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Review

Coastal Monitoring and Coastal Erosion: Engineering Interventions for Coastal Protection and Considerations on the Mediterranean Sea

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Abstract: Coasts are characterized by high biological and ecological productivities, and are theatre of strategic economic activities, including tourism, fishing and aquaculture. Both anthropic and natural hazards can thus affect coasts, causing their deterioration. The monitoring of coasts in terms of evolution, adaptation, contamination and resilience, is a pivotal point composed of both classic measurement approaches, and innovative approaches as remote sensing and the use of unmanned aerial vehicles. In the last years, climate change is increasing its effects all over the world and coasts are a delicate system suffering these effects particularly. Climate change has important impacts on coasts, with a serious consequence represented by sea level rise. The latter causes coastal erosion, leading to ecological and economic issues and with consequences for human health. The Mediterranean Basin, which has always represented an important crossroads of different civilizations and economic and cultural exchanges, is now threatened by the consequences of climate change. This area is decribed as an example of coastal system of strategic importance and subjected to serious challenges. Engineering interventions are countermeasures to cope with coastal erosion and coastal degradation. These countermeasures are aimed at protecting the coasts and the populations living on the coasts. The types of intervention can be defined of hard engineering, as in the case of fixed structures in concrete, and of soft engineering, with structures of protection builted according to the principles of nature. Engineering procedures provide coastal benefits, although they can cause further coastal damage. It is thus necessary to protect the coasts and the same time actions aimed at mitigating climate change must be implemented, according to the rules of sustainability.

Keywords: coasts monitoring; climate change; sea level rise; coastal erosion; hard engineering; soft engineering

1. Introduction

Coasts represent a complex system that can change in response to various geomorphological and marine forces, showing an underlying morphodynamic equilibrium. Coasts are characterized by activities as tourism and fishing. Over the years, populations has concentrated in the coastal areas of the world and still it is growing in these sites. Considering the world population, about 40% live within 100 km of the beach and over 10% live at altitudes below 10 m above sea level. Coasts are thus systems under intense pressures from activities as tourism, industry, agriculture, fishery and aquaculture [1]. The anthropic pressure at coasts interfers with natural processes, such as sediment dynamics. In fact, the presence of constructions and defence barriers at coasts, including ports, infrastructures for industrial and recreational activities, interventions of river basins modifications and regulation of watercourses for the supply of water resources for drinking use, or for the use of water in agriculture for irrigation and for industrial processes, all these interventions can cause modifications to the coasts. Again, the expansion of cities has involved coastal spaces and caused the alteration of the morphology of structures such as beaches, dunes, deltas and river estuaries,

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evidencing phenomena of erosion, accumulation of sediments and shoreline changes. Ports can also cause coastal erosion by altering wave patterns. In the last century, coastal processes have undergone alterations and, consequently, there has been a degradation of ecosystems, with modifications of coasts, in particular with the increase in coastal erosion and related risks [2]. Communities living close to coasts face severe challenges that are exacerbated by a growing population coupled with an aging of existing infrastructure [3].

