 93 countries. The six highest countries include Norway (323), UK (408), Italy (411), China (442), USA (2,406), and Japan (2,843 breakwater structures). The global locations of coastal infrastructure are also clearly illustrated by location (Figure 6), and by country index (Figure 7).

Shifting from hard to soft solutions

Figure 8 illustrates the year-wise distribution of literature from 1970 to 2023. The analysis of the findings from the literature reveals fewer publications on coastal erosion management in the period from the 1970s–1980s. However, there was a gradual increase between 1980 and 1990. Subsequently, there was a surge in global literature production beginning in 2000.

Table 1 shows all coastal erosion management approaches that were categorized into 10-year epochs from 1970. The research findings were categorized according to Malekpour et al.[60] based on the engineering types, coastal protection infrastructure types and dominant strategy used. It is noticed that hard engineering was the exclusive strategy between 1970 and 1999 though at some point some soft engineering was also used.

Global trends in coastal erosion management approaches (Figure 9) indicate decline of hard engineering solutions that had historically dominated coastal protection. After the 70s, the global focus changed sharply from hard engineering (gray infrastructure) toward soft engineering and hybrid (integrated and nature-based) engineering.[1,2]

The trend of used types of infrastructure (Figure 9) is mainly influenced by the implementation in the United States, UK, and Australia. Trends in developing countries follow a similar trend, albeit, at a slow pace. It should therefore be clarified that transitions from hard to soft engineering approaches may have evolved differently in different other regions, both for the implementation of hard and soft engineering. This is true for developing countries where technology, knowledge, and expertise for dredging and beach nourishment were hindered by factors such as the non-availability of expert engineers and the cost and unavailability of dredgers. For instance, most beach nourishment projects in West Africa were discontinued due to the high capital costs of periodic beach replenishment.[6] Similarly, whereas hard engineering in developed nations peaked in the early and mid-20th Century, coastal gray infrastructure in Ghana (and West Africa) peaked between 2000 and 2020. This period saw the implementation of major seawalls, groynes, and revetments.

Before 1950, coastal erosion management had prevailed for many centuries. The dawn of the 20th century saw many governments invest heavily in large-scale erosion and flood control projects, including dams, levees, and dykes to protect coastal and riverine areas. Scholarly findings reveal that coastal interventions

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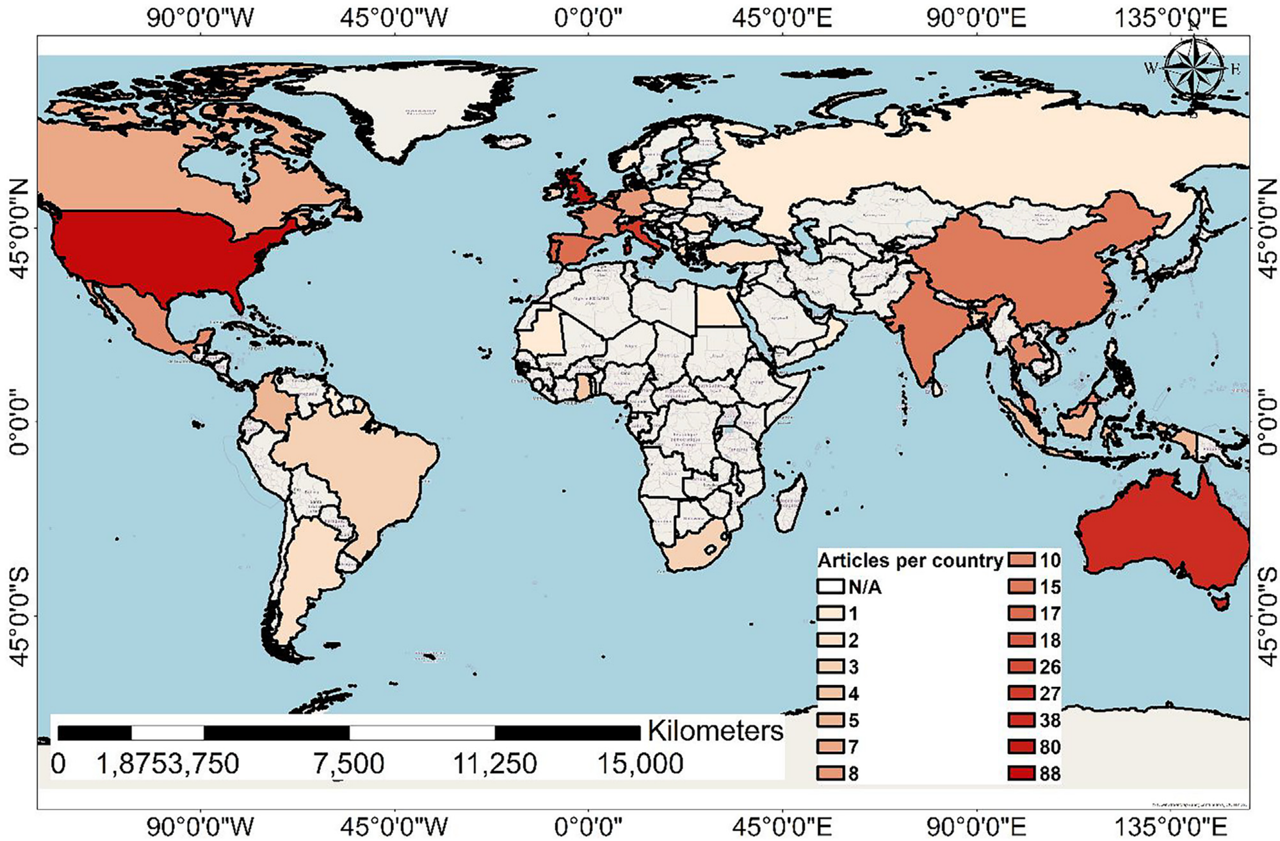

Figure 5. Global distribution of coastal erosion management literature

were hastily and politically implemented, with little knowledge of the environmental and socioeconomic implications.[2,23] In most cases, the emplacement of coastal armoring on an eroding shoreline increased erosion on adjacent beaches. Nevertheless, the lack of data to prove the existence of active erosion, e.g., in front of seawalls arguably contributed to ignorance.[2,83,93,94]

Following the first nourishment project in the US in 1922,[38] beach nourishment projects mushroomed in the US between 1922 and 1952, albeit without proper planning and design.[38] However, post-1952, beach nourishment design in the US and Europe significantly improved and evolved into a highly technical, scientific, and engineering discipline (Davison et al., 1992[38]). Pinto et al.[56] provided an overview of beach nourishment in Portugal from 1950 to 2017 with the objectives of mitigation of erosion and increasing coastline stability, mostly using sediment derived from dredging operations. In their research, the authors also highlight a major shift from hard to soft protection aimed at enhancing regional sediment management. However, the poor performance of beach nourishments between the 1950s and 1970 was attributed to the borrowing of beach material from adjacent surrounding bays and lagoons, which naturally contained large percentages of fine-grained material. However, after the 1970s, beach nourishment projects mostly relied on offshore borrow sites that had comparable grain sizes while also being less invasive to marine ecosystems.[38] In this study, analysis was also carried out cognizant that, beach nourishments are periodic and therefore bound by time and country (e.g., Alves et al.[6] and Pinto et al.[56]). Alves et al.[6] point out that most beach nourishments in Gambia and Nigeria were discontinued over time due to the high costs of periodic beach nourishments.

The mid-20th century (1950–2000) saw a transition from hard to soft approaches as governments grew more conscious of the drawbacks of coastal armoring. Beach nourishment superseded hard engineering approaches and the "Sand Engine" in Netherlands represents the epitome of the paradigm shift in coastal erosion (and coastal flooding) management.[1,36] Seawalls designed during the Victorian era were modified to include stepped seawalls. Similarly, groynes were modified with T, Y and L shapes.[1] Between 1970 and 1992, coastal administrations were more aware of the underlying causes of coastal erosion and avoided using hard engineering.[38]

Between 1980 and 1989, Kraus[64] found that fewer scientific works focused on the effect of seawalls on beaches. The fundamental questions during this period quizzed the installation of seawalls on beaches[2] or the coexistence of seawalls and beaches.[23] Pilkey and Wright[2] studied the dry beach width between stabilized and un-stabilized beaches and observed that the dry beach width in front of seawalls gradually became narrower in comparison to unprotected beaches.[2] It was established that in the absence of beach replenishment, shorelines protected by seawalls had greater levels of beach erosion,

