ISSN: 2754-4982

Journal of Civil Engineering Research & Technology

Review Article

Open Access

Aspects of Coastal Monitoring and Coastal Protection by Engineering Approaches, Focusing on The Mediterranean Sea

Milva Pepi[1]* and Silvano Focardi[2]

[1]Stazione Zoologica Anton Dohrn, Fano Marine Centre, Viale Adriatico, 1-N, 61032 Fano, Italy

[2]Department of Physical sciences, Earth and Environment, Università di Siena, Via Mattioli, 4, 53100 Siena, Italy

ABSTRACT

In this review, aspects of coastal vulnerabilities have been pointed out, highlighting the importance of monitoring approaches and possible interventions by using engineering technologies to counteract coastal deterioration have been considered. This review coupled aspects related to the need for accurate monitoring procedures to detect coastal conditions and to control severe concerns affecting coasts, including sea level rise, offering possible solutions in the form of hard and nature-based engineering interventions. This study provided a focus on the hotspots of the Mediterranean coastal area. Innovative approaches in evidencing features of peculiar coastal sites and in providing countermeasures to be considered by local stakeholders and policy makers have been highlighted. Forthcoming investigations should include studies on engineering structures at coasts, focusing on natural based and hybrid engineering approaches, combined with an important and constant monitoring activity both before and after engineering structures inclusion. This review can give insights into future research and into innovative proposals for coasts protection.

***Corresponding author**

Milva Pepi, Stazione Zoologica Anton Dohrn, Fano Marine Centre, Viale Adriatico, 1-N, 61032 Fano, Italy.

Received: March 03, 2025; **Accepted:** March 06, 2025; **Published:** March 17, 2025

Keywords: Coasts Monitoring, Climate Change, Sea Level Rise, Coastal Erosion, Hard Engineering, Soft Engineering

Introduction

Coasts are complex systems changing in response to various geomorphological and marine forces. Over the years, populations have concentrated on the coastal areas, with about 40% of the world's population living within 100 km of the beach and over 10% living at altitudes below 10 m above sea level [1]. Coasts are under intense pressures from activities such as tourism, industry, agriculture, fishery, and aquaculture and the anthropic pressure interferes with natural processes, such as sediment dynamics [2]. Modification of coasts can originate from construction of defence barriers, the presence of ports, or infrastructures for industrial and recreational activities. The expansion of populations and cities at coasts can cause alteration of the morphology of structures such as beaches, dunes, deltas, and river estuaries, evidencing phenomena of erosion, accumulation of sediments and shoreline changes. Ports activities can also affect the phenomenon of coastal erosion, as in the case of altering wave patterns. Moreover, costal equilibrium can be affected by river basins modifications in case of watercourses modification, favouring drinking water resources supply, or to allow the use of water in agriculture for irrigation and the use of water in industrial processes. It is noteworthy to highlight that seawater quality in coastal environments can be altered by impacts such as spreading of untreated wastewater and dispersion of toxic compounds, shipping activities, agricultural procedures, and industrial waste dissemination. Coastal contamination can be also caused by revealing biological contaminants, including pathogenic and non-pathogenic microorganisms, and chemical pollutants such as hydrocarbons and waste by-products [2]. In the last century, coasts have undergone degradation of ecosystems, morphological alterations with an increase in coastal erosion and related risks, and with the aging of existing infrastructure [2,3].

Climate change can be triggered by human activities with the release of greenhouse gases (GHGs), such as carbon dioxide (CO_2) and methane (CH_4). The warming of seawater temperature is a consequence of climate change that can cause a domino effect on ocean circulation, currents, regional wind patterns, local climate, and sea level [4]. Climate change increases coasts vulnerability due to an intensification of the frequency of extreme events such as sea level rise, increased levels of flooding, coastal erosion, changes in coastal landforms and shoreline modifications, changes in coastal transport rates, and salt intrusion. All these phenomena are posing serious challenges for people living on the coasts and for related social and economic activities [5,6]. This phenomenon can induce modifications in wind intensity, wave energy and significant sea level rise, causing severe coastal damage such as flooding and coastal erosion events [7,8]. As consequence of the expansion in evapotranspiration phenomena and of changes in the intensity of rain and snow precipitations, climate change can cause substantial alterations in river flows and increases in relative sediment displacements [9]. Due to climate change, sandy coasts are subject to an important erosion process, causing increases in the number of extreme events related to weather [9,10]. Climate change can modify wave characteristics, with alterations in coastal drift and in amplitude and frequency of the wave oscillation phase. Changes in extreme waves could cause an increase in coastal erosion [9].

Coastal zones have an important role in the viewpoint of sustainable development, as coasts host most of the population in a specific area and play a key role in the health of communities [4]. In the last years it has emerged that new, efficient, sustainable, adaptable and economically feasible strategies for coastal protection are requested [4]. In this review, aspects of coastal monitoring have been described, trying to point out the importance of a multidisciplinary approach requested in the presence of complex systems as coasts. The phenomenon of sea level rise has been described in terms of causes and considering the consequences at coastal level. A focus on the Mediterranean Sea has been provided, highlighting the hotspots features and the vulnerability of this area. Possible engineering structures protecting coasts have then been reported with the aim of pointing out the most efficient and respectful of sustainability and of human wellbeing.

Coast Monitoring

Monitoring of marine coasts comprehends evaluation of environmental pollution due to anthropic activities, detection of structural alterations, and determination of consequences due to effects of climate change. Coast monitoring requires acquisition of data concerning the main physical, chemical, and biological variables in the aquatic districts, to obtain information on the environmental status. Anthropic activities need to be monitored, such as those that take place in coastal recreational areas, or derived from activities of ships building, or due to the presence of harbours or of aquaculture activities, all can cause biological pollution with diffusion of pathogenic and non-pathogenic microorganisms, and spread of chemical contaminants such as hydrocarbons, antibiotics, organic matter, and waste by-products. Other variables to be checked include releases of untreated sewage waste, impacts of shipping activities, and the presence of agricultural and industrial wastes that can affect coastal water quality and that can pose risks to species biodiversity and natural habitats [11]. Moreover, the impacts of climate change, in terms of temperatures increasing and altered ocean currents, further exacerbate the pressure on coastal environments, stressing the need for accurate monitoring procedures [11].

Coasts are the borders between land and water and data recovery from these sites are of great importance, also from the economic and social point of view. The detection of water quality, the evaluation of the extent of sediment inputs, sediment balances, sea level measurements using tide gauges, all are elements allowing coast monitoring. These approaches have been combined with modern observation techniques such as satellite altimetry, which represent a fundamental support in studies on climatic change and sea level rise at coastal level [12]. In recent decades, tool innovation coupled with remote sensing and data acquisition, processing and storage has enabled applications to be extended to many users and coastal problem managers. State of the art of emerging technologies for coastal ecosystem monitoring includes water sampling for specific analyses in laboratory, in situ monitoring by mean of sensor networks, satellite monitoring, aerial and underwater drones, fiber optic systems, and community science observatories. Moreover, advances in artificial intelligence and deep learning underpin all these technologies by enabling insights to be drawn from increasingly large data volumes. Even with these recent advances, there are still major gaps in coastal ecosystem monitoring that must be addressed to manage coastal ecosystems during a period of accelerating global change [12]. A description of possible monitoring approaches to be adopted at coastal level is reported in Figure 1.

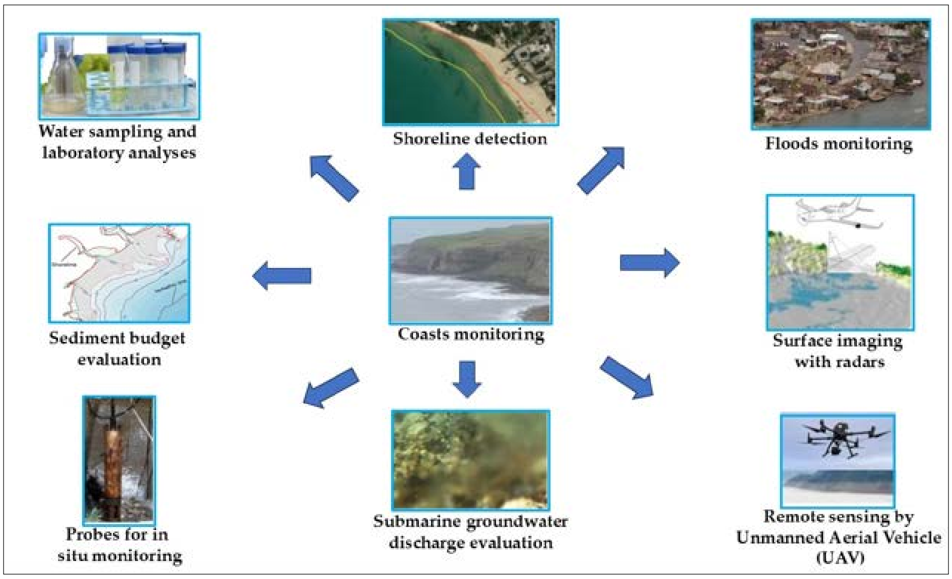

Figure 1: Monitoring Approaches at Coastal Level, Including Laboratory Analyses, *In Situ* Measurements, Use of Remote Sensing Investigations and Detections by Unmanned Aerial Vehicles (UAV)

Water Sampling and *In Situ* Analysis

Sampling of water from sites to be monitored can be treated in laboratory for specific analyses, such as isolation of microorganisms to be characterized from the physiological point of view. Marine environments evidence harsh condition and present extreme environments, with autochthonous microorganisms able to survive by developing unique features of adaptation. These marine microorganisms can give insights in contexts as the ecology of biogeochemical processes and for biotechnological purposes. Water samples can be used for DNA extraction and metagenomic analysis to characterize microbial communities and their functional profiles. In fact, the marine microbiome represents a reservoir of genetic diversity and metabolic potential, and it responds to climate change to maintain the native equilibrium [13].

In situ sensing technology for coastal monitoring presents sensors networks providing real-time data in coastal areas. Sensors operating in coastal marine monitoring are exposed to extreme conditions and sensors must be robust, power efficient, and equipped with suitable antifouling protection to resist to the harsh marine environment [13]. Coastal sensors networks for real-time decision support can give information on water biochemistry and the impacts of anthropogenic pollution. Monitoring coastal lagoon ecosystems that follow Water Framework Directive guidelines (WFD, European Union CE 2000/60) shall include investigations on the biochemical composition of organic matter in sediments, as the latter contains the memory of contamination and of the site characteristics, thus providing a comprehensive delineation of these dynamic ecosystems [14]. In water quality detection by manual sampling in the field followed by laboratory analyses, the concentration of chlorophyll-*a* (Chl-*a*) is revealed [14] (Figure 1).

Recent improvements and technological developments in marine monitoring equipment, including buoys, platforms, drifters, gliders, and in transmission systems, such as terrestrial and satellite modems, able to measure and transmit real-time complex datasets that can be used for traditional oceanography, operating oceanography and forecasting model feeding, was described in detail for the coasts at the Mediterranean Sea [11]. An implementation of the previous research infrastructures with new multi-platform and integrated observing systems have been recently introduced. They include new water samplers coupled to new sensors, that can be remotely controlled, offering the technological instruments required to monitor environmental status and to better understand the mechanisms of environmental modifications due to climate change effects [11].

Remote Sensing Approach

The technology of remote sensing can acquire data about surface of Earth from a distance. Information can be captured remotely, by using sensors and platforms including satellites, aircrafts, drones, and ground-based instruments [15]. Remote sensing allows data collection from hazardous or difficult to reach areas. This technology is extremely important in climate change monitoring by measuring phenomena like sea level rise [15].

Measurements of sea levels involve both the use of tide gauges and satellite observations, which together can provide a global description of sea level changes. However, monitoring sea level rise and related impacts on coastal areas is of fundamental importance. The Intergovernmental Panel on Climate Change (IPCC), along with local and national governments, are involved in developing sea level rise monitoring for coastal regions protection [16]. As an example, data integration of the mapping of the seabed conducted with sonar by acoustic waves, giving information from sea depths can be difficult in the presence of storms and due to the presence of tidal currents. The results obtained by using indicators, or Global Positioning System (GPS), or the method of Light Detection and Measurement (LiDAR), or three-dimensional (3D) terrestrial scanners, once integrated, give a broader view of the whole situation [17]. Normally, measurements in situ are complicated to get. In this context, remote sensing allows the detection of information about objects and sites that are located at a distance, by aircraft or satellites (Figure 1) [18]. To detect coast modifications, reference points are of fundamental importance to select an orientation in the coast. Selection of these reference points is based both on the space-time sense and on the time scale. Detection of coastal changes must consider the wide variety of reference points allowing elaboration of geomorphological information, tide measurements or the configuration of vegetation [19]. Coastal environments include different profiles and there is no one indicator for all profiles and that can adapt to any coast's features. The reference points therefore can change according to coastal profiles and to the aims of monitoring. It is noteworthy to highlight that reference points have a pivotal role in monitoring of coasts and can influence the whole monitoring process. The reference points must evidence coastal modifications, and in the meantime, they must not undergo influences by the same coastal modifications [1]. To overcome the limitations in spatial-temporal resolution, access to large satellite database and use of sustainable technologies can give important solutions. An easy approach to achieve information by these recent technologies is the use of unmanned aerial vehicle (UAV). The latter represents an innovative approach for coasts monitoring, offering the possibility to acquire spatial-temporal information from various sites [20]. In recent years, unmanned aerial vehicles applications for monitoring of different environments has increased. Monitoring of coasts by unmanned aerial vehicles can detect shoreline modifications and degradation of coastal areas [21]. Unmanned aerial vehicles have gradually had an increasingly widespread use for coastal monitoring, because they can give an important support in harvesting information for processing of images and characteristics of the coast [21]. Unmanned aerial vehicles own high detection times frequency, relative low costs, and can include lightweight sensors thus achieving the capability to detect algae at diverse wavelengths. All these features confer to unmanned aerial vehicles the capability to detect algal blooms. The wavelength range in which unmanned aerial vehicles can operate is visible light at 500 nm to near-infrared light at 1,400 nm. Floating macroalgae blooms pose multiple dangers to coastal environments, with effects on the tourism economy, the safety of ship navigation and concerns for public health. The use of an unmanned aerial vehicle allows the quantitative mapping of the Chl-*a* distribution in surface and coastal waters from low altitude, thus allowing floating macroalgae blooms detection. Traditional laboratory analyses combined to analyses obtained using unmanned aerial vehicles will allow to comprehend the causes at the base of the blooms, which could depend on climate change. This type of approach can provide details on sites and amount of algal bloom, in order to propose actions to limit the effects of this phenomenon (Figure 1) [22]. The method of Coastal Risk Index at the Local Scale (CRI-LS) can give evaluations of fractures, weaknesses, hazards and risk indices according to evaluations including physical, environmental and socio-economic factors [23].