The effects of climate change are the causes of a significant increase in coasts vulnerability. Changes occurring at the coastal level, including reductions in river sediment inputs, modifications in offshore bathymetric levels and in wind and wave pathways, can have a major impact on coasts and cause coastal erosion. Climate change produces an intensification of the frequency of extreme events such as increased levels of flooding, changes in coastal landforms and shoreline modifications, changes in coastal transport rates, and finally coastal erosion. The erosion phenomena is considered one of the most relevant consequences of climate change, in particular the sea level rise and the increase in adverse atmospheric phenomena. Coastal flooding could amplify beach erosion and salt intrusion, thus posing a serious danger for people living on the coasts and for related social and economic activities [4]. Sea level rise is one of the most dangerous consequences of global warming on the coasts. In fact, sea level rise could increase by up to 1.10 m by the end of the twenty-first century. Furthermore, it is expected that this phenomenon will not stop, but will record further increases even after the end of the century. Over the past two decades, sea level rise has shown a rate of 2.5 mm yr^{-1}. In low-lying coastal areas, its rate showed values four times faster, with mean relative sea level rise ranging from 7.8 mm to 9.9 mm yr^{-1} [5]. Due to climate change, sandy coasts are subject to an important erosion and nearly half could disappear by the end of the century. Without coastal protection measures and assuming the worst climatic conditions occur, by the end of this century there could be an increased risk of flooding for 48% of the world's land surface, and therefore 52% of the population and 46% of global resources likely to suffer serious damage. [6]. Climate change can alter sea levels, wave conditions, storm surges, and river flows, with significant impacts on the coast. These changes may cause an increase in the number of extreme weather-related episodes [7]. Climate change can modify wave characteristics, with changes in mean swell leading to changes in coastal drift and the amplitude and frequency of the wave oscillation cycle. Additionally, changes in extreme waves could also cause major increases in coastal erosion [7]. An important element of coastal climate change is storm surges that may play a role in sea level rise and coastal erosion. Significant sea level rise can therefore lead to extreme coastal erosion events [8]. In addition, large variations in river flows and increases in relative sediment displacements, induced by the expansion in evapotranspiration phenomena and by changes in the intensity of rainfall and snowfall, are consequences of climate change [7]. It therefore emerges that the coasts are very exposed to the impacts deriving from the rise in sea level, caused primarily by climate change. Climate change induces modifications in wind intensity, wave energy and sea level rise, causing severe coastal damage such as flooding and erosion. These are very serious problems that require urgent action [9].

In this review, the critical situation of coasts was described, focusing on the need of coasts monitoring and also the use of sofisticated approaches. Phenomena of coasts deterioration due to sea level rise and erosion were reported, evidencing serious issues affecting coasts, in particular concerning the coastal area of the Mediterranean Sea. Possible engineering interventions aimed at contrasting coastal degradation were also described, highlighting the role innovation and research can have in restoring coasts and improving the quality of the environment and the human health.

2. Coasts monitoring

Coastal monitoring and data collection are of considerable importance, also for economic and social aspects. Coasts are the border between land and water and it is necessary to have good methods for their examination and to evaluate the best approaches. Coastal monitoring can be achieved by using traditional methods of water quality monitoring, such as the evaluation of the extent of sediment inputs, sediment balances, sea level measurements using tide gauges, with the latter that have been used for over a century. 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. In recent decades, tool innovation coupled with remote data acquisition, processing and storage has enabled applications to be extended to a large number of users and coastal problem managers (Figure 1). Measurements of sea levels involve both the use of tide gauges and satellite observations, which together can provide a global description of sea level change. However, monitoring sea level rise and related impacts on coastal areas it 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 [10]. As an example, the mapping of the seabed can be done through the use of sonar by acoustic waves, giving information from sea depths. Nevertheless, in the presence of storms and due to the presence of tidal currents, data integration can be difficult. These integrations can be obtained using indicators, or by using Global Positioning System (GPS), or the method of Light Detection and Measurement (LiDAR), or three-dimensional (3D) terrestrial scanners [11]. Normally, measurements in situ are complicated to get. Other methods of investigation such as remote sensing are also utilized. Remote sensing allows the detection of information about objects and sites that are located at a distance, generally through the use of aircraft or satellites [12] (Figure 1). Unmanned aerial vehicles have gradually had an increasingly widespread use for coastal monitoring, because they can give an important support in harvesting information forprocessing of images and characteristics of the coast. To detect coast modifications, reference points are of fundamental importance to select a reference in the coast. These reference points must be selected considering both the space-time sense and the time scale. Detection of coastal changes must take into account the wide variety of reference points allowing elaboration of geomorphological information, tide measurements or the configuration of vegetation [13]. Coastal environments include different profiles and there is no one indicator that can be used for all profiles and that can adapt to any coasts 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 to be used in monitoring of coasts have a pivotal role and can influence the whole monitoring process. The reference points must thus be able to evidence coastal modifications, and at the meantime they should not be influenced by the same modifications [1].