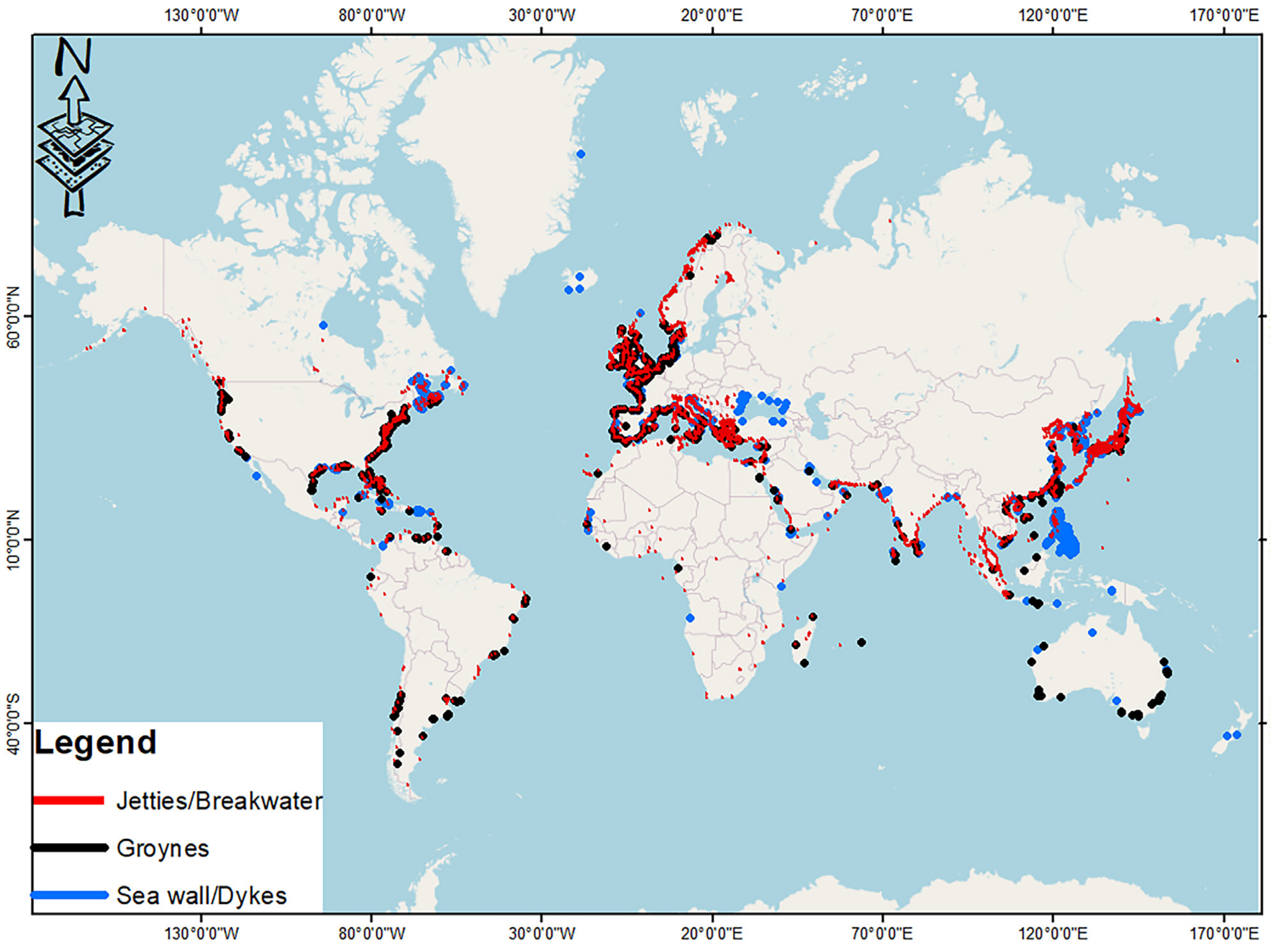

Figure 6. Global locations of hard-engineered coastal management strategies from OpenStreetMaps

resulting in worse beach quality.[2,82] By the late 1980s, the US was the leader in beach nourishment, with approximately 155 beaches nourished across different States. During this period, many developing nations (the Soviet Union, Namibia, South Africa, Brazil, Singapore, and Nigeria) approved and implemented beach nourishment projects.[38]

In the last decade of the twentieth century, beach nourishment continued to dominate coastal protection. Dune systems and beach nourishment dominated coastal erosion and flood protection in Netherlands.[10–12] When deciding on the sort of coastal defenses, more care was taken, taking into account factors such as cost and benefits, environmental impacts, and expected performance.[5,33] For instance, general conclusions of the comparisons of seaward coastal protection strategies against beach nourishment and other approaches in Netherlands indicate that (1) beach nourishment can be implemented virtually everywhere, providing an opportunity to spread the costs; (2) repeated nourishment can be at least as economical as seaward structures, and (3) it is virtually the only structural solution to compensate for the sand deficiency along the coast.[69] On the other hand, despite the advantage of providing long-term protection, hard structural protection disturbed coastal processes and caused sediment transport disturbances and starvation to downstream beaches.[69] Despite this, nourished beaches (1) typically erode much faster, about 1.5–12 times faster than natural beaches and (2) compared to natural beaches, they typically do not recover from storm events.[38]

The 21st century witnessed a fundamental transition from reactive to proactive approaches. Coastal protection strategies increasingly focus on building resilient infrastructure that can adapt to changing environmental conditions using nature and NbS. Evidently, many governments have come to understand and commit to contributing to the global drive toward climate adaptation through green infrastructure and NbS. Stive et al.[36] highlighted the sand engine as an innovative soft engineering intervention to address coastal flooding in Netherlands, emphasizing the need for a paradigm shift from working against nature to working with nature. According to preliminary model results, massive beach nourishment contributed to the widening of the beach along an 8 km stretch of the coastline and a net beach gain of 200 ha over 20 years. Nevertheless, working with nature has many challenges that necessitate adaptive modifications to adapt to a dynamically changing coastal environment.[24,78] In addition, green infrastructures existence is variable based on

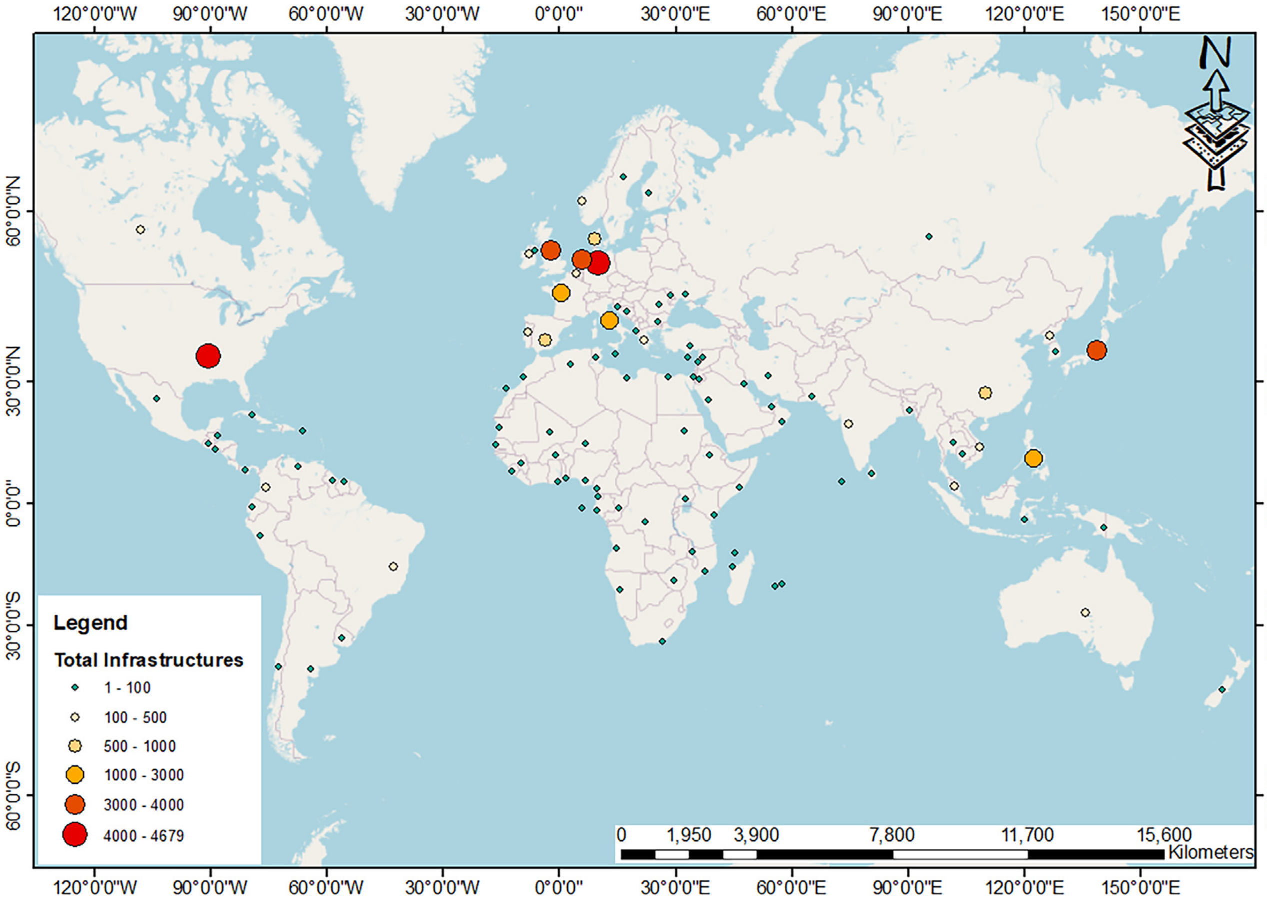

Figure 7. Distribution of total coastal defense infrastructures by country

geography and environmental conditions such as climate, oceanographic conditions (salinity, tidal ranges), nutrient levels, and temperature. For instance, there are more mangroves along the South Atlantic coasts in West and South Africa than along the European Atlantic coasts. This picture also applies to other ecosystems like coral reefs and salt marshes.