Artificial Intelligence, Machine Learning, and Internet of Things can have a role. Different challenges affect coasts, that are especially vulnerable, and their monitoring needs advanced tools and technologies. Artificial Intelligence (AI) has highlighted advances such as machine learning, deep learning, and computer visions. These innovations can change the ways of monitoring, analyzing and protecting coastal areas [24]. An innovative approach consists in the interaction of Artificial Intelligence (AI) with remote sensing to be used in the monitoring of coasts. Cutting edge Artificial Intelligence techniques, when integrated with remote-sensing technologies, offer unprecedent opportunities for monitoring a range of environmental shifts and disasters at coastal areas. Coasts are complex environments and their effective monitoring needs extensive, efficient, and accurate methods. An opportunity for coastal vulnerability assessment is represented by deep learning for broad, automated coastal monitoring informing applications [24]. The monitoring of changes in the shorelines can be obtained by Earth Observation data and the application of spatiotemporal analysis methods, facilitating shoreline change analysis and detection. Separately from remote sensing methods, the advent of machine learning-based techniques shows the capability of supporting the monitoring and modeling of coasts at large scale [25]. Machine learning represents a set of algorithms and methods that can be used for designing and implementing systems, that learn from data, and that are capable of inferring results and/or deducing patterns from the incoming data. Based on the availability of input data and the desired outcome, machine learning algorithms can be assembled into four main categories: i) supervised learning, ii) unsupervised learning, iii) semi supervised learning, iv) reinforcement learning [26].

Concerning tools and approaches that can be used in the service of coastal erosion and coastline change monitoring, they mostly rely on geographic information systems (GIS). This allows users to manage and to generate all the geospatial related information that can be subsequently utilized in the context of other programming environments [27]. Apart from GIS approach, Internet of Things (IoT) represents a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols, where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are faultlessly integrated into the information network [25]. In contexts of coastal erosion, Internet of Things (IoT) is a substantial technology to develop solutions to try solving or mitigating the problem. IoT-based techniques can allow you to manage heterogeneous and massive data for real-time monitoring and decision making [28]. Internet of Things technology can allow observation of coastal spatiotemporal variability, validating remotely sensed data, and characterizing surface water depth profiles. Education and community engagement in coastal health issues with broad international is also part of this kind of approach [29].

Sea Level Rise (SLR)

Causes of sea level rise depend by different agents, including climate change, structural reasons and anthropogenic activities [30]. One of the main causes of sea level rise is thermal expansion of the oceans, that can originate both from occasional changes with climate variations, and from the increases in the concentrations of greenhouse gases. Increases in greenhouse gases emissions are the reasons for the higher temperature detected in water bodies, evidencing modifications in sea water density at constant values of the relative mass [30]. As the temperature increases, an increase in the volume of sea water can be observed, triggering a sea level rise. In recent years, a clear trend to increases in seawater surface temperatures has been observed and since 1960, thermal expansion has been thought to be responsible for approximately 25% of sea level rise [31]. In the period from 1993 to 2009, thermal expansion has been considered the cause of the 30% sea level rise around the world, and by 2100, thermal expansion will cause a sea level rise greater than 12 cm [32]. Melting of the Greenland and Antarctic ice sheets, in addition to the melting of glaciers and small ice sheets are processes caused by climate change, inducing increased values of sea level rise. From 2003 to 2010, a major decrease in ice mass and ice sheet mass of about 148 ± 30 Gt yr^{-1} was recorded, together with increases in continental glacier melt, resulting in sea level rise of about 0.41 ± 0.08 mm yr^{-1} [33]. Antarctic glaciers melt affected sea level rise by about 10.8 mm from 1992 to 2018 [34]. The melting of glaciers and ice sheets, in consideration of the important recent increases in greenhouse gas emissions, represents the main cause of sea level rise, registering contributions equal to about 50% [35]. Further increases in sea level rise are likely to be expected in the future, considering the difficult situations and the many factors involved in this phenomenon [33].

Structural changes are important agents that play a role in sea level rise as they can cause ocean basin shrinkage, leading to ocean volume decrease, and land subsidence may develop due to tectonic movements and structural subsidence. The entity of influence of structural modifications on sea level rise can be estimated in about 10%. Nevertheless, depending on local conditions, structural modifications may have a role far exceeding the effects caused by melting of glaciers and those originated by the thermal expansion of the oceans [36].

Anthropic modifications including mining of water and oil, decrease of forests and construction of dams along rivers, can cause subsidence in coastal areas, inducing lower values of land elevation as respect to the sea level, thus contributing to sea level rise [16]. Groundwater extraction, along with irrigation and deforestation, can cause variation in inland waters, affecting sea level rise, as in the case of freshwater sites replacing in the coastal zone. As regards construction of dams along rivers, this phenomenon was particularly evident during the second half of the twentieth century and led to a reduction of the introduction of sediments into river mouths with consequent sea level rises [37].

All these factors influence sea level rise with values equal to 30%, 50%, 10% and 10% for thermal expansion of the oceans and melting of glaciers, both originated from climate change, man-made modifications and structural modifications, respectively [38]. A description of causes triggering sea level rise (SLR) phenomenon is reported in Figure 2.

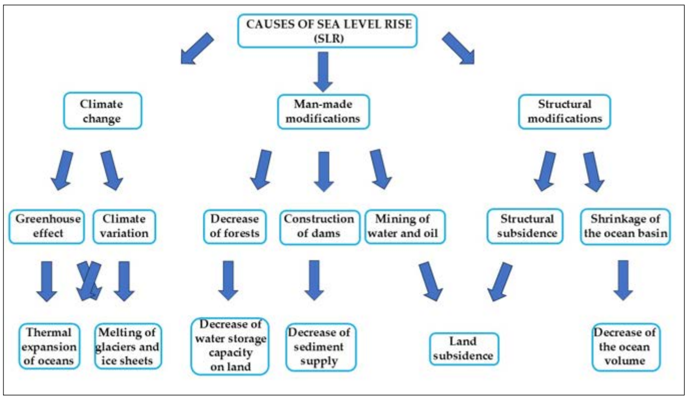

Figure 2: Causes of Sea Level Rise (SLR), Including Climate Change, Structural Modifications and Man-Made Modifications. Cascading Effects Have Been Included

Until about the mid-1800s, sea level rise was detected at values lower than 1 mm yr^{-1}, but after this period, there was a faster sea level rise than previously recorded [6]. For most of the twentieth century, tide gauges highlighted sea level rise measurements included in a range from approximately 1.2 mm yr^{-1} to about 1.7 mm yr^{-1} [39]. According to monitoring during the past 10 years, satellite-based measurements showed an acceleration of sea level rise, with average values that from about 3.4 mm yr^{-1} have reached values of about 4.8 mm yr^{-1} [40]. Over the past two decades, sea level rise has shown a rate of 2.5 mm yr^{-1}, with mean relative sea level rise ranging from 7.8 mm to 9.9 mm yr^{-1} in low-lying coastal areas [6]. It was reported that sea level rise could increase by up to 1.10 m by the end of the twenty-first century [41]. Sea level rise increase by the end of twenty-first century represents a high risk for more than 3 million people for every 2.5 cm sea level rise and for one billion people living within 10 m above high tide [39]. Even considering the Paris Agreement on climate change, it is assumed that sea level rise will continue to develop even after greenhouse gas emissions have been reduced by 2050. Sea level rise is projected to continue after 2100 for decades and even centuries into the future. Even without further greenhouse gas emissions, due to the countermeasures adopted, the inertia of sea level rise will continue. The increase will be approximately 66 m of total sea level rise in the future [40]. Furthermore, populations living on coasts will be the most exposed to the risk of flooding [39,42]. Sea level rise poses a serious threat to coastal regions which can be exposed, in the coming decades, to increased vulnerability resulting from extreme marine events such as flooding, submersion and coastal erosion [43].

Sea level rise (SLR) is projected to affect human health and wellbeing, cultural and natural heritage, freshwater, biodiversity, agriculture, and fisheries. Although many people and the population are planning to adapt to sea level rise, human mobility has been included within climatic and environmental hazards, with sea level rise forcing people away from their coastal homes. It is possible to estimate that half a million people in archipelago and island countries might live in sites that were at risk of submergence or loss of land by 2100, contributing to increased numbers of so-called 'climate refugees [44,45]. Global coastal migration due to sea level rise could represent a growing phenomenon of the 21st century [44]. An accelerated sea level rise and increased coastal flooding have the potential to displace millions of people. It is estimated that 17 to 72 million people globally will have to migrate from coastal areas during the 21st century [46].

Coastal Flooding

Coastal flooding occurs when high sea levels impact land-based structures designed to remain dry [47]. Coastal flooding often occurs because of the combination of storm surges, high tides, seasonal sea level anomalies, and sea-level rise [48]. Coasts are characterized by various morphological types including estuaries, beaches, dunes, low and high cliffs and steep mountains. The most vulnerable type of landforms are the lower-lying coasts, which are often subject to flooding caused by wave action and large storm surges acting simultaneously at very high tides. Based on the effects that sea level rise can cause, it is very likely that in the future flooding will occur more frequently at higher elevations. Sea level rise will also be followed by permanent floods and the consequent loss of beaches and coastal wetlands [39]. It has been demonstrated that increasing coastal hazards combined with development and demographic concentration in coastal areas makes the need for adaptation urgent. Coastal communities need responses, projects and informed action to handle the effects from sea level rise and climate change [39]. Coastal nuisance floods are low-level floodings that do not pose a significant threat to public safety or cause serious property damage, but can disrupt routine daily activities, cause problems such as flooded roads and overloaded stormwater systems which can give rise to serious inconveniences for people and can represent an optimal habitat for microorganisms and mosquitoes. Since 1950, the total number of nuisance flooding events has grown exponentially. More nuisance flood events were recorded in 2019, with the most representative events occurring in estuaries [49]. At coasts and in many of the major estuaries, presenting anthropogenic alterations, nuisance flood may cause significant disruptions [49]. Coastal flooding particularly damages densely populated coastal cities, where sea level rise and extreme weather events may trigger for climate-induced migration, with the poor, women and ethnic minorities being the most vulnerable [39].

Salinity Intrusion

The contamination of groundwater from saltwater intrusion is comprised among consequences of sea level rise [50]. This phenomenon can cause alteration of water quality in coastal sites (e.g., increased salinity), and can be particularly evident in low- and middle-income countries, characterized by untreated drinking water [51]. Salinity deals with the concentration of dissolved salts in water, including Na^{+}, Mg^{2+}, Ca^{2+}, and K^{+}. Due to the greater agricultural demand for groundwater, the increased salinization of surface waters, and impacts of climate change (e.g., more intense droughts), the possible drinking water salinity associated with groundwater aquifer sources is expected to get worse in the future. A significant association between drinking water salts and high blood pressure was pointed out [52]. Considering that more than 600 million people are living in coastal sites <10 m above sea level, different populations may suffer from salt-water intrusion under future climate change circumstances [52]. Sea level rise has negative impacts arising from the intrusion of salinity into freshwater which causes reduction in the growth of freshwater aquatic species and alters the balance of the ecosystem. Furthermore, salinity intrusion into freshwater can reduce coastal agricultural areas, limit agricultural production, restrict grazing areas, and increase the cost of freshwater supply for livestock, again due to salinity intrusion. Other activities that take place along the coasts and that can be affected by salinity intrusion are represented by fishing, agriculture, forestry, the energy sector and transport, as road and rail infrastructure can also be subject to erosion from saltwater intrusion [39].

Coastal Erosion

Coastal erosion is a natural process, but recently the rate of coastal erosion has increased due to climate change [53]. Coastal erosion occurs when wind, waves, and longshore currents move sediment from shore and deposit it somewhere else. These different sites of deposit can include other coastal regions, deeper ocean bottom, or ocean trench. The removal of sediments from shore results in permanent changes in the shape and structure of the coast. One of the most direct consequences of coastal erosion is the coastline retreat, producing important damages to the infrastructure at coast [53]. Climate change is an accelerator impairing the coastal erosion processes by raising mean sea-level, damaging coastal ecosystems, bringing extreme weather events, and increasing wave forces and storm surges [53]. The phenomenon of coastal erosion is represented by the long-term loss of sediment within coastal zones following changes induced by wind, waves and currents. Such hydrodynamic forces that occur along the coast allow for the transport and loss of sediments that provide material for the development of dunes, beaches and marshes in the natural coastal cycle. Coastal erosion can be exacerbated by the combination of natural forces with the effects of climate change. In this context, sea level rise is responsible for long-term coastal erosion [54]. Coasts are highly sensitive regions and whenever erosion occurs, it must be considered that tackling erosion problems along a sandy coast is different from tackling erosion that has developed along a muddy coast, or a mangrove coast, or with clay or rock. Features such as cliff and coastal mountains are areas of higher elevation and more vulnerable to coastal erosion caused by wave action at high tide or at high sea level. For an effective control of erosion phenomena in particularly sensitive stretches of the coast, it is necessary to pay close attention to the details of the coastal morphological characteristics and the existing wave motion [55]. In coastal systems with mangrove, sea level rise can promote coastal erosion with a decrease of the mangrove system, both in terms of quantity and with the reduction of biodiversity, since the increased salinity of water selects for the more resistant species of mangroves [54]. Coastal erosion can cause damage to infrastructures including power plants, fuel lines and other facilities located in coastal areas, causing increases in energy and infrastructures coasts [55]. Wave energy can reach and damage both the base of coastal cliffs and dune, causing increased rates of erosion. Coastal threats will have economic impacts such as passive erosion and gradual beach loss [39]. The phenomenon of coastal erosion is increasing globally, and related investigations should include studies on sea level rise and other causes for coastal erosion, according to a holistic approach [56].