Phenomena of coastal erosion must be detected both considering natural and anthropic causes, in order to plan interventions procedures against erosion of coasts, allowing their sutainable resilience. The monitoring of coastline modification can be achieved by traditional methods including topographic maps interpretation and aerial imagery, consisting in a complex and time consuming approach. Moreover, the obtained information can be not exhaustive in terms of spatial scale and local detail, and more recent time intervals may not be fully covered. In order to overcome the limitations in spatio-temporal resolution, access to large satellite database and use of sustainable technologies can give important solutions. An easy approach to achieve information by these new technologies is represented by the unmanned aerial vehicle (UAV) technology. The latter represents an innovative approach for coasts monitoring, offering the possibility to acquire spatio-temporal information from various sites [14]. In recent years, unmanned aerial vehicles applications for monitoring of different environments has considerably increased. Monitoring of coasts by unmanned aerial vehicles can detect shoreline modifications and degradation of coastal areas. Moreover, future impacts at coastal level can also been predicted [15].

Floating macroalgae blooms pose multiple dangers to coastal environments, with effects on the tourism economy, the safety of ship navigation and possible concerns for public health. Unmanned aerial vehicles are characterized by 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. In classical investigation techniques, water quality is detected by manual sampling in the field followed by laboratory analyses, in this case the concentration of chlorophyll-*a* (Chl-*a*) is detected. In addition to this type of analysis, the use of an unmanned aerial vehicle allows the quantitative mapping of the Chl-*a* distribution in surface and coastal waters from low altitude.

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Traditional laboratory analyses combined to analyses obtained using unmanned aerial vehicles will allow to comprehend the causesat 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 and can fournish information for possible actions against this phenomenon [16] (Figure 1).

Coastal zones can have an important role in the perspective of sustainable development, as they are home to the majority of the population in a specific area and play a key role for the communities well-being. The pressure from population, along with the criticality of climatic and environmental factors altered by climate change, can multiply criticalities at coastal level. Damage and losses are therefore noted in low-lying coastal areas. The method of Coastal Risk Index at the Local Scale (CRI-LS) can give evaluations of fractures, weakness, hazards and risk indices according to evaluations including physical, environmental and socio-economic factors. This approach represents a valid pillar to make decisions on the coast management and contribute to the conservation of the coasts for future generations, thus defending the sustainable development objectives of the 2030 Agenda launched by the United Nations with the aim of eradicating all types of poverty [17].

Following the definition of transitional waters by the Water Framework Directive (WFD, European Union CE 2000/60) "bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal water, but which are substantially influenced by freshwater flows", it must be consider that these ecological systems are taken into account by monitoring programs of the European Union (EU) Water Framework Directive (WFD, CE 2000/60). In this context, the monitoring of coastal lagoon ecosystems that follows Water Framework Directive guidelines shall include investigations on the biochemical composition of organic matter in sediments, as the latter contain the memory of contamination and of the site characteristics in general, thus providing a comprehensive delineation of these dynamic ecosystems [18].