From 2010 to 2023, there was an unprecedented drive toward nature and NbS. From a total of 59 NbS case studies associated with flooding, erosion and biodiversity loss,[95] NbS implementation since the 1990s rapidly increased between 2005 and 2015. Most of the case studies are hybrid solutions employing wetlands, predominantly located in the UK and Netherlands. By combining natural infrastructure with hard solutions—e.g., mangroves or saltmarshes with rock sills[17]— hybrid infrastructure minimizes the setbacks perceived when natural habitats are used alone. Many articles have been published that investigate the potential benefits of natural capital (tidal marshes, beaches and barrier islands, biogenic reefs, and mangroves) for climate change adaptation (e.g., Powell et al.,[15] Safford et al.,[22] Narayan et al.,[96] and Spalding et al.[97]). Great emphasis was placed on green infrastructure, hybrid (nature-based) solutions, and managed retreat strategies. In the United States, for instance, the President's Climate Action Plan underscored the importance of climate-resilient infrastructure[22] and proposed the preservation of forests and wetlands and alternative fuels to reduce CO_2 emissions.

Many other scholarly articles focused on the effectiveness of green versus gray infrastructure,[21,22,98–100] or investigating the potentials of investments in nature and nature-based infrastructure, but also communicating its ability to improve coastal resilience.[15,20,90,101] There has also been increasing support for living shorelines—a hybrid infrastructure type that offers multiple lines of defense and improves coastal resilience,[22,102,103] as well as climate mitigation benefits through blue carbon.[55,103] Living Shorelines Protection Act has also achieved significant policy support in many States in the United States like Maryland, Virginia, North Carolina, New Jersey, New York, Connecticut, Rhode Island, and Mississippi.[17] Assessment of the nature-based coastal defense strategy for Australia indicates that in addition to effective coastal protection, hybrid infrastructure also provides several co-benefits that contribute to national biodiversity, water quality and climate mitigation.[55]

In this period, there is a determined global pressure for innovative coastal erosion management strategies that use nature and NbS to respond to the intensification of coastal hazards and climate-induced coastal change persistence.[13,104] As a result, there has been more substantial investigation of the effectiveness of nature-based coastal protection for both erosion

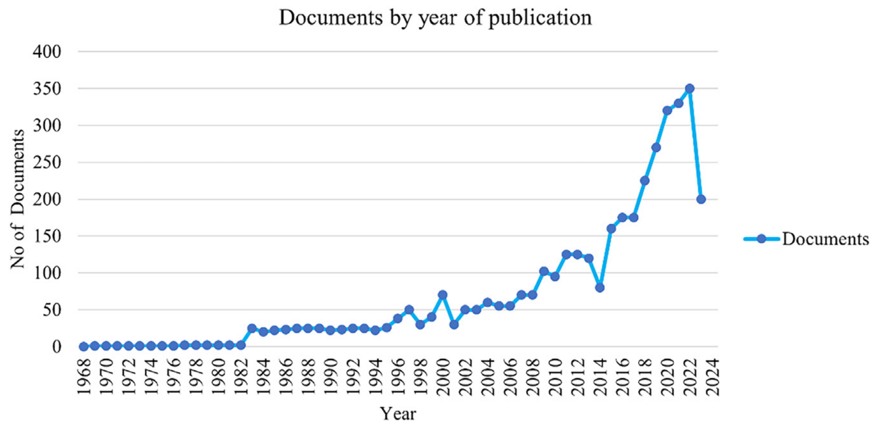

Figure 8. Year-wise trend of scholarly articles on coastal protection

protection and ecosystem benefits.[105] Therefore, holistic planning and adaptive coastal management approaches (that consider coastal erosion, land use, infrastructure, community well-being and resilience) are increasingly prioritized. In this regard, NbS and ecosystem-based adaptation through co-design and co-management approaches using mangroves and other natural infrastructure have become central to both coastal resilience and climate change mitigation endeavors.

In addition, there is a global consensus to support coastal adaptation approaches that integrate and include all stakeholders. Consequently, several studies have been conducted to better understand the perceptions, challenges, and lessons learned while employing NbS and cultural preservation. Similarly, other studies (e.g., Mallette et al.[50]) investigated knowledge gaps to further understand factors for the acceptance of NbS. Unlike in the 70s and 80s when coastal protection was mainly hard-engineering-centric, coastal managers and regulators are now informed of the environmental and socio-economic impacts of hard engineering and the urgent need for NbS and ecological engineering.

Challenges in managing coastal erosion in an unprecedented changing climate

Climate change is one of the biggest challenges already happening in our times. Temperatures are rising, drought and wildfires are happening too frequently, rainfall patterns are shifting, glaciers and snow are melting, and the global mean sea level is rising. Coastal defense structures are proliferating and becoming dominant coastal features, particularly in urbanized areas and these challenges of climate change will have devastating effects on such structures. Already, existing solutions were implemented with limited knowledge of climate change, which means that all those interventions must either be redone or are at risk of being destroyed, but this varies for different regions. Static engineering solutions would not be able to overcome rising sea levels. For effective coastal management, climate change must therefore be addressed urgently.

Even though coastal erosion challenges are interconnected, the study highlights the major challenges identified when constructing a structure for the protection of a beach against coastal erosion globally (Table 2). The challenges in the construction of sea defenses, NbS or hybrid solutions are contingent on various factors such as finance, maintenance, technological gaps, and land use land cover issues.

Summary of key lessons learned from the synthesis of global literature

Many lessons have been reported from coastal erosion management efforts across the globe in the past half-century. Stakeholder inclusion and participation are pivotal to coastal management and good governance. The knowledge and experiences gained provide the basis for the revision of policies, technological innovations and transformations in the way people perceive coastal erosion and its management.

Pope[5] summarized 10 lessons that are important to coastal managers and regulators. These lessons were added to others here in a universal agreement that (1) there is no such thing as “permanent” shore protection, (2) no one type of shore protection is best for all locations, (3) no shore protection approach will work equally well in all conditions, (4) there is no such thing as “low cost” shore protection, (5) there are approaches that can protect a project area for an effective economic life, (6) there are engineering practices that can work with coastal processes predictably, (7) there are areas where the degree of human intervention precludes doing nothing, (8) there are areas where hard structures are appropriate, (9) there are areas where soft structures are appropriate, and (10) there are areas where no shore protection should be undertaken. In this study, the lessons learned were further synthesized through the lenses of scholarly articles from 1970 through 2023. Throughout the analysis, it was observed that balancing coastal erosion management interventions and the potential negative environmental and socioeconomic impacts from coastal defenses remains a global challenge.