Mediterranean Sea Coastal Areas

Coasts in the Mediterranean Sea are exposed to important climate change impacts, such as extreme weather events, and to human induced pressures such as houses building at coasts, leading to an increase in coasts vulnerability. The coastal areas of the Mediterranean basin are disturbed by climate change effects, including sea level rise, storms, droughts and coastal erosion, and these phenomena are expected to continue [57].

In the Mediterranean region, sea level rise and flooding events related to storms will put low land areas in danger of submersion, with damage to coasts and beaches. Marine habitats and coastal ecosystems in the Mediterranean region are also threatened by the risk of loss of portions of these ecosystems. In the coastal region of the Mediterranean Sea, about 46% of low sedimentary coasts such as beaches, dunes, reefs, lagoons, estuaries and deltas are present. The coasts of the Mediterranean are therefore more changing than the rocky coasts, based on the balance that is established between the force of the sea and the contribution of sediments, to determine the growth of the coast, or its erosion or stability [58]. The stability of the coasts can be influenced by the presence of artificial interventions in the coastal areas. In the Northern Mediterranean, 25% of the coast is affected by erosion and along the same Northern Mediterranean coast there is a concentration of 10% of marine defenses [58]. The northern coast of the Mediterranean was transformed by artificial interventions during the twentieth century, with an extension equal to 1,500 km [58].

The current increase in sea level rise will accelerate coastal erosion, due to the presence of higher waves and modifications in current dynamics, thus affecting sediment balances. Furthermore, enhanced coastline type and geomorphology, frequency of storms and moderate winds may further contribute to coastal erosion [59]. The rate of sea level rise showed significant modifications in the Mediterranean Sea. During the period between 1960 and 2000, the sea level in the Mediterranean remained at constant values or showed a slight decrease (average rate of -0.3 ± 0.5 mm yr^{-1}), while in the same period, in the eastern North Atlantic Sea, the level rose by more than 1 mm yr^{-1} [60]. In the period from 1960 to 2000, small rates of sea level change only, have been observed in the Mediterranean Sea. These sea level changes were at least in part due to a constant increase in the atmospheric pressure over the Mediterranean basin which was related to the North Atlantic Oscillation (NAO) [61]. Instead, the level of sea water in the Mediterranean Sea initiated to accelerate after 1989, with an average rate of sea level rise of 3.6 ± 0.3 mm yr^{-1} over the period from 2000 to 2018, due to current changes and ice melting and in line with global average rate [62]. Sterodynamic sea level changes, originating from changes in the circulation of oceans, currents, temperature, density, and saltiness, along with melting of land ice could have caused an increase of sea level rise in the Mediterranean [63]. Since 2000, the higher values of sea level rise have been evidenced in the Adriatic, Aegean and Levantine seas, with respect to values detected in other parts of the Mediterranean Sea [63]. Risks associated with climate change, including sea level rise, storms and droughts, can heavily affect Mediterranean coastal areas, with the highest evidence in Eastern and Southern Mediterranean coasts [64]. Sea level rise and flooding will represent serious challenges in the Mediterranean basin, along with losses of coastal and marine habitats and related ecosystems [64]. Moreover, climate change has a role in inducing drying trends, with droughts mainly centered in countries of the eastern portion of Mediterranean, including Greece and the Middle East. Besides, it is expected that droughts will intensify in the future in the Mediterranean region, with water scarcity representing a major concern. The effects of droughts coupled with those triggered by sea level rise and storms represent serious concerns for estimation of coastal erosion [57].

The local rate of sea level change can be changed by global modification, such as the enhanced melting rates of land glaciers and thermal expansion of the oceans [41,65]. Concerning future sea level changes in the Mediterranean, the Intergovernmental Panel on Climate Change (IPCC) has reported projections of sea level rise sea in the range of 10 to 30 cm by 2050 and 10 to 90 cm by 2100, with severe impacts on the southern Mediterranean region and a future increase in storms in the Adriatic and Aegean seas [66, 67]. The level of the Mediterranean Sea is estimated to rise at least 150 mm by 2050 and 500-1000 mm by the end of the century, worsening coastal flooding risks [68].

The urban development represents a process that can influence the future of coasts and related flood risk, with higher impacts in low lying coastal areas than in other regions [69]. The Mediterranean region is a hotspot of urban development, and this area is characterized by a high population density, with the presence of rapid demographic, social, economic and environmental changes. During the period from 1960 to 2010, a doubling of the population from 240 million to 480 million has been recorded in the Mediterranean area, with the urban population showing an increase of 20% [58]. It is expected that this area region will encounter a 160% increase in urban amount between 2000 and 2030. Therefore, many cities of the Mediterranean basin will be potentially exposed to climate-related hazards such as coastal flooding and erosion. These phenomena are likely to increase in the future, also due to socio-economic development in the Mediterranean region [69].

In the Mediterranean countries, the situation is further influenced by the effects of tourism, which has been registered in continuous growth and mainly along the coast. To deal with these threats, political decision makers and coastal administrations in Mediterranean countries require estimation of impacts and levels of vulnerability. To reach these goals it is thus necessary to collect a high amount of information on various aspects, from physical and ecological to socio-economic pathways at the level of the Mediterranean coastal area [70].

Mediterranean Coastal Hotspots

Mediterranean coastal hotspots are sites showing a high sensitivity in this area. The Mediterranean basin is one of the most affected regions worldwide by continuing climate change effects and extreme atmospheric events (Table 1). The Mediterranean region is located approximately between 30°N and 45°N of latitude and 6°W and 35°E of longitude. This area is mainly characterized by warm/hot dry summers and mild winters over the Southern European coastal regions, some strips along the North African coast and part of the Middle East, or by arid climates, with hot and dry conditions all year round, over the North African region. Phenomena of extreme precipitations can occur in the Mediterranean area, mainly due to cut-off lows and to warm-core mesoscale cyclones that are occasionally generated over the Mediterranean Sea, known as "medicanes" [71]. Based on observational and on model-based studies, the Mediterranean basin is defined a significant climate change hotspot. Global warming, a consequence of climate change, determines an increase in the frequency and intensity of extreme events. It is thus essential to identify the most affected areas and develop strategies to mitigate the associated risk. This underscores the necessity for a more localized definition of hot spots to enhance targeted interventions and adaptive measures. Definition and assessment of hot spot areas by combining the results of different indices evidenced six hotspot areas in the Mediterranean region [72]. Based on historical changes, these six regions resulted as the most vulnerable to climate change in the Mediterranean. The identified hotspot regions that are the most vulnerable areas due to recorded changes in temperature and precipitation values are: the Iberian Peninsula, south Italy, and Cyprus Island. The hotspots due to changes in extreme climate events comprehend north Italy, Greece, and Israel [72]. The Eastern Mediterranean is a sub-region that needs significant attention as it is affected by changes in both extreme and mean climate conditions. The area of Israel evidences a high sensitivity to increase in minimum temperature [72]. The Cyprus island is characterized by important changes in mean values of temperature and precipitations. This is in accordance with the fact that Eastern Mediterranean and the middle East are greatly affected by climate change and are warming almost twice as fast as the global average and other inhabited parts of the world [73].

Another area designed as a hotspot is the northern part of Greece, when significant warning was noted in summer over the past three decades [72]. In Italy, the northern part shows vulnerability to extreme conditions, and the Alpine Area responds to the principles as a hotspot, with an intense response to climate change. The southern part of Italy presents intense climate change responses, with extreme rainfall events and extreme phenomena like draughts and floods. In the western part of the Mediterranean, the Iberian Peninsula is a region characterized as a hotspot. This region is susceptible to changes in precipitation and temperature, with a high risk of extreme temperatures and summer heatwaves [72].

In Table 1, several coastal hotspots and critical sites have been reported. Table 1 includes hotspot sites belonging to regions that present high vulnerability due to important changes in temperatures and precipitation values. Among these hotspots, Iberian Peninsula was mentioned for the Deltas of the rivers Ebro and Tordera, for the Gulf of Valencia, and for coasts of the Baleari Islands. Flooding and coastal erosion phenomena have been evidenced in all these hotspots of the Iberian Peninsula (Table 1). South Italy was also included as a Mediterranean area including hotspots presenting changes in temperatures and precipitation values. South Italy included coasts of Southern Italy, in general, and Apulian Coasts, characterized by phenomena of flooding and shoreline changes. The Cyprus island, in the Eastern Mediterranean, is included in the area with changes in temperatures and precipitation values, with sea level rise and coastal erosion phenomena, as reported in Table 1. Considering different characteristics of Mediterranean hotspots, specifically changes in extreme climate events, in Table 1 it is reported the area of north Italy, with the hotspot of the Delta Po River. The latter presents soil salinization and altered water distributions regimes, causing an increase in flood events and coastal erosion. In Table 1, further hotspots characterized by the same features consisting in changes in extreme climate events includes Greece, with Deltas of the rivers Axios and Aliakmonas, the island of Rhodes, the coasts of south Greece, and the Thermaikos Gulf. In these hotspots, sea level rise and increases in coastal erosion have been pointed out. In the Eastern Mediterranean Sea, Israel is included among the Mediterranean hotspots characterized by changes in extreme climate events. Coasts of Israel are highlighted form coastal shoreline changes and coastal erosion and their restoration by using seagrass meadows in protecting coasts from waves forces. In Table 1, other critical points of the coasts of the Mediterranean Sea have been included, specifically coasts of Albania, Algeria, Croatia, Egypt, France, and Tunisia. Table 1 reports hotspots in the coasts of the Mediterranean Sea that can be considered for possible future interventions of recovery with the participation of citizens, stakeholders and policymakers.

Table 1: Mediterranean Coastal Highlighted Hotspots/Critical Sites

Mediterranean coastal hotspots/ critical sites	Specific features	Potential impacts	References
Albania, Albanian coast	Local phenomena such as subsidence and land elevation	Salinization of coastal aquifers and deterioration of the quality of drinking water	[74,75]
Algeria, Gulf of Oran	Vulnerability of coastal areas	Coastal erosion, flooding and salt intrusion	[76]
Croatia, Cres-Lolinj	Increased salinization of Lake Vrana	Coastal erosion and flooding	[74,77]

Croatia, Kaštela Bay	Increased salinization of estuaries and groundwater	Flooding of Pantana spring and Zrnovnica estuary and deterioration of historic buildings and increased water needs in homes, industries and agriculture	[74,77]
Cyprus, Eastern Mediterranean	Long-term erosion due to sea level rise (SLR) and severe storm erosion projected by 2050	The 100-year extreme sea level event (ESL100) may temporarily overwhelm 49% of the currently unprotected Cypriot beaches, with the most exposed located along the northern coast	[78]
Egypt, Delta of Nile	Sea level rise	Increased coastal erosion, increase in floods with damage to port and city infrastructures, retreat of the barrier dunes, decrease in soil humidity, increase in water salinity in the soils and in lagoon areas, and decrease in fish production	[74,79,80,81,82,83]
Egypt, Fuka Matrouh	Increase in evapotranspiration and decrease in rainfall	Extension of aridity levels in the summer period and increase in coastal erosion phenomena and decrease in soil fertility	[74,84]
France, Delta of Rhône	Coastal erosion and reduction of wetlands and agricultural land	There is therefore a greater impact of the waves and an increase in the salinization of coastal lakes, as well as a destabilization of the dunes	[74,85]
Greece, wetland delta of the Axios and Aliakmonas rivers	Conformation of the dynamics of the Mediterranean river delta	Requirement of the use of Earth Observation technologies and GIS as tools to collect information	[86]
Greece, Island of Rhodes	Soil erosion in the Maltese Islands and groundwater salinization phenomena in the island of Malta	Increased coastal erosion phenomena, salinization of groundwater, increased soil erosion with loss of freshwater habitat. Additionally, there may be increased risks from pathogens to human health, livestock health, as well as agriculture	[74,87]
South Greece	Geomorphological conformations and morphology of coastal slope	Coasts erosion	[88]
Greece, Thermaikos Gulf	Sea level rise	Coastal lowland flooding, saline water intrusion into rivers, groundwater salinization, damage to coastal protection structures, changes in the tourist season	[74,89]
Israel, Eastern Mediterranean	Climate change hotspot and coastline alterations	Coasts protection by using the *Cymodocea nodosa* seagrass	[90]
Italy, Apulian Coastline	Geomorphological conformations, aspects of the coastal slope, width of beaches and dune sand of vegetation behind the beach	Coasts erosion	[91]
Italy, Delta of Po	Soil salinization, altered water distribution regimes, reduced nearshore water mixing	Increased flood events and coastal erosion, dune retreat, damage to coastal infrastructure,	[74,92,93]
Italy, coasts	Changes in distance from shoreline, elevation, coastal slope, geological coastal type, land roughness	Shoreline pathways change	[94]