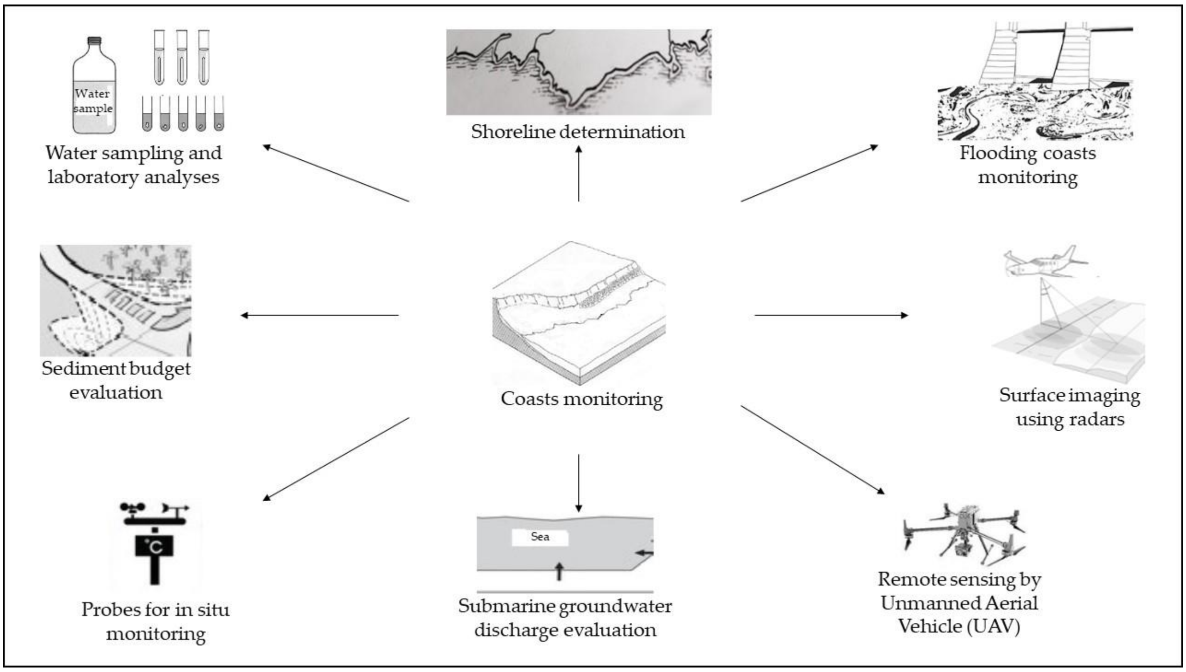

Figure 1. Monitoring approaches at coastal level, including laboratory analyses, in situ measurements, use of remote sensing investigations and detections by unmanned aerial vehicles (UAV).

3. Sea level rise (SLR)

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. Causes of sea level rise depend by different agents, including climate change, structural reasons and human factors [19]. Climate change comprehends the effects of occasional changes, with climate variations, and the increases in the concentrations of greenhouse gases. These effects can cause a thermal expansion of the oceans that is one of the main causes of sea level rise. Increases in greenhouse gases emissions are the reasons of the higher temperature detected in water bodies, evidencing modifications in sea water density at constant values of the relative mass. As the temperature increases, an increase in the volume of sea water can be observed, triggering a sea level rise (Figure 2). 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 [20]. In the period from 1993 to 2009, thermal expansion has been considered the cause of the 30% of sea level rise around the world, and by 2100, thermal expansion will cause a sea level rise greater than 12 cm [21]. 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} [22]. Antarctic glacier melt affected sea level rise by about 10.8 mm from 1992 to 2018 [23]. 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% [24]. Further increases of sea level rise are likely to be expected in the future, considering the difficult situations and the many factors involved in this phenomenon [22].

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 the 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 [25] (Figure 2).

Man-made 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 [10]. Groundwater extraction, along with irrigation and deforestation, can cause variation in inland waters, affecting sea level rise, as in the case of fresh water sites replacing in the coastal zone. As regards to 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 [26].

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 [27] (Figure 2).