Although many coastal armoring structures may provide some protection, they have shown substantial negative impacts on adjacent beaches and dune systems.[6,23] Coastal projects need constant monitoring by implementing bodies, executing agencies, and project governance bodies. Projects also need rigorous monitoring and evaluation throughout the life span and are accompanied by adaptive management and modifications when issues arise. The capacity of the implementing partner should also be assessed from project inception/design onward. Governance structures and responsibilities within a project need to be clearly laid out from the very beginning of a project, this will reduce political interference. The heavy reliance of governments on consultancies to generate solutions is detrimental to institutional capacity building and ownership of a project and performance. Several problems are realized at armored beaches, namely (1) eroding beaches might limit public access to the beach, e.g., if the beach is narrowed to only a wet sand beach that cannot be

Table 1. Historical analysis of coastal erosion management approaches from 1970 to 2023

Epoch	Dominant management strategies	Literature	Engineering	Infrastructure types
1970–1979	Reactive, protect strategies	Mitchell and Ritchie[61,62]	Hard and soft	Seawalls, breakwaters, groynes, jetties
1980–1989	Reactive, protect, managed retreat strategies.	Pilkey; Terchunian; Smith; Kraus; Marios; Waite; Finnell and Hudson[2,23,63–68]	Hard and Soft	Seawalls, breakwater, groynes, jetties. Beach preservation and nourishment
1990–1999	Proactive, protect, managed retreat, accommodation strategies.	Davison et al.; de Ruig; McInnes; Leafe; Turner; Verhagen; Kosterf; Jensen and Simeonova[10,38,69–75]	Hard and Soft	Seawalls, breakwaters, groynes
2000–2009	Proactive, protect, managed retreat, accommodation strategies.	Tol et al.; Klein et al.; Cooper and Pilkey; Cooper; Basco; Kraus; Campbell and Benedet; Campbell; Peterson; Galloway; Mai; McKenna et al.; Feagin et al.; Doody; French[7,8,24,39,40,45,46,76–81]	Only soft	
2010–2019	Proactive, protect, managed retreat, accommodation strategies.	Powell et al.; Sutton-Grier et al.; Sutton-Grier et al.Rangel-Buitrago; Brayshaw and Lemckert; Cooper and Pilkey; Smith et al.Stive et al.; Leatherman; Jackson; Linham and Nicholls[15–17,25–28,36,82–84]	Soft and hybrid	Seawalls, breakwaters, groynes
2020-2023	Proactive, protect, managed retreat, accommodation strategies.	Houston; Lubchenco and Haugan; Frohlich et al.; Jebakumar et al.; Tu et al. ; Singhvi et al.; Tiggeloven; Tubridy et al.[85–92]	Soft and hybrid	

used by the public; (2) higher erosion rates and low-lying beaches contribute to increased coastal flooding and erosion vulnerability[23]; and (3) the unprotected areas adjacent to coastal armoring will continue to erode at rates higher than historic rates.[23] Therefore, the implementation of hard structures should be void of bias, a judgment that requires sufficient data and knowledge of physical processes, including erosion rates, littoral transport, bathymetry, and particle size, among other parameters.[23]

DISCUSSION

Mediations for coastal erosion

Coastal protection has a long and evolving history that spans centuries and has been shaped by various factors, including human settlement patterns, technological advancements, and environmental changes. This study reviewed the global history of coastal protection, with a focus on key developments, milestones, challenges, and lessons learned. Through these lenses, main studies in the past half-century[2,23,33,64] provided evidence of the environmental impacts of coastal hardening and the need to preserve natural beaches. Accordingly, modern trends in coastal management encourage adaptive management, and natural beach evolution through approaches like managed realignment and no active interventions.

The challenges and lessons learned in global coastal erosion implementation reveal significant knowledge gaps and inconsistencies globally. Coastal protection efforts in the early 19th and 20th centuries were plagued by ill-informed defense implementation that created several obstacles. Erosion control measures are central public issues because beach control approaches (structural or non-structural) could result in negative impacts on the environment. Following these lessons, 21st-century coastal management has transitioned toward adaptive management centered on preserving the ecological functions of ecosystems. Nevertheless, hard engineering remains a foundation of coastal protection globally despite the growth of novel coastal protection technologies.[1] Beach dewatering, for example, has had ambiguous results in numerous areas like Sweden, Denmark, the UK, and France.[1]

Valuable lessons are learned both from successful and failed coastal erosion management throughout the history of coastal erosion management. First, the challenges of coastal erosion are numerous and interconnected. Second, there is no one solution or adaptation option, but many categories range from hard, soft, and integrated solutions. Based on the various lessons learned in this study, it was established that addressing coastal erosion requires comprehensive and multidisciplinary approaches, as well as the engagement of government agencies, scientists, coastal communities, and other stakeholders.

Developed countries dominate the literature production and the development of solutions to address coastal erosion. Based on the results, the UK, the United States, and Australia dominate scholarly literature across all scales, from hard engineering, soft

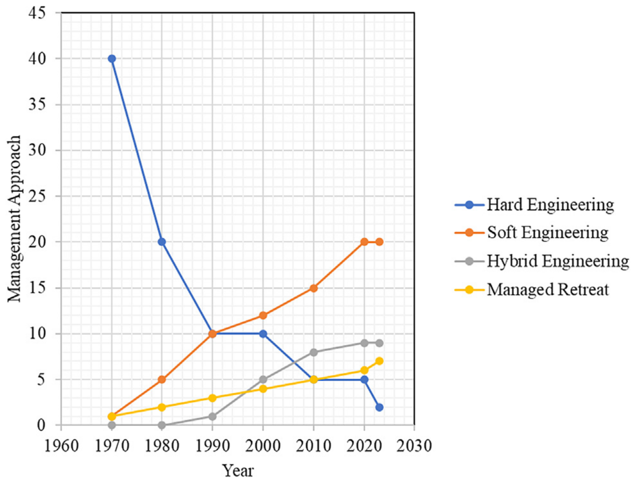

Figure 9. Global trends in erosion management approaches between 1960 and 2023 based on identified literature

engineering, and hybrid engineering with nature and nature-based features for managing coastal erosion (and flooding). Given this, it may be argued that countries that are most affected by coastal erosion (e.g., progressive erosion, perennial storms, landslides, and cliff recessions) and extreme storm and tidal events also dominate global literature production. This is also true when analyzing the subcategories of "challenges," "solutions," and "lessons learnt." Soft approaches like dredging and beach nourishment have transformed coastal protection; yet, these measures are technologically demanding and costly.[36–38] In addition, they have a significant impact on beach ecosystems. Studies have indicated that the dredging of sediment to the bedrock may imply that marine ecosystems may never recover, putting ecosystems at risk of extinction.

Throughout the literature, there is increasing recognition of the importance of green infrastructure and NbS and their acceptance as the sustainable option to complement hard-engineered solutions.[16,19,48,49,96,105] From 2010 to 2023, scholarly articles on hybrid infrastructure and NbS have taken center stage in ecological engineering. Over the years, knowledge and confidence in natural infrastructure have improved. For instance, Ng et al.[109] (2015) established that the ecological value of hard structures (seawalls) can be enhanced by transplanting nursery-reared reef biota onto intertidal seawalls to improve their ecological properties. Other studies established the synergies among different NbS, such as salt marshes and dunes or marshes and mangroves to mitigate coastal hazards.[110,111] Altogether, these lessons underscore the need for a flexible, integrated, and adaptive approach to coastal erosion management. Entirely, this means the consideration of the complexities of natural systems and land-sea interactions with human activities. These valuable lessons can guide future coastal erosion management strategies and, ultimately, the achievement of sustainable coastal futures.

Data limitations, knowledge gaps, and threats

Despite the approaches that were used in this paper to gather information, there is no effective coverage of the length of coastline that has been protected with hard structures, soft structures, or hybrid methods because many interventions are not published. For instance, OSM was used to collate the exact locations where hard coastal protections have been implemented. However, OSM data are provided by individual volunteers. Our review identified that in developing nations, OSM is poorly sourced. For instance, Charuka et al.[112] show many groynes and revetments are implemented in Ghana but only a few were captured by OSM. This work therefore exposes the limitations of OSM in underdeveloped locations and opens opportunities for many nations to make use of OSM to provide information on coastal management solutions in their localities. This current paper demonstrates that there has not been a single fit-for-all coastal management solution. Besides, climate change has become the biggest threat to all coastal management types. Static hard engineering solutions will have challenges to function properly against dynamic sea level rise due to climate change.

Need for sustainable coastal area management

Sustainability and innovation in coastal protection have also increased over the past few decades. Coastal management entails managing the coastline while keeping the environmental and socioeconomic factors in mind. While sustainability is rigorously emphasized for future coastal engineering approaches, Cooper et al.[9] in their analysis of SMPs in the UK argue that sustainability needs to be clearly defined, but varies greatly with geography. Throughout the literature, there is a universal consensus that the coastline is dynamic, and acknowledgment that coastal erosion is a natural part of this evolution. In this regard, many scholarly articles agree that attempting to interfere with the natural processes through the installation of seawalls has detrimental implications.[1,2,33,39,64,113] French[81] emphasized that the coastlines cannot be held to a position indefinitely, pointing to the need to be flexible when choosing coastal protection options, including managed retreat.[81]

Over the past few decades, there has been an increasing emphasis on sustainable coastal protection practices that seek to balance human needs with ecological preservation. This includes integrated coastal zone management and the development of resilient, hybrid infrastructure that integrates green and gray infrastructure. Cooper and McKenna[24] highlight that the challenge for coastal protection is to balance coastal planning and engineering perspectives with human-centered ecosystem perspectives. Precisely, coastal protection must strive to protect coastal ecosystems rather than just properties, highlighting the need for a paradigm shift toward solutions that promote natural processes as much as possible.