Spain, Balearic Islands	Important effects due to impacts of sea level rise on coasts	*Posidonia oceanica* seagrass meadows along coast increase resistance to marine heat waves	[95]
Spain, Delta of Ebro	Sea level rise	Increases in coastal erosion rates and coastal reshaping, inundation and loss of wetlands, reductions in fisheries	[74,96]
Spain, Delta of Tordera	Very high "hotspotness" condition	Extensive and frequent damage to the site in recent decades	[97]
Spain, Delta of Ebro	Changes in the urban area near coasts	Flooding and erosion phenomena	[98]
Spain, Gulf of Valencia	Sea water level rises, storms and wave surges	Coastal vulnerability to erosion, flooding and saline intrusion	[99]
Syria, Syrian coast	Increase in soil erosion phenomena, groundwater salinization, exceptional storm surges	Beach erosion and damage to coastal structures and human settlements	[74]
Tunisia, Gulf of Gabes	The islands on this site could be flooded in the presence of significant sea level rise phenomena	Phenomena of salinization of groundwater and coastal erosion	[99,100]
Tunisia, Gulf of Tunis	In recent years, a dramatic increase in population migration has been noted in this area with particular importance for the coastal areas	Important coastal retreat phenomena, with alterations in fishing activities, due to sea level rise	[83]
Tunisia, Ichkeul Bizerte	Increase in evapotranspiration	Decrease in soil moisture, decrease in lakes, increase in lake salinity, decrease in wetlands and loss of habitats	[74]
Tunisia, Sfax coastal area	The mean sea level at this site reached a value of 116 cm, with an annual increase of 2.8 ± 0.2 mm yr^{-1}	Groundwater salinization, erosion and possible flooding	[74,101]

Mediterranean Sea Monitoring

The Mediterranean coasts are affected by extreme climate change episodes, coupled with anthropic pressures, with both phenomena leading to high vulnerability. Monitoring is a key step to adding knowledge and to protect this area. Asan example, the method of Coastal Risk Index allows risk assessment in the Mediterranean region (CRI-MED), by achieving an integrated assessment of risk and vulnerability in respect to the physical and socioeconomic impacts of climate change and to other forces acting at coastal level. The CRI-MED method gave information on risk evaluation in eleven countries of the Mediterranean basin, counting Albania, Algeria, Bosnia and Herzegovina, Croatia, Egypt, Libya, Montenegro, Morocco, Palestine, Syria and Tunisia. Later the CRI-MED method was used to measure risk in France, Greece, Israel, Italy, Lebanon, Malta, Slovenia, Spain, and Turkey. This approach can detect the possible consequences climate change effects can have on coastal ecosystems and on populations living on the coasts of the Mediterranean Sea [57] (Table 1). The method allowing identification of coastal hotspots in the Mediterranean area is finalized to highlight the need of intervention by policy makers and administrators, by considering the evaluations based on Integrated Coastal Zone Management (ICZM). This approach enables identification of suitable coastal sites to be allocated for urban settlements and for others economic and social actions [57]. Another approach for monitoring the Mediterranean basin, defined as the Mediterranean Coastal Database (MCD), focuses on the coastal impacts of sea level rise and on adaptation assessment and associated hazards of sea level rise in a regional context. This method uses details about morphology of coasts, population settlements and governmental entities, collected at coastal assessment units along Mediterranean coasts. Using this method, various parameters are taken into consideration ranging from the characteristics of natural and socio-economic subsystems, such as extreme sea levels, or aspects related to the vertical movement of the land, or the number of people who are exposed to these phenomena. This method provides insight into both current conditions and subsequent trends, including rates of sea level rise and of socio-economic development. Moreover, the method of Mediterranean Coastal Database allows us to obtain advice on risk and impact assessment [70]. This approach was developed for Mediterranean Sea monitoring according to concepts of interdisciplinarity. This approach brings together different geoscientific disciplines, including sedimentology, geochemistry, hydrology, paleontology, ecology, biochemistry and archaeology. This method is based on analyses of sand reservoir sources, allowing the quantification of sediment current occurring at sea-land level, thus permitting to identify sediment flows and to evaluate hydrodynamic parameters. Such approach enables to highlight local environmental concerns related to urbanization of Mediterranean coastal areas. This kind of approach could give original data about relationships between construction of dams, hydrology of rivers and origins of sediments, and could shed light on the impacts of both effects of climate change and man-made actions, on the coastal geography, morphology development and on ecosystem features. These data represent important support to policy makers and to the socio-economic actors for planning interventions for remediating altered Mediterranean coasts [102]. Based on the principles of Ocean Literacy, a movement born in the United States and made up of essential principles and fundamental concepts, now widely accepted around the world for use in both traditional and non-traditional educational contexts, a literacy of the Mediterranean was born. The latter is developed according to features of the Mediterranean area, with assumptions and notions that serve as a guide for developing studies and to give advice to decision-makers and to improve the quality of life, thus contributing to the defense of the environment, to the maintenance and reconstruction of the Mediterranean Sea and to make their contribution to a sustainable blue economy. Mediterranean Sea Literacy can help the development of the Mediterranean Sea aimed at achieving an innovative and sustainable blue economy and thus to the accomplishment of Sustainable Development Goal 14 in the Mediterranean region [103].

Mediterranean Sea and Migrations

Sea level rise (SLR) causes increase of storm surge heights and inundation levels, exposing coastal population to an increase of the coastal flood risk. Sea level rise causes shoreline recession, with modifications of beach profiles according to the new prevailing wave conditions [104]. Loss of sandy beaches can affect coastal communities due to an increasing flood risk that may drive coastal communities out of the coastal floodplain [105,106]. Changes in flood risk and in erosion rates induced by sea level rise, could reinforce the migration of millions of coastal inhabitants before the end of this century [44,45].

Climate change affects people living in poverty, many of whom live in disadvantaged informal settlements, often along coasts. These populations are often at risk of flooding and have little or no visibility [107]. The serious problem of migration in the Mediterranean was dramatically revealed in 2015, in the presence of an extraordinary entrance of migrants from the regions of Middle East, Maghreb and sub-Saharan Africa that involved Europe [108]. As consequences of inundations and of increase of hazards due to sea level rise, large proportions of communities are subjected to move, with an increase in migration responses. Direct flooding influences migrations, along with socioeconomic and demographic inequalities that can interact with climate change effects, enhancing migration responses [105]. Currently, the processes of migration, triggered by sea level rise, also depend on other aspects such as the economic, social and cultural, with migration that can remain the only possible alternative [44]. Interventions to avoid migration through protection and housing are well developed, but relocations are not equally developed and cannot guarantee equity. Knowing the thresholds of migration resulting from sea level rise are key points for knowledge about climate change related migration [105]. Migration because of climate change could represent a growing phenomenon of the twenty-first century, as the population that is exposed to environmental effects will probably significantly augment [109]. Phenomena such as the increase of temperature along with modifications of the precipitations and of sea level rise will also cause extreme weather events, including changes in wave energy and frequent droughts and floodings. As consequence, people can then address these impacts through migration [110]. As a measure to contain the migration process, protection of coasts can represent a way to reduce this phenomenon and to maintain stable the populations living along coastal areas [111].

Risks for World Heritages in The Mediterranean Area

The Mediterranean region occupies a unique position at the ideal interface between Europe, Africa and the Orient. The Mediterranean Sea represents a multicultural crossroads and an important source of creativity, with a true Mediterranean, historical and multicultural identity. The Mediterranean embodies a celebrated sea, frame of glorious civilizations, and source of great changes, the theater of exchanges and economic activities. The institution named United Nations Educational, Scientific and Cultural Organization (UNESCO) includes heritage under the World Heritage Convention [112]. Coasts host a large portion of unities included in the cultural World Heritage Convention, that are in coastal areas as human activity has traditionally concentrated in these locations. The Mediterranean Sea is considered among the hotspots as respect to climate change. Moreover, 86% of the World Heritage sites are already located in this area at risk from flooding and coastal erosion [113]. Considering that, caused by sea level rise, in the future flooding and erosion will increase, a high number of coastal World Heritage sites will be threatened by these hazards. High concentrations of cultural World Heritage sites are distributed along the coasts in the Mediterranean region, because of ancient civilizations that developed in this region [114]. In the Mediterranean area, both the ancient cities and those of today are located along the coast and just above sea level. Therefore, adaptation and protection interventions are needed throughout the Mediterranean area. However, the socio-economic differences between the northern, eastern and southern Mediterranean countries make interventions difficult and these sites remain poorly protected from coastal risks [113]. In the period from 2000 to 2100 there will be most of the World Heritage Convention at risk, and particularly those already threatened under current conditions. As a function of the sea level rate, there will be a large increase in the risk of flooding for World Heritage sites. In this context, it is important that decision-makers detect the areas with higher probabilities of being damaged and propose possible countermeasures [113] (Table 1).

Engineering Approaches for Coasts Protection

Sea level rise causes flooding, increased rates of coastal erosion, saltwater intrusion, and land subsidence. Sea level rise and coastal erosion have serious impacts such as disruption of economic activities, degradation of natural ecosystems and alteration of biodiversity [115]. Cities in coastal areas suffer from problems related to sea level rise, and several defense approaches need to be adopted to combat these serious challenges [39,116,117]. The Coastal Management Subgroup and Response Strategies Working Group has identified three measures to address sea level rise, namely protection, retreat and accommodation [118]. In Europe, risk reduction in coastal zones has included additional specific strategies [54], which have been described in various studies [119,120]. These adaptation measures improve the coastal environment both from a natural point of view and considering socio-economic aspects. Furthermore, measures to reduce risks related to climate change and limit greenhouse gas emissions should be included [54]. Defense interventions against sea level rise and erosion include a) “do nothing”, a procedure without action, with free areas and wetlands without physical and economic impacts that are lost to receive the impact of downstream flooding or erosion; b) “seaward movement” which consists of advancement interventions by constructing structures above sea level, using sand or other materials, with the aim of reducing the risk of flooding at coasts. This strategy can lead to compression and an increase in susceptibility for coasts and for adjacent ecosystems, wetland, salt marches and mangroves; c) “line maintenance strategy”, an intervention that consists in the introduction of elements capable of reducing the impact of seawater to avoid flooding. These elements include rigid protections such as dams, sea walls, barriers and weirs, while also preventing erosion at coasts and intrusion of water into the soil; d) "managed realignment" interventions that consist of an adaptation strategy including moving, displacement and relocation of people. Moving involves the permanent or semi-permanent transfer of an individual for a minimum of one year. Displacement is a voluntary movement by an individual for the impacts of climate change or any other climate-related risk. Relocation involves administration agencies helping people move to a different location; e) "adaptation or accommodation" consisting of continued use of land at risk with interventions such as raising the platform level, the introduction of elevated structures, floating houses, contingency planning and retreat areas. This intervention aims to reduce coastal risks by diminishing impacts on human lives, livestock, ecosystems and human activities; f) "limited interventions" consisting of adaptation interventions that provide combinations of protection and enhanced advantages, preserving and restoring coastal ecosystems. The system acts as a barrier to reducing the waves energy and the speed of storms. This intervention can counteract soil erosion by stabilizing sediments at coasts, and they can be expensive to maintain and take longer to deliver results [54,121].

Hard Engineering Interventions at Coasts

Hard engineering, also defined as "grey infrastructures", offers adaptation solutions for the resilience of coastal areas [122]. Hard engineering can protect coasts due to absorption of waves energy and can diminish probabilities of coastal erosion and flooding [123]. Structures of hard engineering are characterized by a high visibility and are frequent in northwestern Europe, eastern Asia, and in deltas of rivers or in coastal cities with high density of population [124]. On the other hand, these structures, as sea walls, can worsen erosion, and decrease the ability of coast resilience. Hard engineering approaches include dikes and fixed sea walls which can stabilize coasts but can trigger erosion and threaten coasts. Hard structures also include groins able to block sand transport along the coast and are successful in beach development but can induce erosion phenomena. Detached sea walls and artificial reefs which reduce wave energy and are effective in beach construction, again can cause erosion downstream [120].

Cliff fixing is a countermeasure adopted in case of coastal erosion that can interest both rocky coasts and sandy beaches, representing approximately 52% and 31% of the whole coastlines, respectively. Erosion of rocky coasts comprehends cliff collapse and recession through movements, reversals, falls, and reductions [125]. The waves cause erosion at the base of cliffs, originating a typical notch. In the case of rocky cliff collapse, coasts changes are more evident than gradual modifications of coasts due to sandy beach erosion. Cliff fixing are hard engineering procedures built by inserting metal bars into cliffs and conferring cliff reinforcement and shorelines protection from erosion [126]. Coastal barrage is another hard-engineering procedure using dam-like structures in partly submerged, that have the role to control tidal flow. This intervention can control storm surges changing water levels and may provide protection against coastal flooding [127]. Moreover, coastal barrage can originate consistent water levels used for hydroelectricity production through the conversion of energy in marine and tidal currents to electricity [128]. Gabions are structures that reduce the impact of waves and consist of bundles of wire mesh or bare boulders placed overhanging [129]. Gabions are anti-erosion devices that protect the piers and supports of a bridge. These structures significantly decrease flooding by washout and impinging debris against the bridge superstructure. Debris can also divert flows, increasing friction and limiting the damage caused by sea level rise [129]. Groynes consist of wooden fence-like barriers built at right angles to the beach. These hard engineering devices partially or completely block shoreline drift. Each single groyne originates smaller sediment cells on the beach, acting against the wave direction, or limiting quantity of sediments deposited in tidal vents and navigation channels. These structures act by blocking the transport of sediments along the coast, to fix the seabed towards the land with respect to the tip of the breakwater with an action against the prevailing wave motion [130]. Revetments are structures placed along a cliff and consists of inclined concrete, wooden, or rock structures preventing cliff erosion by absorbing wave energy. These structures require maintenance work and can therefore be quite expensive [131]. Rock armour consists of large boulders or rocks piled into the beach in front of a cliff or seawall. These structures absorb wave energy and help build beaches. Rock reinforcements are rigid engineering structures whose stability needs monitoring as controls in the presence of high, non-linear waves which can damage such structures [132]. Sea walls, also called breakwaters, are hard engineering devices consisting of large walls placed along the shoreline of the coast and built in concrete, steel, or stone. This hard engineered structure protects cliffs from erosion and acts as a barrier to flooding. It is a wooden or stone wall that extends from the shore to the sea to protect a port or beach from the force of the waves [133]. Hard engineered coastal protection devices can have disadvantages. In fact, they can be expensive or can represent short-term solutions, or they can have a negative impact on the environment. The introduction of heavy engineering structures into coasts can modify the environment, thus suggesting the need for frequent monitoring activities. Hard engineering features are reported in Table 2.