History is temporal and bound to specific geographies; hence, there are geographic similarities as much as differences in global implementation. The paradigm shifts in policies and infrastructure typologies are explained in different geographic contexts. Many lessons have been learnt from geographic successes and failures. This highlights the need to have policies in place to govern the development of coastal protection strategies. Monitoring physical and numerical modeling of coastal processes have enhanced further understanding of coastal processes in the vicinity of coastal structures.[1,33]

Table 2. Coastal erosion management complexities identified in the literature

Challenge	Description	Sources
Financial challenges	Managing coastal erosion involves very complex and capital-intensive strategies, from seawalls, beach recharge, groynes, and managed retreats. Insufficient funds prohibit the construction of desired structures.	Bolle et al.; Stive et al.; and Davison et al.[34,36,38]
Erosion migration to adjacent beaches	Adaptations by hard-engineered coastal defenses induced coastal erosion migration to adjacent beaches. Increased erosion at the site due to scour, eventually led to the deterioration and destruction of implemented hard structures.	Pilkey and Wright; Terchunian; Rangel-Buitrago et al.and Angnuureng et al.[2,23,25,106]
High maintenance cost in the long run	Solutions like beach nourishment require periodic top-ups that eventually become expensive. The same applies to gray structures like seawalls and breakwaters that require regular inspection and repair to maintain their integrity, especially in high wave energy and stormy areas	Williams et al.; Tol et al. and Klein et al.[1,7,8]
Technological gaps	The sheer difference in the country's level of technological development restrictions inhibits the application of certain technological options.	Tol et al. and Klein et al.[7,8]
Lack of skilled human capital	In developing countries, there is a shortage of skilled expertise in coastal engineering.	Alves et al. and Klein et al.[6,8]
Habitat destruction and impact on biodiversity	Establishing coastal protection in any form destroys important coastal habitats such as salt marshes, mangroves, nesting grounds and dunes that are vital for various species. Environmental impact assessment should therefore be considered *a priori* to any intervention.	Pilkey and Wright; Weggel and Kraus[2,33,64]
Conflicting objectives in decision-making	In some cases, political decision-making to armor beaches without accurate and reliable data on coastal processes	Chapman and Blockley; Bulleri and Chapman[107,108]

Coastal protection in the context of the Middle East, south east Asia, and Africa

Several challenges and lessons can be identified that are unique to the regions of the Middle East and Africa that reflect the complexity,[114] and diverse environmental, socioeconomic, and geopolitical contexts of these regions. Over the past century, coastal areas in these regions experienced rapid coastal urbanization and development leading to increased pressure on coastal ecosystems and heightened vulnerability to erosion. For example, coastal cities like Dubai and Abu Dhabi in the United Arab Emirates, and Lagos in Nigeria, are expanding rapidly,[115,116] often at the expense of natural coastal ecosystems such as mangroves and coastal dunes that provide natural coastal protection. In addition, these regions are highly susceptible to the impacts of climate change, including sea-level rise, increased storm intensity, and changing precipitation patterns. These factors exacerbate coastal erosion and necessitate adaptive coastal protection strategies. Furthermore, countries in the Middle East and Africa have limited financial resources, inadequate infrastructure, and insufficient institutional capacity constraints making it difficult to implement large-scale coastal protection projects and maintain existing defenses effectively. Overall, addressing coastal erosion in the Middle East and Africa requires a multifaceted approach that community engagement, integrating NbS, and international cooperation for capacity building and technology transfer. By learning from past experiences and implementing innovative strategies, countries in these regions can enhance coastal resilience and mitigate the impacts of erosion on communities and ecosystems.

CONCLUSION

Coastal protection history is filled with human inventions in response to coastal erosion in the face of changing environmental conditions and population growth. The coastal protection system has evolved from simple ancient structures to complex, integrated systems that address multiple challenges, including sea-level rise and associated hazards. Numerous challenges have been encountered and lessons learnt in the effort to accomplish coastal protection. In this study, the challenges, solutions, and lessons learnt from the global implementation of hard-engineered coastal protection such as seawalls to soft protection measures like beach nourishment have been established. The analysis cut across the spectrum of hard, soft, hybrid engineering, and managed realignment approaches. By understanding the challenges and lessons learned from both successful and failed strategies in history, coastal managers, regulators, researchers, and practitioners can enhance their understanding of the complexities surrounding coastal erosion and collaboratively develop sustainable solutions adapted to their geographical contexts to achieve sustainable coastal protection. This is very necessary considering the increasing sea-level rise and human appetite for coastal development.

Comparatively, coastal infrastructure is dominant in the Global North than South. In addition, the pitfalls of hard-engineered coastal infrastructure have contributed to the significant decline in their implementation over the years while soft engineering and NbS are on the rise. Nonetheless, unprecedented rapidly changing climate seems to undermine the efforts of both hard and soft engineering that necessitates dynamic solutions that are sensitive to climate change.

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AUTHOR CONTRIBUTIONS

Conceptualization, B.D.A. and B.C.; writing – original draft, B.D.A., B.C., O.A.D., and R. Almar; analyzed and interpreted the data, B.D.A., O.A.D., N.A.A., and G.T.O.; writing – review & editing, R. Almar, R. Asumadu, and O.A.D. All authors contributed to the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Williams, A.T., Giardino, A., and Pranzini, E. (2016). Canons of Coastal Engineering in the United Kingdom: Seawalls/Groynes, a Century of Change? J. Coast Res. *321*, 1196–1211.
2. Pilkey, O.H., and Wright, H.L. (1988). Seawalls Versus Beaches. J. Coast Res., 41–64.
3. Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., and Aarninkhof, S. (2018). The State of the World's Beaches. Sci. Rep. *8*, 6641. https://doi.org/10.1038/s41598-018-24630-6.
4. Mentaschi, L., Vousdoukas, M.I., Pekel, J.-F., Voukouvalas, E., and Feyen, L. (2018). Global Long-Term Observations of Coastal Erosion and Accretion. Sci. Rep. *8*, 12876–12911. https://doi.org/10.1038/s41598-018-30904-w.
5. Pope, J. (1997). Responding to Coastal Erosion and Flooding Damages. J. Coast Res. *13*, 704–710.
6. Alves, B., Angnuureng, D.B., Morand, P., and Almar, R. (2020). A Review on Coastal Erosion and Flooding Risks and Best Management Practices in West Africa: What Has Been Done and Should Be Done. J. Coast Conserv. *24*, 38. https://doi.org/10.1007/s11852-020-00755-7.
7. Tol, R.S.J., Klein, R.J.T., and Nicholls, R.J. (2008). Towards Successful Adaptation to Sea-Level Rise along Europe's Coasts. J. Coast Res. *242*, 432–442. https://doi.org/10.2112/07A-0016.1.
8. Klein, R.J.T., Nicholls, R.J., Ragoonaden, S., Capobianco, M., Aston, J., and Buckley, E.N. (2001). Technological Options for Adaptation to Climate Change in Coastal Zones. J. Coast Res. *17*, 531–543.
9. Cooper, N.J., Barber, P.C., Bray, M.J., and Carter, D.J. (2002). Shoreline Management Plans: A National Review and Engineering Perspective. Proceedings of the Institution of Civil Engineers - Water and Maritime Engineering *154*, 221–228. https://doi.org/10.1680/wame.2002.154.3.221.
10. Verhagen, H.J. (1996). Analysis of Beach Nourishment Schemes. J. Coast Res. *12*, 179–185.
11. Verhagen, H.J. (1990). Coastal Protection and Dune Management in the Netherlands. J. Coast Res. *6*, 169–179.
12. Verhagen, H.J. (1990). Sea Defence and Flood Protection in the Netherlands, Anticipating Increased Sea-Level Rise. J. Coast Res., 838–850.
13. Sayers, P., Moss, C., Carr, S., and Payo, A. (2022). Responding to Climate Change around England's Coast - The Scale of the Transformational Challenge. Ocean Coast Manag. *225*, 106187. https://doi.org/10.1016/j.ocecoaman.2022.106187.
14. Marshall, A., Robinson, L., and Allen Owens, M. (2011). Coastal Construction Trends in Response to Coastal Erosion: An Opportunity for Adaptation. J. Coast Conserv. *15*, 61–72.
15. Powell, E.J., Tyrrell, M.C., Milliken, A., Tirpak, J.M., and Staudinger, M.D. (2019). A Review of Coastal Management Approaches to Support the Integration of Ecological and Human Community Planning for Climate Change. J. Coast Conserv. *23*, 1–18. https://doi.org/10.1007/s11852-018-0632-y.
16. Sutton-Grier, A., Gittman, R., Arkema, K., Bennett, R., Benoit, J., Blitch, S., Burks-Copes, K., Colden, A., Dausman, A., DeAngelis, B., et al. (2018). Investing in Natural and Nature-Based Infrastructure: Building Better Along Our Coasts. Sustainability *10*, 523. https://doi.org/10.3390/su10020523.
17. Sutton-Grier, A.E., Wowk, K., and Bamford, H. (2015). Future of Our Coasts: The Potential for Natural and Hybrid Infrastructure to Enhance the Resilience of Our Coastal Communities, Economies and Ecosystems. Environ. Sci. Pol. *51*, 137–148. https://doi.org/10.1016/j.envsci.2015.04.006.
18. Hill, K. (2015). Coastal Infrastructure: A Typology for the next Century of Adaptation to Sea level Rise. Front. Ecol. Environ. *13*, 468–476. https://doi.org/10.1890/150088.
19. Bridges, T.S., Smith, J.M., King, J.K., Simm, J.D., Dillard, M., deVries, J., Reed, D., Piercy, C.D., van Zanten, B., Arkema, K., et al. (2022). Coastal Natural and Nature-Based Features: International Guidelines for Flood Risk Management. Front. Built Environ. *8*. https://www.frontiersin.org/articles/10.3389/fbuil.2022.904483.
20. Waryszak, P., Gavoille, A., Whitt, A.A., Kelvin, J., and Macreadie, P.I. (2021). Combining Gray and Green Infrastructure to Improve Coastal Resilience: Lessons Learnt from Hybrid Flood Defenses. Coast. Eng. J. *63*, 335–350. https://doi.org/10.1080/21664250.2021.1920278.
21. Ruckelshaus, M.H., Guannel, G., Arkema, K., Verutes, G., Griffin, R., Guerry, A., Silver, J., Faries, J., Brenner, J., and Rosenthal, A. (2016). Evaluating the Benefits of Green Infrastructure for Coastal Areas: Location, Location, Location. Coast. Manag. *44*, 504–516. https://doi.org/10.1080/08920753.2016.1208882.
22. Burke, T., Dickinson, T., and Sullivan, K. (2015). Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure. https://doi.org/10.13140/RG.2.1.4385.8009.
23. Terchunian, A.V. (1988). Permitting Coastal Armoring Structures: Can Seawalls and Beaches Coexist? J. Coast Res., 65–75.

24. Cooper, J.A.G., and Mckenna, J. (2008). Working with Natural Processes: The Challenge for Coastal Protection Strategies. Geogr. J. *174*, 315–331.
25. Rangel-Buitrago, N., Williams, A.T., and Anfuso, G. (2018). Hard Protection Structures as a Principal Coastal Erosion Management Strategy along the Caribbean Coast of Colombia. A Chronicle of Pitfalls. Ocean Coast Manag. *156*, 58–75. https://doi.org/10.1016/j.ocecoaman.2017.04.006.
26. Brayshaw, S., and Lemckert, C. (2012). Pitfalls of Shoreline Stabilisation – Tweed River Mouth, Gold Coast, Australia. In Pitfalls of Shoreline Stabilization, J.A.G. Cooper and O.H. Pilkey, eds. (Dordrecht: Springer Netherlands), pp. 1–13. https://doi.org/10.1007/978-94-007-4123-2_1.
27. Cooper, J.G., and Pilkey, O.H. (2012). Pitfalls of Shoreline Stabilization: Selected Case Studies. Vol. 3. Coastal Research Library (Springer Netherlands). https://doi.org/10.1007/978-94-007-4123-2.
28. Smith, A.M., Bundy, S.C., and Mather, A.A. (2012). Failed Coastal Stabilization: Examples from the KwaZulu-Natal Coast, South Africa. In Pitfalls of Shoreline Stabilization, J.A.G. Cooper and O.H. Pilkey, eds. (Springer Netherlands), pp. 121–130. https://doi.org/10.1007/978-94-007-4123-2_8.
29. Clayton, K.M. (1989). Sediment Input from the Norfolk Cliffs, Eastern England A Century of Coast Protection and Its Effect. J. Coast Res. *5*, 433–442.
30. Saengsupavanich, C., Ariffin, E.H., Yun, L.S., and Pereira, D.A. (2022). Environmental Impact of Submerged and Emerged Breakwaters. Heliyon *8*, e12626. https://doi.org/10.1016/j.heliyon.2022.e12626.
31. Martinez, M.L., Silva, R., Lithgow, D., Mendoza, E., Flores, P., Martínez, R., and Cruz, C. (2017). Human Impact on Coastal Resilience along the Coast of Veracruz, Mexico. J. Coast Res. *77*, 143–153.
32. Bush, D.M., Pilkey, O.H., and Neal, W.J. (2001). Human Impact on Coastal Topography. In Encyclopedia of Ocean Sciences, Second Edition (Academic Press), pp. 581–590. https://doi.org/10.1016/B978-012374473-9.00078-3.
33. Weggel, J.R. (1988). Seawalls: The Need for Research, Dimensional Considerations and a Suggested Classification. J. Coast Res., 29–39.
34. Bolle, A., das Neves, L., and Rooseleer, J. (2015). Coastal Protection for Ada, Ghana: A Case Study. Proceedings of the Institution of Civil Engineers - Maritime Engineering *168*, 125–133. https://doi.org/10.1680/jmaen.15.00013.
35. Angnuureng, B.D., Adade, R., Chuku, E.O., Dzantor, S., Brempong, E.K., and Mattah, P.A.D. (2023). Effects of Coastal Protection Structures in Controlling Erosion and Livelihoods. Heliyon *9*, e20633. https://doi.org/10.1016/j.heliyon.2023.e20633.
36. Stive, M.J.F., de Schipper, M.A., Luijendijk, A.P., Aarninkhof, S.G., van Gelder-Maas, C., van Thiel de Vries, J.S., de Vries, S., Henriquez, M., Marx, S., and Ranasinghe, R. (2013). A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine. J. Coast Res. *290*, 1001–1008.
37. Capobianco, M., Hanson, H., Larson, M., Steetzel, H., Stive, M.J.F., Chatelus, Y., Aarninkhof, S., and Karambas, T. (2002). Nourishment Design and Evaluation: Applicability of Model Concepts. Coast. Eng. *47*, 113–135. https://doi.org/10.1016/S0378-3839(02)00123-0.
38. Davison, A.T., Nicholls, R.J., and Leatherman, S.P. (1992). Beach Nourishment as a Coastal Management Too: An Annotated Bibliography on Developments Associated with the Artificial Nourishment of Beaches. J. Coast Res. *8*, 984–1022.
39. Basco, D.R. (2006). Seawall Impacts on Adjacent Beaches: Separating Fact from Fiction. J. Coast Res., 741–744.
40. Kraus, N.C., and Rankin, K.L. (2004). Functioning and Design of Coastal Groins: The Interaction of Groins and the Beach. J. Coast. Res. *Special Issue 3*, 367.
41. Basco, D.R., and Pope, J. (2004). Groin Functional Design Guidance from the Coastal Engineering Manual. J. Coast Res., 121–130.
42. Kana, T.W., White, T.E., and McKee, P.A. (2004). Management and Engineering Guidelines for Groin Rehabilitation. J. Coast Res., 57–82.
43. Mai, V., Cong, A.N., Mai, T., and Dao, H.T. (2021). Bamboo Fences as a Nature-Based Measure for Coastal Wetland Protection in Vietnam. Front. Mar. Sci. *8*, 756597. https://www.frontiersin.org/articles/10.3389/fmars.2021.756597.
44. James, R.K., Silva, R., van Tussenbroek, B.I., Escudero-Castillo, M., Mariño-Tapia, I., Dijkstra, H.A., van Westen, R.M., Pietrzak, J.D., Candy, A.S., Katsman, C.A., et al. (2019). Maintaining Tropical Beaches with Seagrass and Algae: A Promising Alternative to Engineering Solutions. Bioscience *69*, 136–142.
45. Campbell, T.J., and Benedet, L. (2006). Beach Nourishment Magnitudes and Trends in the U.S. J. Coast. Res., 57–64.
46. Peterson, C.H., and Bishop, M.J. (2005). Assessing the Environmental Impacts of Beach Nourishment. Bioscience *55*, 887–896. https://doi.org/10.1641/0006-3568(2005)055[0887:ateiob]2.0.co;2.
47. Cruz, M. (2020). Impact of the Use of Dolomite in Beach Nourishment in Manila Bay (GOVPH). https://mgb.gov.ph/2015-05-13-02-02-11/mgb-news/890-impact-of-the-use-of-dolomite-in-beach-nourishment-in-manila-bay.
48. Bouw, M., and Eekelen, E. (2021). Building with Nature: Creating, Implementing and Upscaling Nature-Based Solutions. https://www.wetlands.org/publication/building-with-nature-creating-implementing-and-upscaling-nature-based-solutions/.
49. Cohen-Shacham, E., Walters, G., Janzen, C., and Maginnis, S. (2016). Nature-based Solutions to Address Global Societal Challenges (IUCN International Union for Conservation of Nature).
50. Mallette, A., Smith, T.F., Elrick-Barr, C., Blythe, J., and Plummer, R. (2021). Understanding Preferences for Coastal Climate Change Adaptation: A Systematic Literature Review. Sustainability *13*, 8594. https://doi.org/10.3390/su13158594.
51. Xiao, Y., and Watson, M. (2019). Guidance on Conducting a Systematic Literature Review. J. Plann. Educ. Res. *39*, 93–112. https://doi.org/10.1177/0739456X17723971.
52. Shirin, M., Brown, R.R., and de Haan, F.J. (2015). Strategic Planning of Urban Infrastructure for Environmental Sustainability: Understanding the Past to Intervene for the Future. Cities *46*, 67–75. https://doi.org/10.1016/j.cities.2015.05.003.
53. Arksey, H., and O'Malley, L. (2005). Scoping Studies: Towards a Methodological Framework. Int. J. Soc. Res. Methodol. *8*, 19–32. https://doi.org/10.1080/1364557032000119616.
54. Moher, D., Liberati, A., Tetzlaff, J., and Altman, D.G.; PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. BMJ *339*, b2535. https://doi.org/10.1136/bmj.b2535.
55. Morris, R., Strain, E.M.A., Konlechner, T.M., Fest, B.J., Kennedy, D.M., Arndt, S.K., and Swearer, S.E. (2019). Developing a Nature-Based Coastal Defence Strategy for Australia. Aust. J. Civ. Eng. *17*, 167–176. https://doi.org/10.1080/14488353.2019.1661062.
56. Pinto, C.A., Silveira, T.M., and Teixeira, S.B. (2020). Beach Nourishment Practice in Mainland Portugal (1950–2017): Overview and Retrospective. Ocean Coast Manag. *192*, 105211. https://doi.org/10.1016/j.ocecoaman.2020.105211.
57. Coelho, C., Lima, M., and Ferreira, M. (2022). A Cost–Benefit Approach to Discuss Artificial Nourishments to Mitigate Coastal Erosion. J. Mar. Sci. Eng. *10*, 1906. https://doi.org/10.3390/jmse10121906.
58. Paxton, A.B., Riley, T.N., Steenrod, C.L., Smith, C.S., Zhang, Y.S., Gittman, R.K., Silliman, B.R., Buckel, C.A., Viehman, T.S., Puckett, B.J., and Davis, J. (2023). What evidence exists on the performance of nature-based solutions interventions for coastal protection in biogenic, shallow ecosystems? A systematic map protocol. Environ. Evid. *12*, 11. https://doi.org/10.1186/s13750-023-00303-4.