Table 2: Types of Hard Engineering Interventions at Coastal Level

Intervention type	Intervention features	Relevant advantages	Important disadvantages	References
Hard engineering				
Cliff fixing	Metal bars insertion in cliffs for reinforcement	Improvement of cliffs strength and rocks falling prevention	Possible metal mess	[126,134]
Coastal barrage	A partly submerged dam-like structure modulating tidal flow	Originating a higher water level thus allowing the production of hydroelectricity	Possible strong impacts on the environment and high costs for implementation and maintenance	[127,135,136]
Gabion	Rocks and boulders encased in a wired mesh	Absorption of the energy from waves	It cannot be very effective or attractive	[137,138]

Groyne	Insertion of barriers like wooden fences arranged at right angles on the beach	Drift along the coast allows for flood and erosion prevention and beach formation	This structure may encompass the possibility of triggering further erosion downstream and, in addition, the need for high maintenance costs	[130,139,140]
Revetement	These are sloping structures made of concrete, wood or rocks positioned along a cliff	Waves energy absorption and cliff erosion prevention	Possible strong wave backwash and expensive to implement	[131,141]
Rock armour	They consist of large boulders or rocks that are assembled on the beach in front of a cliff or seawall	The absorption of wave energy favors the expansion of beaches	High costs for implementation and maintenance	[132,142]
Sea wall	Large concrete, steel or stone walls positioned along the shoreline of the beach	Protection of cliffs from erosion and establishment of a flood barrier	These structures can give rise to waves capable of eroding the wall and furthermore maintenance is expensive	[133,143,144]

Soft Engineering Interventions at Coasts

Soft engineering protection approaches facing to coastal degradation gained recognition for the benefits in coasts protection. This kind of engineering approach allows coasts to dynamically respond to changes, respecting environmental equilibrium. Such applications, defined as "building with Nature," consist in strategies that provides an effective response to protect beaches and coastal areas. These responses offer economic and social benefits. Soft adaptation is an environmentally friendly protection response in coastal ecosystems [145]. The principles of conservation, restoration, and use of vegetated coastal habitats in eco-engineering processes for coastal protection, provide an effective strategy, giving important insights for climate change effects mitigation and adaptation [146]. Coping with the problems of coastal erosion with the use of vegetation allows to dissipate the energy of the waves, whose flow separated, and the friction given by their presence makes the bottom more irregular, reducing the speed of the wave flow. Furthermore, the contribution of vegetation to bathymetric changes through sediment accumulation and shoreline accretion is critical for shoreline protection [146]. The soft engineering approach works in consonance with nature to protect the coast and are defined as "Nature-based solutions," actively promoting nature participation for climate mitigation and adaptation purposes. The definition of "Nature-based solutions" by European Community is: 'aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions. Nature-based solutions use the features and complex system processes of nature in order to achieve desired outcomes, such as reduced disaster risk and an environment that improves human wellbeing and socially inclusive green growth' [147,148].

One way to stabilize the coasts, and particularly the dunes, while respecting the natural principles of the vegetation, includes the planting of trees, with the method defined afforestation of the coastal dunes. Coastal dunes are in fact considered major elements in the coastal response to waves during a storm and to the impacts of storm surges on coastal plains. The soft engineering approach of coastal dune afforestation presents a vegetation cover that binds existing sediments, allows accumulation of fresh sediments and dune volume and dune crest elevation expanding. This type of process offers advantages by stabilizing the dunes, thus minimizing coastal erosion [149,150]. Beach nourishment is a soft engineering approach that allows increasing the path that the wave must travel, diminishing wave energy and preventing erosion. Beach nourishment procedure aims to maximize the time of sand permanence on the beach, to promote populations safety, recreation of aquatic environments, groundwater dynamics, and ecosystem resilience [151]. In approaches of beach stabilization, addition of dead trees to the sand stabilizes the beach (Table 2). This soft engineering approach can widen the beach, slowing down the waves and preventing erosion. Beach stabilization interventions can respect local ecological conditions, moreover this approach can also lead to a sustainable growth of the local economy [152]. Beach stabilization strongly sustains the use of eco-friendly approaches for coastal protection [153]. Coral reef preservation and enhancement is another soft engineering approach and requests the protection of existing coral reefs and the implantation of artificial reefs including environmentally friendly materials on the seabed. Coral reefs reduce the energy of waves, thus protecting coasts against erosion [154]. Studies on innovative techniques and new ecological engineering approaches in processes of coral reef restoration are in progress [155]. Dune regeneration is a soft engineering approach that allow for setting up barriers and for absorption of wave energy, finally reducing coastal erosion and protecting against flooding. Dune regeneration procedure allows the establishment of new sand dunes or the restoration of the existing ones. These nature-based solutions can have a key role in responding to the challenges of climate change in coastal areas [156]. Managed retreat is a soft engineering procedure where certain coastal areas identified based on their low value, become naturally subjected to erosion and flooding. The approach of naturally eroded and flooded coasts therefore favours the development of beaches and salt marshes with a low-cost and sustainable procedures [157]. Mangrove preservation and planting are soft engineering procedures requiring the planting of mangrove trees along the coast. These restored mangrove ecosystems have important ecological, economic, and social values for the coast [158]. Roots of mangrove trees hold the ground preventing erosion and allowing wave energy dissipation. Coastal wetlands such as mangroves and salt marshes are of high interest as they represent important ecosystems for reducing the vulnerability of coastal communities. Mangrove preservation is a widely applicable type of intervention to enhance coastal safety [159]. Soft engineering implements and maintains coasts providing more sustainable long-term solutions than hard engineering projects and, moreover, it is less expensive than hard engineering. Soft engineering aims to work with nature by respecting coastal systems that can adapt to wave and tidal energy [160].

Nature-based options incorporate ecology and ecosystems services to achieve coastal protection and hybrid models combined with hard engineering solutions are gaining interest [95]. Traditional hard engineering solutions, although mitigating coastal erosion processes, contribute in some cases too their aggravation. Protection engineering solutions like groins and breakwaters have contributed to the acceleration of erosion rates in coastal areas [161]. Soft engineering features are reported in Table 3.

Table 3: Types of Soft Engineering Interventions at Coastal Level

Intervention type	Intervention features	Relevant advantages	Important disadvantages	References
Soft engineering				
Afforestation of coastal dunes	Dunes stabilization by planting trees	Sand drift and erosion minimization by dunes stabilization	Planting non-native trees can impact soil nutrients deposition	[150,162]
Beach nourishment	Rendering beach wider by using sand and shingle	Increasing distances slow down the waves and their energy, preventing coastal erosion	Sand and gravel required for this type of action must be dredged from other sites and their maintenance can be expensive	[151,163,164]
Beach stabilization	Introducing dead trees in the sand, stabilizing beaches	Beaches widening waves slowing and erosion prevention	Intervention with trees needs to be sourced and their maintenance can be costly	[153,165]
Coral reef preservation and enhancement	Protection of existing coral reefs and construction of artificial reefs by placing artificial materials on the seabed	Coral reefs reduce wavelength and energy, thus protecting coasts from erosion	The materials used for the construction of the artificial reefs can give rise to a new type of contamination, furthermore the artificial reefs may not be as stable as the natural ones	[155,166,167]
Dune regeneration	Construction of new sand dunes or rehabilitation of existing dunes	The dunes act as barriers and absorb the energy of the waves thus reducing their effects that lead to erosion and protecting the coasts from flooding	Dunes can act as barriers to beach access, and new dunes can also cause land loss	[168]
Managed retreat	Some coastal areas may experience erosion and natural flooding due to their low value	The natural material originated by erosion can favor the development of beaches and the process is low cost	This approach can be time consuming and costly	[157,169,170]
Mangrove preservation and planting	The method involves the planting of mangroves along the coasts	Mangrove roots keep the soil stable, preventing erosion and helping to dissipate wave energy	Non-native mangroves can become invasive and pose a risk to the natural plants of a given area	[158,171]

Hard Engineering Drawbacks, Soft Engineering and Hybrid Solutions Opportunities

The hard engineering structures in coastline registered a rapid increase in the last years, causing an imbalance in the shape of the coast, eventually leading to the erosion of local beaches. In many cases such artificial structure negatively affects beach preservation in adjacent areas as well, because of downdrift erosion [172]. Coasts are dynamic systems and shorelines are subject to constant change influenced by wind, tides, waves and currents, to reach a dynamic equilibrium. When rapidly increasing artificial engineering structures are constructed to prevent coastal erosion, an imbalance in the shape of the coast, leading to the erosion of the local beaches, can be also triggered. Moreover, due to a lack of careful evaluation, or low control, increasingly artificial structures can be introduced along the coastlines. This can alter the natural dynamics of systems and can worsen the erosion situation [173].

The construction of sea walls, consisting in massive sloping concrete structures that resist to the force of strong waves and that can be enforced by so called “tetrapods” which are concrete tetrahedral structures designed to dissipate the force of incoming waves, appear to have an adverse effect on the fronting beaches or result in downdrift erosion [174]. Waves can top over the sea wall and erode the shoreline behind it. In case of sea walls built up out of inadequate, cheap materials quicky leads to erosion and loss of utility of these structures. Besides, erosion occurs immediately in the front of a sea wall due to increase in reflected wave energy [175]. Breakdown in seawalls and in revetments can happen on the front side due to active wave energy, but also on the back sides, because of extreme centre pressure. This pressure leads to soil fluidization inside the seawall, registering the collapse and destruction of the sea wall [175]. Sea walls are installed parallel to the coastline, and they provide shelter from wave action. These structures also result in sediment accumulation in the lee zone, meaning the area in between the structure and the coastline, thus decreasing the littoral transport along the shoreline. With offshore sea walls typically, a tombolo is created when sediment accumulates. The construction of sea walls results in changes in the wave field, nearshore current system (sometimes creating dangerous currents for recreational users) and longshore sediment transport. The reduction in longshore sediment transport can significantly increase erosion at nearby beaches, as seen with other structures interrupting the sediment flux [174]. A case study on sea walls causing sandspit disturbance was conducted at Loc A beach in Vietnam. To collect data on shoreline erosion detected shoreline positions were extracted from using long-term satellite images and historical maps studied. In the field, evidence of coastal erosion is uncovered and explored in the beach morphologies, such as formation of beach scarps, sharps edges, fallen trees, collapsed, or damaged houses and structures, etc. After construction of the inlet seawall for navigation purposes, the NE seawall blocked the south-westward longshore drift, resulting in sand deposition northeast of the seawall, resulting in the formation of a wide foreshore. At the downdrift side, adjacent to the SW seawall, downdrift erosion will increase because the sediment flow is interrupted. After the construction of the seawall, the navigation channel frequently needs to be dredged, as it turned out that the channel in between the seawalls traps a lot of sediment. Thus, by interrupting the natural dynamics, the sandspit formation is halted and there is no more equilibrium as the surrounding morphology gradually changes and more erosion will occur at fixed points [176]. Another case was registered at the recreational beach Jinshawan (golden sand bay) in Taiwan, with satellite images and numerical simulations that were used to analyse morphological changes [177]. Sea walls were installed at the Hommei fishing port in northern Taiwan and after 1984 when the northern breakwater was extended, the sediment transport has been further blocked. This has led to severe erosion of the neighbouring Jinshawan beach. Although the breakwater helps to provide shelter for the harbour (by reducing wave heights), it also results in changes to the wave field and the nearshore current system and sediment transport pattern have been altered. Reversed currents are one of the side effects of the sea walls extension, and the sediment from the adjacent beach is transported towards the harbour entrance. Due to these changes in wave patterns, sand has been removed from the Jinshawan beach, and the beach has been disappearing [177].

Groins (or groynes) are often installed to trap moving sand at erosion sites. Groins are often constructed in parallel rows extending from the shoreline into the sea. During storm events, when waves approach the shoreline from a different angle, the protective role of groins is reduced, and the safeguarded beach will erode nevertheless [178]. The so-called "groin effect" occurs when these structures interrupt the longshore sediment transport and sand accumulates along the structures, while erosion occurs in downdrift direction. A case studies with hard engineering in Duc Long Ward and Doi Duong beach at Phan Thiet city in Vietnam, evidenced groin effect. Study of coastline dynamics in this local case evidenced changes of beach morphologies over more than a decade [176]. Remote sensing (RS) and Geographical Information System (GIS) resulted effective tools to determine the shoreline change over time and for this study shoreline changes have been mapped in GIS to detect erosion patterns at Doi Duong beach. Erosion has been observed at Doi Duong beach, because sand that would have naturally spread along the shoreline has been blocked by the groin [179]. Over 40 m of beach has been lost in a period of 9 years, related to the construction of new land and groins. This has led to increased threats for residential areas along the shoreline and the low seawall that is protecting the newly reclaimed land is at high risk of flooding, and waves are constantly washing over the seawall [179].

New engineering nature preservation and sustainability-based approaches are being developed and implemented. The requirement of smart coastal protection strategies that are sustainable, adaptable and multi-functional has emerged [120,124]. Natural approaches facing to coastal erosion and salinity intrusion showed a high efficiency over the long term. Natural approaches rely on the long-term sustainability and resilience of healthy coastal ecosystems and provide multiple benefits for biodiversity and human well-being [180]. A method to reduce hazard vulnerability is Ecosystem-based Disaster Risk Reduction (Eco-DRR); a sustainable management solution established through conservation and restoration of ecosystems, to provide facilities that reduce disaster risk and mitigate hazards, for example through restoration of coastal dune systems and active plantation near the shore. This will increase the resilience capacity of both ecosystems and social systems. Ecosystems can be adapted as a tool in coastal management strategies to deal with coastal erosion and encourages community participation in coastal erosion management processes [181]. Alternatives to hard engineering for shoreline management introduced soft engineering practices using sustainable and ecological principles to restore shorelines and reduce coastal erosion. To support these approaches, integrated coastal zone management (ICZM) represents a multidisciplinary framework that is being developed and adapted to local settings to promote sustainability in coastal zones. An integrated coastal zone management attempts to find a balance between environmental, social, economic, cultural and recreational objectives for long-term periods and co-operate in the process of decision making, implementation, management and monitoring [182]. Future functional and sustainable coastal barriers were proposed, based on nature and using nature as model. This innovative approach included the simulation of natural forms, processes, systems, and strategies to enhance coastal barrier design, in the respect of sustainability. This approach was finalized to focus on the "learning from nature" attitude. A coherent use of sustainable materials, computational design, and fabrication will allow the development of a new coastal design able to imitate and integrate nature for coasts protection [183].

When nature-based measures are implemented in combination with hard engineering, they are called hybrid approaches. They can include the use of natural substrates such as sediments and dunes along with hard engineering concrete structures [54,121]. Different hybrid solutions have been introduced to deal with coastal erosion, such as hybrid approaches, combining hard and soft engineering approaches [184]. These solutions are more sustainable and could last for a longer period, since they consider the natural processes and system dynamics, using nature as part of the solution [173].

A case study was represented by mangrove-based hybrid flood infrastructures at Sungai Haji Dorani, in Malaysia. Hybrid infrastructures were aimed at rehabilitating mangroves by constructing a permeable wall in front of the shoreline. Permeable walls were able to improve conditions for mangrove growth, through attenuating high wave energy and increasing sediment accretion rates. Such conditions help decrease shoreline erosion and increase mangrove seedling establishment [184,185]. The performance of hybrid infrastructure in relation to their coastal flood defense functions. These include land accretion, wave attenuation, survival of planted vegetation, and their ecosystems service co-benefits. All hybrid flood defense procedures incorporated monitoring schemes to assess their success. Monitoring time following project completion ranged from one to 22 years. Hybrid infrastructures showed measurable advantages over green infrastructure. For example, coastal vegetation expanded seaward behind the artificial reef structure and retreated landward in no-reef control site [184,185].

Another case of hybrid infrastructure is represented by the implementation in tidal marsh at Abbotts Hall Essex, UK, where an important aging of hard engineering coastal defenses was registered, along with damages due to extreme events, with consequent loss of coasts protection from sea level rise. The hybrid infrastructure implementation was conducted via managed realignment, consisting in the acquisition of new areas, mostly landward, adjacent to sea walls to be subsequently included into the tidal marsh. Managed realignment consists in giving valuable land back to the sea and needs social acceptance [184,186]. Moreover, this hybrid approach requests suitability assessment, with a focus on site sediment dynamics and hydrology, and environmental impact assessment of potential managed realignment. Engineering activities are commonly necessary to prepare the site to be exposed to a tidal regime and to promote tidal marsh vegetation establishment, as key factors to successful defense against floods [186]. Managed realignments increased levels of coastal protection by means of leveling works, supporting colonization of intertidal areas by wetland vegetation and inducing sediment accretion. Monitoring of vegetation recovery and respective sediment accretion rate were moreover assumed.

Conclusions

Coasts are the borders between land and sea and are of fundamental importance for the environment, the economy, and for human health. The need of a multidisciplinary approach in coasts monitoring has emerged, evidencing the requirement for participation of different professional skills. Results of coastal monitoring are necessary for decision making and for administrations to achieve decisions about coasts degradation countermeasures to be adopted. In this review, possible solutions for coasts protection have been described, focusing on Mediterranean coastal hotspots, with both hard and soft engineering interventions. Their advantages and disadvantages have been discussed, and the need of detailed investigations with approaches based on hybrid solutions has emerged. The evolution from hard engineering to soft engineering will lead to further research concerning hybrid approaches. The need of detailed monitoring procedures to be adopted at coasts, even in presence of engineering structures, has been pointed out. Future investigations should include further studies on engineering structures at coasts, combined with an important monitoring activity both before and after engineering structures implementation.

Funding

This research received no external funding.

Acknowledgments

The authors are grateful to Fano Marine Centre of the Stazione Zoologica Anton Dohrn that allowed to conduct this study.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Toure S, Diop O, Kpalma K, Maiga AS (2019) Shoreline Detection using Optical Remote Sensing: A Review. ISPRS Int. J. Geo-Inf 8: 75.
2. Cantasano N, Pellicone G, Ietto F (2017) Integrated coastal zone management in Italy: A gap between science and policy. J. Coast. Conserv 21: 317-325.
3. González-Dueñas C, Padgett JE (2021) Performance-Based Coastal Engineering Framework. Front. Built Environ 7: 690715.
4. Dong WS, Ismailluddin A, Yun LS, Ariffin EH, Cherdvong Saengsupavanich, et al. (2024) The impact of climate change on coastal erosion in Southeast Asia and the compelling need to establish robust adaptation strategies. Heliyon 10: e25609.
5. Bruno MF, Molfetta MG, Pratola L, Mossa M, Nutricato R, et al. (2019) A combined approach of field data and earth observation for coastal risk assessment. Sensors 19: 1399.
6. Nicholls RJ, Lincke D, Hinkel J, Brown S, Vafeidis AT, et al. (2021) A global analysis of subsidence, relative sea-level change and coastal flood exposure. Nat. Clim. Change 11: 338-342.
7. Vousdoukas MI, Mentaschi L, Voukouvalas E, Verlaan M, Jevrejeva S, et al. (2018) Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nat. Commun 9: 2360.
8. De Serio F, Armenio E, Mossa M, Petrillo AF (2018) How to Define Priorities in Coastal Vulnerability Assessment. Geosci 8: 415.
9. Toimil A, Camus P, Losada IJ, Le Cozannet G, Nicholls RJ, et al. (2020) Climate change-driven coastal erosion modelling in temperate sandy beaches: Methods and uncertainty treatment. Earth-Sci. Rev 202: 103110.
10. Sarkar N, Rizzo A, Vandelli V, Soldati M A (2022) Literature Review of Climate-Related Coastal Risks in the Mediterranean, a Climate Change Hotspot. Sustainability 14: 15994.
11. Zappalà G, Caruso G (2023) Coastal Marine Monitoring Experiments at the National Research Council in Messina, Italy: 30 Years of Research. J. Mar. Sci. Eng 11: 1958.
12. Cavanaugh KC, Bell TW, Aerni KE, Jarrett EK Byrnes, Seth McCammon, et al. (2024) New Technologies for Monitoring Coastal Ecosystem Dynamics. Annual Review of Marine Science 17: 409-433.
13. Briciu Burghina C, Power S, Delgado A, Regan F (2023) Sensors for Coastal and Ocean Monitoring. Annual Review of Analytical Chemistry 16: 451-469.
14. Renzi M, Provenza F, Pignattelli S, Cilenti L, Specchiulli A, et al. (2019) Mediterranean Coastal Lagoons: The Importance of Monitoring in Sediments the Biochemical Composition of Organic Matter. Int. J. Environ. Res. Public Health 16: 3466.
15. Masria A (2024) Bridging coastal challenges: The role of remote sensing and future research. Regional Studies in Marine Science 73: 103502.
16. Zanchettin D, Bruni S, Raicich F, Lionello P, Adloff F, et al. (2021) Sea-level rise in Venice: historic and future trends (review article). Nat. Hazards Earth Syst. Sci 21: 2643-2678.
17. CMRC-Coastal & Marine Resource Centre (2009) Methodology for Coastal Monitoring Programme at Portrane; Technical Report for Fingal County Council; Rush Beaches, Co.: Dublin, Ireland.
18. NOAA-National Oceanic and Atmospheric Administration (2023) What is Remote Sensing? National Ocean Service https://oceanservice.noaa.gov/facts/remotesensing.html.
19. Faye BN (2010) Dynamics of the coastline on the sandy

coasts from Mauritania to Guinea-Bissau (West Africa): Regional and local approaches by photo-interpretation, image processing and analysis of old maps, Thesis of the University of Western Brittany https://tel.archives-ouvertes.fr/tel-00472200/PDF/DYNAMIQUE-DU-TRAIT-DE-COTEEN-AFRIQUE-DE-L_OUEST-MAURITANIE-GUINEE-BISSAU-VOLUME1.pdf.

20. Minervino Amodio A, Di Paola G, Rosskopf CM (2022) Monitoring Coastal Vulnerability by Using DEMs Based on UAV Spatial Data. ISPRS Int. J. Geo-Inf 11: 155.
21. Isha IB, Adib MRM (2021) Shoreline monitoring using Unmanned Aerial Vehicle (UAV) at Regency Beach, Port Dickson. IOP Conf. Ser.: Mater. Sci 1144.
22. Qi L, Wang M, Hu C, Holt B (2022) On the capacity of Sentinel-1 synthetic aperture radar in detecting floating macroalgae and other floating matters. Remote Sens. Environ 280: 113188.
23. Agharroud K, Puddu M, Ivčević A, Satta A, Kolker AS, et al. (2023) Climate risk assessment of the Tangier-Tetouan-Al Hoceima coastal Region (Morocco). Front. Mar. Sci 10, 1176350.
24. Çelik OI, Gazioğlu C (2024) Bridging coastal challenges: The role of remote sensing and future research. Regional Studies in Marine Science 73: 103502.
25. Tsiakos CAD, Chalkias C (2023) Use of Machine Learning and Remote Sensing Techniques for Shoreline Monitoring: A Review of Recent Literature. Appl. Sci 13: 3268.
26. Ferreira B, Silva RG, Iten M (2022) Earth Observation Satellite Imagery Information Based Decision Support Using Machine Learning. Remote Sens 14: 3776.
27. Gómez Pazo A, Payo A, Paz Delgado MV, Delgadillo Calzadilla MA (2022) Open Digital Shoreline Analysis System: ODSAS v1.0. J. Mar. Sci. Eng 10: 26.
28. Girau R, Anedda M, Fadda M, Farina M, Floris A, et al. (2019) Coastal Monitoring System based on Social Internet of Things Platform. IEEE Internet of Things Journal 7: 1260-1272.
29. Bresnahan P, Cyronak T, Brewin RJW, Andersson A, Taylor Wirth, et al. (2022) A high-tech, low-cost, Internet of Things surfboard fin for coastal citizen science, outreach, and education. Continental Shelf Research 242: 104748.
30. Hansen J, Sato M, Hearty P, Ruedy R, Kelley M, et al. (2016) Ice melt, sea level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous. Atmos. Chem. Phys 16: 3761-3812.
31. Domingues CM, Church JA, White NJ, Gleckler PJ, Wijffels SE, et al. (2008) Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453: 1090-1093.
32. Micheal O, Bruce G, Hinkel J, Roderik V, Frederikse T (2019) Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities; IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland https://www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/.
33. Kopp RE, De Conto RM, Bader DA, Hay CC, Horton RM, et al. (2017) Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections. Earth's Future 5: 1217-1233.
34. Shepherd A, Ivins E, Rignot E, Smith B, van den Broeke M, et al. (2020) Mass balance of the Greenland Ice Sheet from 1992 to 2018. Nature 579: 233-239.
35. Edwards TL, Nowicki S, Marzeion B, Hock R, Goelzer H, et al. (2021) Projected land ice contributions to twenty-first-century sea level rise. Nature 593: 74-82.
36. Antonioli F, De Falco G, Lo Presti V, Moretti L, Scardino G, et al. (2020) Relative Sea-Level Rise and Potential Submersion Risk for 2100 on 16 Coastal Plains of the Mediterranean Sea. Water 12: 2173.
37. Chao BF, Wu YH, Li YS (2008) Impact of artificial reservoir water impoundment on global sea level. Science 320: 212-214.
38. Dong L, Cao J, Liu X (2022) Recent Developments in Sea-Level Rise and Its Related Geological Disasters Mitigation: A Review. J. Mar. Sci. Eng 10: 355.
39. Griggs G, Reguero BG (2021) Coastal Adaptation to Climate Change and Sea-Level Rise. Water 13: 2151.
40. Lievin M, Kocha C, Courcol B, Philipps S, Denis I, et al. (2020) Reprocessing of Sea Level L2P Products for 28 Years of Altimetry Missions. OSTST https://www.aviso.altimetry.fr/en/data/ucts/ocean indicator products/mean sea level.html.
41. De Conto RM, Pollard D (2016) Contribution of Antarctica to past and future sea-level rise. Nature 531: 591-597.
42. Focardi S, Pepi M (2023) Sea Level Rise Impacts in Coastal Areas and Possible Mitigation Engineering Approaches. Ann. Civil Environ. Eng 7: 030-036.
43. Enríquez AR, Marcos M, Álvarez Ellacuría A, Orfila A, Gomis D (2016) Changes in beach shoreline due to sea level rise and waves under climate change scenarios: application to the Balearic Islands (Western Mediterranean). Nat. Hazards Earth Syst. Sci. Discuss 361.
44. Lincke D, Hinkel J (2021) Coastal migration due to 21st century sea-level rise. Earth's Future 9: e2020EF001965.
45. Tierolf L, Haer T, Athanasiou P, Arjen P Luijendijk, AP Botzen, et al. (2024) Coastal adaptation and migration dynamics under future shoreline changes. Science of the Total Environment 917: 170239.
46. Bachner G, Lincke D, Hinkel J (2022) The macroeconomic effects of adapting to high-end sea-level rise via protection and migration. Nature Communications 13: 5705.
47. Hague BS, McGregor S, Jones DA, Reef R, Jakob D, (2023) The global drivers of chronic coastal flood hazards under sea-level rise. Earth's Future 11: e2023EF003784.
48. Smith G, Juria N (2019) Diagnosis of historical inundation events in the Marshall Islands to assist early warning systems. Natural Hazards 99: 189-216.
49. Li S, Wahl T, Talke SA, Jay DA, Orton PM, et al. (2021) Evolving tides aggravate nuisance flooding along the U.S. coastline. Sci. Adv 7: eabe2412.
50. Tully K, Keryn Gedan, Rebecca Epanchin Niell, Aaron Strong, Emily S Bernhardt, et al. (2019) The invisible flood: The chemistry, ecology, and social implications of coastal saltwater intrusion. BioScience 69: 368-378.
51. Nijhawan A, Howard G (2022) Associations between climate variables and water quality in low-and middle-income countries: A scoping review. Water Research 210: 117996.
52. Mueller W, Daniel Zamrsky D, Essink GO, Fleming LE, Deshpande A, et al. (2024) Saltwater intrusion and human health risks for coastal populations under 2050 climate scenarios. Scientific Reports 14: 15881.
53. Pang T, Wang X, Nawaz RA, Keefe G, Adekanmbi T (2023) Coastal erosion and climate change: A review on coastal-change process and modeling. Ambio 52: 2034-2052.
54. Rashidi MAH, Jamal MH, Hassan MZ, Mohd SS, Mohd SL, et al. (2021) Coastal Structures as Beach Erosion Control and Sea Level Rise Adaptation in Malaysia: A Review. Water 13: 1741.
55. Sundar V, Sannasiraj SA, Babu SR (2022) Sustainable hard