59. Phong, N.T., Nuong, C.T., and Quang, N.H. (2023). Local perceptions of mangrove protection and livelihood improvement in Co-management: Lessons learnt and recommendations. Ocean Coast Manag. *237*, 106530. https://doi.org/10.1016/j.ocecoaman.2023.106530.

60. Malekpour, S., Brown, R.R., and De Haan, F.J. (2015). Strategic planning of urban infrastructure for environmental sustainability: Understanding the past to intervene for the future. Cities *46*, 67–75. https://doi.org/10.1016/j.cities.2015.05.003.

61. Mitchell, J.K. (1975). The Rush to the Shore: How to Live with Coastal Erosion. Landscape Architecture *65*, 170–177.

62. Ritchie, W. (1979). The Status of Coastal Research in Scotland. Area *11*, 344–346.

63. Smith, S.E., and Abdel-Kader, A. (1988). Coastal Erosion along the Egyptian Delta. J. Coast Res. *4*, 245–255.

64. Kraus, N.C. (1988). The Effects of Seawalls on the Beach: An Extended Literature Review. J. Coast Res., 1–28.

65. Marios, C., and Coccossis, H. (1982). Coastal Planning and Management Perspectives. Ekistics *49*, 92–97.

66. Waite, C. (1982). Coastal Management in England and Wales. Ekistics *49*, 124–127.

67. Finnell Jr, G.L. (1980). Coastal Land Management in Florida. Am. Bar Found Res. J. *5*, 303–400.

68. Hudson, B.J. (1980). Anthropogenic Coasts. Geography *65*, 194–202.

69. de Ruig, J.H.M. (1998). Seaward Coastal Defence: Limitations and Possibilities. J. Coast Conserv. *4*, 71–78.

70. McInnes, R.G., Jewell, S., and Roberts, H. (1998). Coastal Management on the Isle of Wight, UK. Geogr. J. *164*, 291–306. https://doi.org/10.2307/3060618.

71. Leafe, R., Pethick, J., and Townend, I. (1998). Realizing the Benefits of Shoreline Management. Geogr. J. *164*, 282–290. https://doi.org/10.2307/3060617.

72. Turner, R.K., Lorenzoni, I., Beaumont, N., Bateman, I.J., Langford, I.H., and McDonald, A.L. (1998). Coastal Management for Sustainable Development: Analysing Environmental and Socio-Economic Changes on the UK Coast. Geogr. J. *164*, 269–281. https://doi.org/10.2307/3060616.

73. Kosterf, M.J., and Hillen, R. (1995). Combat Erosion By Law Coastal Defence Policy for the Netherlands. J. Coast Res. *11*, 1221–1228.

74. Jensen, F. (1994). Dune Management in Denmark: Application of the Nature Protection Act of 1992. J. Coast Res. *10*, 263–269.

75. Simeonova, G.A. (1992). Coastal Protection against Erosion along the Bulgarian Black Sea. J. Coast Res. *8*, 745–751.

76. Galloway, G.E., Boesch, D.F., and Twilley, R.R. (2009). Restoring and Protecting Coastal Louisiana. Issues Sci. Technol. *25*, 29–38.

77. Mai, C.V., Stive, M.J.F., and Pieter Van Gelder, P.H.A.J.M. (2009). Coastal Protection Strategies for the Red River Delta. J. Coast Res. *25*, 105–116.

78. McKenna, J., Cooper, J.A.G., and O'Hagan, A.M. (2009). Coastal Erosion Management and the European Principles of ICZM: Local versus Strategic Perspectives. J. Coast Conserv. *13*, 165–173.

79. Koch, E.W., Barbier, E.B., Silliman, B.R., Reed, D.J., Perillo, G.M., Hacker, S.D., Granek, E.F., Primavera, J.H., Muthiga, N., Polasky, S., et al. (2008). Vegetation's Role in Coastal Protection [with Response]. Science *320*, 176–177.

80. Doody, J.P. (2004). Coastal Squeeze': An Historical Perspective. J. Coast Conserv. *10*, 129–138.

81. French, P.W. (2004). The Changing Nature of, and Approaches to, UK Coastal Management at the Start of the Twenty-First Century. Geogr. J. *170*, 116–125.

82. Leatherman, S.P. (2018). Coastal Erosion and the United States National Flood Insurance Program. Ocean Coast Manag. *156*, 35–42. https://doi.org/10.1016/j.ocecoaman.2017.04.004.

83. Jackson, C.W., Bush, D.M., and Neal, W.J. (2012). Documenting Beach Loss in Front of Seawalls in Puerto Rico: Pitfalls of Engineering a Small Island Nation Shore. In Pitfalls of Shoreline Stabilization, J.A.G. Cooper and O.H. Pilkey, eds. (Springer Netherlands), pp. 53–71. https://doi.org/10.1007/978-94-007-4123-2_4.

84. Linham, M.M., and Nicholls, R.J. (2010). Technologies for Climate Change Adaptation. Coastal Erosion and Flooding (United Nations Environment Programme (UNEP)). https://www.osti.gov/etdeweb/biblio/1010716.

85. Houston, J.R. (2023). Measured Fate of Beach Nourishment Sand. J. Coast Res. *39*, 407–417.

86. Lubchenco, J., and Haugan, P.M. (2023). Coastal Development: Resilience, Restoration and Infrastructure Requirements. In The Blue Compendium: From Knowledge to Action for a Sustainable Ocean Economy, J. Lubchenco and P.M. Haugan, eds. (Springer International Publishing), pp. 213–277. https://doi.org/10.1007/978-3-031-16277-0_7.

87. Frohlich, M., Smith, T.F., Fidelman, P., Baldwin, C., Jacobson, C., and Carter, R.B. (2022). Towards Adaptive Coastal Management Law: Lessons from Australia and Brazil. Ocean Coast Manag. *219*, 106057. https://doi.org/10.1016/j.ocecoaman.2022.106057.

88. Jebakumar, J., Prakash, P., Nandhagopal, G., RajanBabu, B., Ragumaran, S., Kiran, A.S., and Ravichandran, V. (2022). Ecological Appraisal of Geotextiles in Coastal Erosion Protection Engineering. J. Coast Res. *38*, 345–354.

89. Tu, L.X., Ba, H.T., Thanh, V.Q., Wright, D.P., Tanim, A.H., and Anh, D.T. (2022). Evaluation of Coastal Protection Strategies and Proposing Multiple Lines of Defense under Climate Change in the Mekong Delta for Sustainable Shoreline Protection. Ocean Coast Manag. *228*, 106301. https://doi.org/10.1016/j.ocecoaman.2022.106301.