and soft measures for coastal protection – Case studies along the Indian Coast. Mar. Georesources Geotechnol 40: 600-615.
56. Angnuureng DB, Charuka B, Almar R, Dada OA, Asumadu R, et al. (2025) Challenges and Lessons Learned from Global Coastal Erosion Protection Strategies. ISCIENCE https://www.sciencedirect.com/science/article/pii/S2589004225003153.
57. Satta A, Puddu M, Venturini S, Giupponi C (2017) Assessment of coastal risks to climate change related impacts at the regional scale: The case of the Mediterranean region. Int. J. Disaster Risk Reduct 24: 284-296.
58. UNEP/MAP (2016) Mediterranean Strategy for Sustainable Development 2016-2025. Plan Bleu, Regional Activity Centre, Valbonne https://planbleu.org/sites/default/files/publications/mssd_2016-2025_final.pdf.
59. Sánchez Arcilla A, Mösso C, Sierra JP, Mestres M, Harzallah A, et al. (2011) Climatic drivers of potential hazards in Mediterranean coasts. Reg. Environ. Change 11: 617-636.
60. Tsimplis MN, Baker TF (2000) Sea level drop in the Mediterranean Sea: An indicator of deep-water salinity and temperature changes? Geophys. Res. Lett 27: 1731-1734.
61. Tsimplis MN, Josey S (2001) Forcing the Mediterranean Sea by atmospheric oscillations over the North Atlantic. Geophys. Res. Lett 28: 803-806.
62. Mohamed B, Abdallah AM, Alam El Din K, Nagy H, Shaltout M (2019) Inter-annual variability and trends of sea level and sea surface temperature in the Mediterranean Sea over the last 25 years. Pure Appl. Geophys 176: 3787-3810.
63. Calafat FM, Frederikse T, Horsburgh K (2022) The sources of sea-level changes in the Mediterranean Sea since 1960. J. Geophys. Res. Oceans 127: e2022JC019061.
64. Gualdi S, Somot S, May W, Castellari S, Déqué M, et al. (2013) Future Climate Projections, Chapter 3. Volume 1: Air, Sea and Precipitation and Water, Regional Assessment of Climate Change in the Mediterranean, Antonio Navarra and Laurence Tubiana Editors https://link.springer.com/book/10.1007/978-94-007-5781-3.
65. Frederikse T, Landerer F, Caron L, Adhikari S, Parkes D, et al. (2020) The causes of sea-level rise since 1900. Nature 584: 393-397.
66. TF Stocker, D Qin, GK Plattner, M Tignor, SK Allen, et al. (2013) IPCC. Climate change 2013: the physical science basis, in: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York https://www.ipcc.ch/report/ar5/wg1/.
67. Guedes Soares C, Carretero Albiach J, Weisse R, Alvarez Fanjul E (2002) A 40 years hindcast of wind, sea level and waves in European waters, in: Proceedings of the 21st International Conference on Offshore Mechanics and Arctic Engineering, Oslo, Norway 669-675.
68. Ciampa F, Seifollahi Aghmiuni S, Kalantari Z, Ferreira CSS (2021) Flood Mitigation in Mediterranean Coastal Regions: Problems, Solutions, and Stakeholder Involvement. Sustainability 13: 10474.
69. Wolff C, Nikoletopoulos T, Hinkel J, Vafeidis AT (2020) Future urban development exacerbates coastal exposure in the Mediterranean. Scientific Reports 10: 14420.
70. Wolff C, Vafeidis AT, Muis S, Lincke D, Satta A, et al. (2018) Data Descriptor: A Mediterranean coastal database for assessing the impacts of sea-level rise and associated hazards. Sci. Data 5: 180044.
71. Claro AM, Fonseca A, Fraga H, Santos JA (2024) Future Agricultural Water Availability in Mediterranean Countries under Climate Change: A Systematic Review. Water 16: 2484.
72. Lazoglou G, Papadopoulos Zachos A, Georgiades P, Zittis G, Velikou K, et al. (2024) Identification of climate change hotspots in the Mediterranean. Scientific Reports 14: 29817.
73. Zittis G, M Almazroui, P Alpert, P Ciais, W Cramer, et al. (2022) Climate change and weather extremes in the Eastern Mediterranean and Middle East. Rev. Geophys 60: e2021RG000762.
74. UNEP/EEA (1999) State and pressures of the marine and coastal Mediterranean environment https://www.unep.org/resources/report/state-and-pressures-marine-and-coastal-mediterranean-environment.
75. World Bank (2009) Adapting vulnerable energy infrastructure to climate change. Climate change projections for Albania 30.
76. Sahabi Abed S (2021) Future Climate Projections in Algeria Using Statistical Down Scaling Model. Res. Sq https://www.researchsquare.com/article/rs-627355/v1.
77. Baric A, Grbec B, Bogner D (2008) Potential Implications of Sea-Level Rise for Croatia. J. Coast. Res 24: 299-305.
78. Monioudi IN, Velegrakis AF, Chatzistratis DD, Vousdoukas MI, Savva C, et al. (2023) Climate change -induced hazards on touristic island beaches: Cyprus, Eastern Mediterranean. Front. Mar. Sci 10: 1188896.
79. El Raey M, Dewidar Kr, El Hattab M (1999) Adaptation to the impacts of sea level rise in Egypt. Mitig. Adapt. Strateg. Glob. Chang 4: 343-361.
80. Frihy OE (2003) The Nile Delta-Alexandria coast: Vulnerability to Sea-Level Rise, consequences and Adaptation. Mitig. Adapt. Strateg. Glob. Chang 8: 115-138.
81. Hereher ME (2010) Vulnerability of the Nile Delta to sea level rise: an assessment using remote sensing. Geomat. Nat. Hazards Risk 1: 315-321.
82. Hassaan MA, Abdrabo MA (2013) Vulnerability of the Nile Delta coastal areas to inundation by sea level rise. Environ. Monit. Assess 185: 6607-6616.
83. Hzami A, Heggy E, Amrouni O, Mahé G, Maanan M, et al. (2021) Alarming coastal vulnerability of the deltaic and sandy beaches of North Africa. Sci. Rep 11: 2320.
84. Yousif M, Bubenzer O (2012) Perched groundwater at the northwestern coast of Egypt: a case study of the Fuka Basin. Appl. Water Sci 2: 15-28.
85. Tol RJ, Bohn M, Downing TE, Guillerminet ML, Hizsnyik E, et al. (2006) Adaptation to Five Metres of Sea Level Rise. J. Risk Res 9: 467-482.
86. Petropoulos GP, Kalivas DP, Griffiths HM, Dimoub PP (2015) Remote sensing and GIS analysis for mapping spatio-temporal changes of erosion and deposition of two Mediterranean river deltas: The case of the Axios and Aliakmonas rivers, Greece. Int. J. Appl. Earth Obs. Geoinf 35: 217-228.
87. Raphael Sauter, Patrick Ten Brink, Sirini Withana, Leonardo Mazza (2012) Impacts of Climate Change on all European Islands. Final Report 47.
88. Tragaki A, Gallousi C, Karymbalis E (2018) Coastal Hazard Vulnerability Assessment Based on Geomorphic, Oceanographic and Demographic Parameters: The Case of the Peloponnese. Land 7: 56.
89. Poulos SE, Ghionis G, Maroukian H (2009) The consequences of a future eustatic sealevel rise on the deltaic coasts of Inner Thermaikos Gulf (Aegean Sea) and Kyparissiakos Gulf (Ionian Sea), Greece. Geomorphology 107: 18-24.
90. Hepner Ucko O, Arle E, Malamud S, Winters G, Belmaker J (2024) Surprising widespread Cymodocea nodosa occurrence along Israel's Mediterranean coast and Implications for Seagrass Conservation in a hotspot of climate change.

Mediterranean Marine Science 25.
91. Pantusa D, D Alessandro F, Riefolo L, Principato F, Tomasicchio G (2018) Application of a Coastal Vulnerability Index. A Case Study along the Apulian Coastline, Italy. Water 10: 1218.
92. Torresan S, Critto A, Rizzi J, Marcomini A (2012) Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. Nat Hazards Earth Syst Sci12: 2347-2368.
93. Taramelli A, Valentini E, Righini M, Filipponi F, Geraldini S, et al. (2020) Assessing Po River Deltaic Vulnerability Using Earth Observation and a Bayesian Belief Network Model. Water 12: 2830.
94. Furlan E, Pozza PD, Michetti M, Torresan S, Critto A, et al. (2021) Development of a Multi-Dimensional Coastal Vulnerability Index: Assessing vulnerability to inundation scenarios in the Italian coast. Sci Total Environ 772: 144650.
95. Agulles M, Marba N, Duarte CM, Jorda G (2024) Mediterranean seagrasses provide essential coastal protection under climate change. Scientific Reports 14: 30269.
96. Sanchez Arcilla A, Jimenez JA, Valdemoro HI, Gracia V (2008) Implications of Climatic Change on Spanish Mediterranean Low-Lying Coasts: The Ebro Delta Case. J Coast Res 24: 306-316.
97. Jimenez JA, Sanuy M, Ballesteros C, Valdemoro HI (2018) The Tordera Delta, a hotspot to storm impacts in the coast northwards of Barcelona. Coast Eng 134: 148-158.
98. Grases A, Gracia V, García León M, Lin Ye J, Pau Sierra J (2020) Coastal Flooding and Erosion under a Changing Climate: Implications at a Low-Lying Coast. Water 12: 346.
99. Navarra A, Tubiana L (2013) Regional Assessment of Climate Change in the Mediterranean. Adv Glob Chang Res 50-52.
100. Gzam M, Moncef SM, Ouaja M, Jedoui Y (2013) Coastal progradation in response to the recent sea level rise: a case study of El Grine coast, Gulf of Gabes. Arab J Geosci 6: 5007-5016.
101. Saidani LVN (2007) Rapport du Centre Hydrographique et Océanographique de la Marine Nationale de la Tunisie. Analysis of the tidal data in the port of Sfax 1-5.
102. Amrouni O, Abderraouf Hzami A, Heggy E (2019) Photogrammetric assessment of shoreline retreat in North Africa: Anthropogenic and natural drivers. ISPRS J Photogramm Remote Sens 157: 73-92.
103. Mokos M, Cheimonopoulou MTh, Olori P, Previati M, Realdon G, et al. (2020) Mediterranean Sea Literacy: When Ocean Literacy becomes region-specific. Medit Mar Sci 21: 001-607.
104. Zhang K, Douglas BC, Leatherman SP (2004) Global warming and coastal erosion. Clim Chang 64: 41.
105. Hauer ME, Fussell E, Mueller V, Burkett M, Call M, et al. (2020) Sea-level rise and human migration. Nature Reviews Earth & Environment 1: 28-39.
106. Toimil A, Alvarez Cuesta M, Losada IJ (2023) Neglecting the effect of long- and short-term erosion can lead to spurious coastal flood risk projections and maladaptation. Coast Eng 179: 104248.
107. Global Commission Report (2019) Work for a brighter future https://www.ilo.org/publications/work-brighter-future.
108. Michael Werz, Max Hoffman (2017) Climate Change and Migration in the Mediterranean: Challenges for the Future. Strategic Sectors | Economy & Territory https://www.iemed.org/wp-content/uploads/2021/01/Climate-Change-and-Migration-in-the-Mediterranean-Challenges-for-the-Future.pdf.
109. Global Warming of 1.5°C an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. The Intergovernmental Panel on Climate Change https://www.ipcc.ch/sr15/download/.
110. Cristina Cattaneo, Michel Beine, Christiane J. Fröhlich, Dominic Kniveton, Inmaculada Martinez-Zarzoso, et al. (2019) Human migration in the era of climate change. Rev Environ Econ Policy 13: 189-206.
111. Oppenheimer M, Glavovic BC (2019) Chapter 4: Sea level rise and implications for low lying islands, coasts and communities https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/08_SROCC_Ch04_FINAL.pdf.
112. UNESCO (1972) Convention Concerning the Protection of the World Cultural and Natural Heritage https://whc.unesco.org/archive/convention-en.pdf.
113. Reimann L, Vafeidis AT, Brown S, Hinkel J, Tol RSJ (2018) Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. Nat Commun 9: 4161.
114. Cazenave A (2014) Anthropogenic global warming threatens world cultural heritage. Environ Res Lett 9: 51001.
115. Ghazali NHM, Awang NA, Mahmud M, Mokhtar A (2018) Impact of Sea Level Rise and Tsunami on Coastal Areas of North-West Peninsular Malaysia. Irrig Drain 67: 119-129.
116. Williams AT, Rangel Buitrago N, Pranzini E, Giorgio Anfuso G (2018) The management of coastal erosion. Ocean Coast Manag 156: 4-20.
117. Reguero BG, Storlazzi CD, Gibbs AE, Shope JB, Cole AD, et al. (2021) The value of US coral reefs for flood risk reduction. Nat Sustain 1: 11.
118. Dronkers J, Gilbert JTE, Butler LW, Carey JJ, Campbell J, et al. (1990) Strategies for Adaptation to Sea Level Rise. Intergovernmental Panel on Climate Change Response Strategies Working Group https://papers.risingsea.net/federal_reports/IPCC-1990-adaption-to-sea-level-rise.pdf.
119. Sarkar MSK, Begum R, Pereira J, Jaafar A, Saari MY (2014) Impacts of and Adaptations to Sea Level Rise in Malaysia. Asian J Water Environ Pollut 11: 29-36.
120. Gracia A, Rangel Buitrago N, Oakley JA, Williams AT (2018) Use of ecosystems in coastal erosion management. Ocean. Coast Manag 156: 277-289.
121. Focardi S, Pepi M (2023) Monitoring of Coastal Areas by Remote Sensing and Engineering Approaches. Current Trends in Eng Sci 3: 1033.
122. Armenio E, Mossa M (2020) On the Need for an Integrated Large-Scale Methodology of Coastal Management: A Methodological Proposal. J Mar Sci Eng 8: 385.
123. Singhvi A, Luijendijk AP, van Oudenhoven APE (2022) The grey - green spectrum: A review of coastal protection interventions. J Environ. Manage 311: 114824.
124. Hans Otto Pörtner, Debra C. Roberts, Valérie Masson Delmotte, Panmao Zhai, Melinda Tignor, et al. (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/02_SROCC_FM_FINAL.pdf.
125. Sunamura T (1992) Geomorphology of Rocky Coasts. John Wiley & Sons https://archive.org/details/geomorphologyofr0000suna.
126. Kogure T (2022) Rocky coastal cliffs reinforced by vegetation roots and potential collapse risk caused by sea-level rise.

Catena 217: 106457.
127. Ma Q, Marcondes Moreira T, Adcock TAA (2019) The impact of a tidal barrage on coastal flooding due to storm surge in the Severn Estuary. J Ocean Eng Mar Energy 5: 217-226.
128. Etemadi A, Emami Y, Asef Afshar O, Emdadi A (2011) Electricity Generation by the Tidal Barrages. Energy Procedia 12: 928-935.
129. Ramli M, Karasu TJr, Dawood ET (2013) The stability of gabion walls for earth retaining structures. Alex Eng J 52: 705-710.
130. Kristensen SE, Drønen N, Deigaard R, Fredso J (2016) Impact of groyne fields on the littoral drift: A hybrid morphological modelling study. Coast Eng 111: 13-22.
131. Abd-Elmonem I, Abedio TI, Kheireldin KA, Soliman MR (2022) Assessment of Coastal Revetment: Case study of Rosetta Revetment. Ain Shams Eng J 13: 101623.
132. Eldrup MR, Lykke Andersen T (2019) Extension of shallow water rock armour stability formulae to nonlinear waves. Coast Eng 153: 103536.
133. Salauddin M, O'Sullivan JJ, Abolfathi S, Pearson JM (2021) Eco-Engineering of Seawalls—An Opportunity for Enhanced Climate Resilience from Increased Topographic Complexity. Front Mar Sci 8: 674630.
134. Mancini F, Castagnetti C, Rossi P, Dubbini M, Fazio NL, Perrotti M, Lollino P (2017) An Integrated Procedure to Assess the Stability of Coastal Rocky Cliffs: From UAV Close-Range Photogrammetry to Geomechanical Finite Element Modeling. Remote Sens 9: 1235.
135. Ringwood JV, Faedo N (2022) Tidal barrage operational optimization using wave energy control techniiques. IFAC PapersOnLine 148-153.
136. Vandercruyssen D, Baker S, Howard D, Aggidis G (2022) Tidal range electricity generation: A comparison between estuarine barrages and coastal lagoons. Heliyon 8: e11381.
137. Cherkasova L J (2019) Application of gabions for strengthening marine coastal slopes. Phys Conf Ser 1425: 012206.
138. Adi HP, Wahyudali SI, Soebagyo A (2022) Gabion as a coastal protection structure: a case study in Panjang Island Indonesia. IOP Conf Ser Earth Environ Sci 955: 012005.
139. Choufu L, Abbasi S, Pourshahbaz H Taghvaei P Tfwala S (2019) Investigation of Flow, Erosion, and Sedimentation Pattern around Varied Groynes under Different Hydraulic and Geometric Conditions: A Numerical Study. Water 11: 235.
140. Valsamidis A, Reeve DE (2020) A new approach to analytical modelling of groyne fields. Cont Shelf Res 211: 104288.
141. Crawford TW, Islam MS, Rahman MK, Paul BK, Curtis S, Miah MG, Islam MR (2020) Coastal Erosion and Human Perceptions of Revetment Protection in the Lower Meghna Estuary of Bangladesh. Remote Sens 12: 3108.
142. Van der Meer, JW Rock Armour (2021) Slope Stability under Wave Attack; the Van der Meer Formula revisited. JCHS 1.
143. Dong S, Abolfathi S, Salauddin M, Tan ZH, Pearson JM (2020) Enhancing climate resilience of vertical seawall with retrofitting - A physical modelling study. Appl Ocean Res 103: 102331.
144. Wu YT (2022) Breaking Solitary Wave Impact on a Vertical Seawall. Water 14: 583.
145. Bongarts Lebbe T, Rey Valette H, Chaumillon É, Camus G, Almar R, et al. (2021) Designing Coastal Adaptation Strategies to Tackle Sea Level Rise. Front Mar Sci 8: 740602.
146. Duarte CM, Losada IJ, Hendriks IE, Mazarrasa I, Marbà N (2013) The role of coastal plant communities for climate change mitigation and adaptation. Nat Clim Change 3: 961-802.
147. European Commission (2015) Towards an EU research and innovation policy agenda for nature-based solutions & renaturing cities: Final report of the horizon 2020 expert group on 'nature-based solutions and re-naturing cities https://op.europa.eu/en/publication-detail/-/publication/fb117980-d5aa-46df-8edc-af367cddc202.
148. Cohen-Shacham E, Walters G, Janzen C, Maginnis S (2016) Nature-based solutions to address global societal challenges. IUCN International Union for Conservation of Nature https://portals.iucn.org/library/sites/library/files/documents/2016-036.pdf.
149. Akça E, Kapur S, Tanaka Y, Kaya Z, Bedestenci HC, Yaktı S (2010) Afforestation Effect on Soil Quality of Sand Dunes. Pol J Environ Stud 19: 1109-1116.
150. Jackson DWT, Costas S, González Villanueva R, Cooper AA (2019) Global 'greening' of coastal dunes: An integrated consequence of climate change? Glob. Planet. Change 182: 103026.
151. De Schipper MA, Ludka BC, Raubenheimer B, Luijendijk AP, Schlacher TA (2021) Beach nourishment has complex implications for the future of sandy shores. Nat. Rev. Earth Environ 2: 71.
152. Corral LR, Schling M (2017) The impact of shoreline stabilization on economic growth in small island developing states. J. Environ. Econ. Manage 86: 210-228.
153. Escudero M, Mendoza E, Silva R (2020) Micro Sand Engine Beach Stabilization Strategy at Puerto Morelos, Mexico. J. Mar. Sci. Eng 8: 247.
154. Hein MY, Vardi T, Shaver EC, Pioch S, Boström Einarsson L, et al. (2021) Perspectives on the Use of Coral Reef Restoration as a Strategy to Support and Improve Reef Ecosystem Services. Front. Mar. Sci 8: 618303.
155. Arias González JE, Baums IB, Banaszak AT, Prada C, Rossi S (2022) Hernández-Delgado, E.A.; Rinkevich, B. Editorial: Coral Reef Restoration in a Changing World: Science-Based Solutions. Front. Mar. Sci 9: 919603.
156. Lawlor P, Jackson DWT (2022) A Nature Based Solution for Coastal Foredune Restoration: The Case Study of Maghery, County Donegal, Ireland. In Human-Nature Interactions, Ieva Misiune, Daniel Depellegrin, Lukas Egarter Vigl Eds., Springer, Switzerland 417-429.
157. Tubridy F, Scott M, Lennon M (2021) Managed retreat in response to flooding: lessons from the past for contemporary climate change adaptation. Plan. Perspect 36: 1249:1268.
158. Ellison AM, Felson AJ, Friess DA (2020) Mangrove Rehabilitation and Restoration as Experimental Adaptive Management. Front. Mar. Sci 7: 327.
159. Van Bijsterveldt CEJ, Debrot AO, Bouma TJ, Maulana M, Pribadi R, et al. (2022) To Plant or Not to Plant: When can Planting Facilitate Mangrove Restoration? Front. Environ. Sci 9: 690011.
160. Jordan P, Fröhle P (2022) Bridging the gap between coastal engineering and nature conservation? J. Coast. Conserv 26: 4.
161. Vieira B, Pinho J, Barros J, Antunes do Carmo J (2024) Optimizing coastal protection: Nature-based engineering for longitudinal drift reversal and erosion reduction. Ocean and Coastal Management 256: 107288.
162. Valcheva M, Sopotlieva D, Apostolova I, Tsvetkova N (2021) Vegetation Characteristics and Recent Successional Trends of Sand Dune Habitats at the Bulgarian Black Sea Coast. Coasts 1: 1-24.
163. Staudt F, Gijsman R, Ganal C, Mielck F, Wolbring J, et al. (2021) The sustainability of beach nourishments: a review of nourishment and environmental monitoring practice. J.

Coast. Conserv 25: 34.
164. Chen WL, Muller P, Grabowski RC, Dodd N (2022) Green Nourishment: An Innovative Nature-Based Solution for Coastal Erosion. Front. Mar. Sci 8: 814589.
165. Manakul C, Mohanasundaram S, Weesakul S, Shrestha S, Ninsawat S, et al. (2022) Classifying Headland-Bay Beaches and Dynamic Coastal Stabilization. J. Mar. Sci. Eng 10: 1363.
166. Kleypas J, Allemand D, Anthony K, Baker AC, Beck MW, et al. (2021) Designing a blueprint for coral reef survival. Biol. Conserv 257: 109107.
167. Hilmi N, Basu R, Crisóstomo M, Lebleu L, Claudet J, et al. (2023) The pressures and opportunities for coral reef preservation and restoration in the Maldives. Front. Environ. Econ 2: 1110214.
168. Rinaldo T, Ramakrishnan KA, Rodriguez Iturbe I, Duran Vinent O (2021) Probabilistic structure of events controlling the after-storm recovery of coastal dunes. Proc. Natl. Acad. Sci. USA 118: e2013254118.
169. Carey J (2020) Managed retreat increasingly seen as necessary in response to climate change's fury. Proc. Natl. Acad. Sci. USA 117: 13182-13185.
170. Donnell OT (2022) Managed retreat and planned retreat: a systematic literature review. Phil. Trans. R. Soc B 377: 20210129.
171. Monga E, Mangora M M, Trettin C C (2022) Impact of mangrove planting on forest biomass carbon and other structural attributes in the Rufiji Delta Tanzania Glob Ecol Conserv 35.
172. Saengsupavanich C (2020) Deconstructing a jetty to rectify the downdrift erosion. J Sustain Sci Manag 15: 79-88.
173. Van Onselen V M, Lin T Y Vo, P L Nguyen (2023) T D Coastal Hazards Management: Hard Engineering Solutions along the Taiwanese and Vietnamese Coastline Unintentional Consequences and Future Humanitarian Engineering Implications 77-97.
174. Lin T Y (2016) Morphological response to the installation of detached breakwaters along the Cigu coast of Tainan Taiwan J Coast Res 1: 887-891.
175. Hsu T W, Tseng I.F, Lin T Y, Shin C Y, Ou S H (2008) Review of countermeasures against beach erosion on the Taiwanese coast. Coastal Manage 36: 274-293.
176. Lin T Y, Onselen van V M Vo P (2021) Coastal erosion in Vietnam: Case studies and implication for integrated coastal zone management in the Vietnamese south central coastline. IOP Conf Ser Earth Environ Sci 652: 0-11.
177. Hsu T, Lin T, Tseng I (2007) Human Impact on Coastal Erosion in Taiwan J Coast Res. 234: 961-973.
178. Alves B, Angnuureng D B, Morand P 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 Advance online publication 24: 38.
179. Takagi H, Nguyen DT, Miquel E, Tran T T, Hanne L K, Takahito M, Mitsuko L (2012) Assessment of Disaster Vulnerability of Coastal Areas in Vietnam and Basic Study for Disaster Mitigation. JST FY2011 SATREPS https://www.preventionweb.net/english/hyogo/gar/2013/en/bgdocs/Takagi,%202012.pdf.
180. Cohen Shacham E, Andrade A, Dalton J, Dudley N, Jones M et al. (2019) Core principles for successfully implementing and upscaling Nature-based Solutions. Environ Sci Policy 98: 20-29.
181. Gesing F (2019) Towards a more-than-human political ecology of coastal protection: Coast Care practices in Aotearoa New Zealand. Environ Plan E Nat https://journals.sagepub.com/doi/10.1177/2514848619860751.
182. Anderson C C, Renaud F G (2021) A review of public acceptance of nature based solutions: The why when and how of success for disaster risk reduction measures. Ambio Advance online publication 50: 1552-1573.
183. Perricone V, Mutalipassi M, Mele A, Buono M, Vicinanza D (2023) Nature-based and bioinspired solutions for coastal protection: an overview among key ecosystems and a promising pathway for new functional and sustainable designs. ICES J Mar Sci 80: 1218-1239
184. Waryszak P, Gavoille A, Whitt A A, Kelvin J, 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.
185. Hashim R, Kamali B, Tamin N M., RZakaria R (2010) An Integrated Approach to Coastal Rehabilitation: Mangrove Restoration in Sungai Haji Dorani Malaysia Estuar Coast Shelf S 86: 118-124.
186. Mc Alinden B (2015) Managed Realignment at Abbotts Hall Essex. Institute of Civil Engineers https://coastadapt.com.au/sites/default/files/case_studies/SS46_UK_Coastal_Realignment.pdf