90. Singhvi, A., Luijendijk, A.P., and van Oudenhoven, A.P.E. (2022). The Grey – Green Spectrum: A Review of Coastal Protection Interventions. J. Environ. Manag. *311*, 114824. https://doi.org/10.1016/j.jenvman.2022.114824.

91. Tiggeloven, T., de Moel, H., van Zelst, V.T.M., van Wesenbeeck, B.K., Winsemius, H.C., Eilander, D., and Ward, P.J. (2022). The Benefits of Coastal Adaptation through Conservation of Foreshore Vegetation. J. Flood Risk Manag. *15*. https://doi.org/10.1111/jfr3.12790.

92. Tubridy, F., Walsh, C., Lennon, M., and Scott, M. (2022). Contextualising Coastal Management and Adaptation: Examining Situated Practices and Path Dependencies in Ireland and Germany. Ocean Coast Manag. *220*, 106095. https://doi.org/10.1016/j.ocecoaman.2022.106095.

93. Pilkey, O.H., and Cooper, J.A.G. (2014). Are Natural Beaches Facing Extinction? J. Coast Res. *70*, 431–436. https://doi.org/10.2112/SI70-073.1.

94. Pilkey, O.H., and Cooper, J.A.G. (2014). The Last Beach (Duke University Press), p. 256. https://doi.org/10.1515/9780822375944.

95. Moraes, R.P.L., Reguero, B.G., Mazarrasa, I., Ricker, M., and Juanes, J.A. (2022). Nature-Based Solutions in Coastal and Estuarine Areas of Europe. Front. Environ. Sci. *10*, 829526. https://doi.org/10.3389/fenvs.2022.829526.

96. Narayan, S., Beck, M.W., Reguero, B.G., Losada, I.J., van Wesenbeeck, B., Pontee, N., Sanchirico, J.N., Ingram, J.C., Lange, G.-M., and Burks-Copes, K.A. (2016). The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences Maura (Gee) Geraldine Chapman. PLoS One *11*, e0154735. https://doi.org/10.1371/journal.pone.0154735.

97. Spalding, M.D., Ruffo, S., Lacambra, C., Meliane, I., Hale, L.Z., Shepard, C.C., and Beck, M.W. (2014). The Role of Ecosystems in Coastal Protection: Adapting to Climate Change and Coastal Hazards. Ocean Coast Manag. *90*, 50–57. https://doi.org/10.1016/j.ocecoaman.2013.09.007.

98. Chávez, V., Lithgow, D., Losada, M., and Silva-Casarin, R. (2021). Coastal green infrastructure to mitigate coastal squeeze. J. Infrastruct. Preserv. Resil. *2*, 7. https://doi.org/10.1186/s43065-021-00026-1.

99. Monteiro, R., Ferreira, J., and Antunes, P. (2020). Green Infrastructure Planning Principles: An Integrated Literature Review. Land *9*, 525. https://doi.org/10.3390/land9120525.
100. Kuc Castilla, A., Mendoza, E., Posada, G., and Silva, R. (2019). Design of hybrid ecosystem based strategies for the control of erosion at Sabancuy beach, Campeche, Mexico. In Integrating Biophysical Components in Coastal Engineering Practices. *J. C*oastal Researc*h*, R. Silva, M.L. Martínez, V. Chávez, and D. Lithgow, eds. (Coconut Creek (Florida)), pp. 85–91. Special Issue No. 92.
101. Hamin, E.M., Abunnasr, Y., Roman Dilthey, M., Judge, P.K., Kenney, M.A., Kirshen, P., Sheahan, T.C., DeGroot, D.J., Ryan, R.L., McAdoo, B.G., et al. (2018). Pathways to Coastal Resiliency: The Adaptive Gradients Framework. Sustainability *10*, 2629. https://doi.org/10.3390/su10082629.
102. Curin, C.A. (2019). Living Shorelines for Coastal Resilience. In Elsevier eBooks (Elsevier), pp. 1023–1053. https://doi.org/10.1016/B978-0-444-63893-9.00030-7.
103. Davis, J.L., Currin, C.A., O'Brien, C., Raffenburg, C., and Davis, A. (2015). Living Shorelines: Coastal Resilience with a Blue Carbon Benefit. PLoS One *10*, e0142595. https://doi.org/10.1371/journal.pone.0142595.
104. Bongarts Lebbe, T., Rey-Valette, H., Chaumillon, É., Camus, G., Almar, R., Cazenave, A., Claudet, J., Rocle, N., Meur-Férec, C., Viard, F., et al. (2021). Designing Coastal Adaptation Strategies to Tackle Sea Level Rise. Front. Mar. Sci. *8*, 740602. https://doi.org/10.3389/fmars.2021.740602.
105. Chee, S.Y., Firth, L.B., Then, A.Y.H., Yee, J.C., Mujahid, A., Affendi, Y.A., Amir, A.A., Lau, C.M., Ooi, J.L.S., Quek, Y.A., et al. (2021). Enhancing Uptake of Nature-Based Solutions for Informing Coastal Sustainable Development Policy and Planning: A Malaysia Case Study. Front. Ecol. Evol. *9*, 708507. https://doi.org/10.3389/fevo.2021.708507.
106. Angnuureng, B.D., Apeaning Addo, K., and Wiafe, G. (2013). Impact of Sea Defense Structures on Downdrift Coasts: The Case of Keta in Ghana. Acad. J. Environ. Sci. *1*, 104–121. https://doi.org/10.15413/ajes.2013.0102.r.
107. Chapman, M.G., and Blockley, D.J. (2009). Engineering Novel Habitats on Urban Infrastructure to Increase Intertidal Biodiversity. Oecologia *161*, 625–635. https://doi.org/10.1007/s00442-009-1393-y.
108. Bulleri, F., and Chapman, M.G. (2010). The Introduction of Coastal Infrastructure as a Driver of Change in Marine Environments. J. Appl. Ecol. *47*, 26–35. https://doi.org/10.1111/j.1365-2664.2009.01751.x.
109. Ng, C.S.L., Lim, S.C., Ong, J.Y., Teo, L.M.S., Chou, L.M., Chua, K.E., and Tan, K.S. (2015). Enhancing the Biodiversity of Coastal Defence Structures: Transplantation of Nursery-Reared Reef Biota onto Intertidal Seawalls. Ecol. Eng. *82*, 480–486. https://doi.org/10.1016/j.ecoleng.2015.05.016.
110. Unguendoli, S., Biolchi, L.G., Aguzzi, M., Pillai, U.P.A., Alessandri, J., Valentini, A., and Valentini, A. (2023). A Modeling Application of Integrated Nature Based Solutions (NBS) for Coastal Erosion and Flooding Mitigation in the Emilia-Romagna Coastline (Northeast Italy). Sci. Total Environ. *867*, 161357. https://doi.org/10.1016/j.scitotenv.2022.161357.
111. Temmerman, S., Horstman, E.M., Krauss, K.W., Mullarney, J.C., Pelckmans, I., and Schoutens, K. (2023). Marshes and Mangroves as Nature-Based Coastal Storm Buffers. Ann. Rev. Mar. Sci *15*, 95–118. https://doi.org/10.1146/annurev-marine-040422-092951.
112. Charuka, B., Angnuureng, D.B., and Agblorti, S.K.M. (2023). Mapping and Assessment of Coastal Infrastructure for Adaptation to Coastal Erosion along the Coast of Ghana. Anthropocene Coasts *6*, 11. https://doi.org/10.1007/s44218-023-00026-6.
113. Zhi, L., Li, X., Bai, J., Shao, D., Cui, B., Mu, Y., Ma, T., Xie, X., Bilal, H., and Abdullahi, U. (2023). Seawall-Induced Impacts on Large River Delta Wetlands and Blue Carbon Storage under Sea Level Rise. Sci. Total Environ. *859*, 159891. https://doi.org/10.1016/j.scitotenv.2022.159891.
114. Eslamian, S., Barua, P., and Eslamian, F. (2022). Water Scarcity Global Perspectives, Issues and Challenges (Nova Science Publishers, Inc.), p. 249.
115. Sengupta, D., Chen, R., and Meadows, M.E. (2018). Building beyond Land: An Overview of Coastal Land Reclamation in 16 Global Megacities. Appl. Geogr. *90*, 229–238. https://doi.org/10.1016/j.apgeog.2017.12.015.
116. Sengupta, D., Choi, Y.R., Tian, B., Brown, S., Meadows, M., Hackney, C.R., Banerjee, A., Li, Y., Chen, R., and Zhou, Y. (2023). Mapping 21st Century Global Coastal Land Reclamation. Earths Future *11*. https://doi.org/10.1029/2022EF002927.