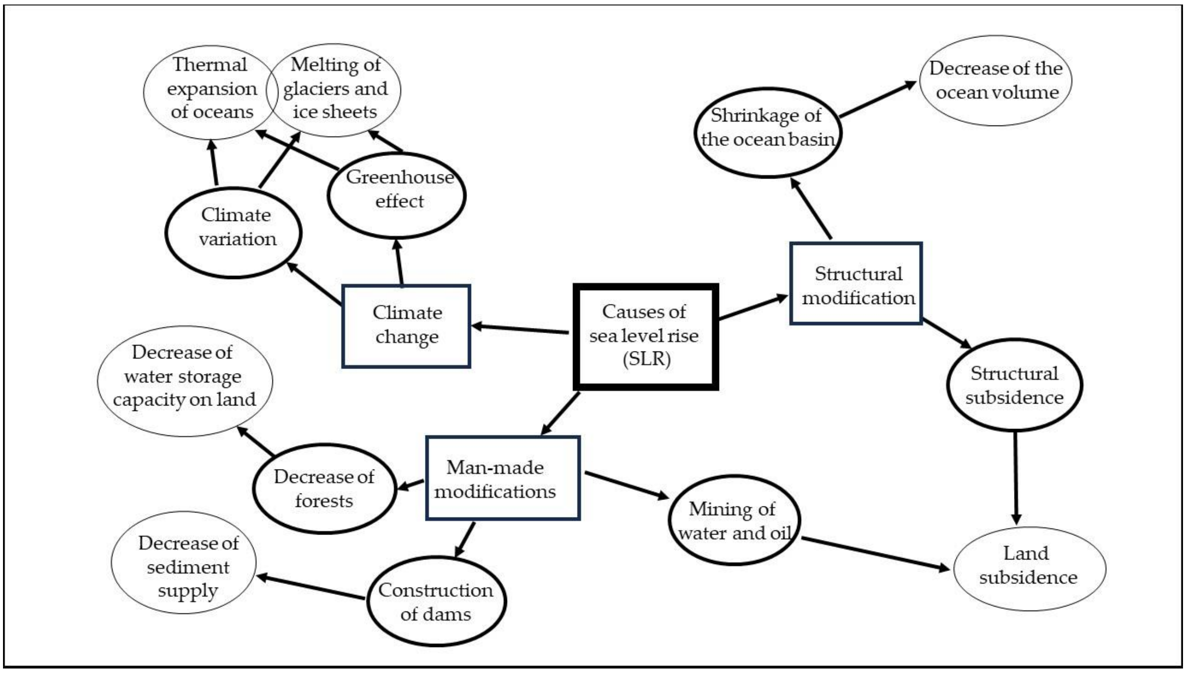

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Figure 2. Causes of sea level rise (SLR), including climate change, structural modifications and man-made modifications. Cascading effects have been included.

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 [28]. 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 has reached values of about 4.8 mm yr−1 [29]. Models used for sea level rise projections include uncertainties concerning the intensities of hereafter greenhouse gas emissions, climate change and ice melt contribution. By 2100, values of sea level rise are supposed to vary from a minimum of ~50 cm to a maximum of ~310 cm, as a function of greenhouse gas emissions and the Greenland and Antarctic ice sheets melting [30]. Sea level rise increase by the end of twentyfirst century represents a high risk for more than 3 million people that are at risk for every 2.5 cm of sea level rise and for one billion people living within 10 m above high tide [28]. Compared to the past,there have been frequent high-risk episodes related to climate change in the twentyfirst century. 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. Furthermore, populations living on coasts will be the most exposed to the risk of flooding [28,31]. 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 of approximately 66 m of total sea level rise in the future, consistent with the potential that exists if the ice sheets and glaciers of Antarctica, Greenland and the mountain glaciers were to melt [29]. Sea level rise poses a serious threat to coastal regions which are prone to increased vulnerability resulting from extreme marine events such as flooding, submersion and coastal erosion and these effects could also be exacerbated in the coming decades [32].

3.1. Coastal flooding

Coasts are characterized by various morphological types including estuaries, beaches, dunes, low and high cliffs and steep mountains. Obviously, 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 and not just at lower coasts. Sea level rise will also be followed by permanent floods and the consequent loss of beaches and coastal wetlands [28]. Coastal nuisance floods are low-level floodings that do not pose a significant threat to public safety or cause serious property damage, but which can disrupt routine daily activities, cause problems such as flooded roads and overloaded stormwater systems and which can give rise to serious inconveniences for people and can represent an optimal habitat for bacteria and mosquitoes. Since 1950, the total number of nuisance flooding events has grown exponentially. An increase of 27% more nuisance flood events was recorded in 2019, with the most representative events occurring in estuaries [33]. Coastal flooding particularly damages densely populated coastal cities. In these densely populated coastal cities, rising sea levels and extreme weather events may be a trigger for climate-induced migration, with the poor, women, children and ethnic minorities being the most vulnerable [28].

3.2. Salinity intrusion

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, limiting agricultural production, restricting grazing areas, and increasing the cost of freshwater supply for livestock, again due to salinity intrusion. Other activities that take place along the coasts and that are affected by this phenomenon are represented by fishing, agriculture, forestry, the energy sector and transports, as road and rail infrastructure can also be subject to erosion from saltwater intrusion [28].

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3.3. Coastal erosion

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 [34]. 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 coast, it is necessary to pay close attention to the detail of the coastal morphological characteristics and the existing wave motion [35]. In the coasts with mangrove, sea level rise can promote coastal erosion, following the decrease of the mangrove ecosystem, both in terms of quantity and with the reduction of biodiversity, as the increased salinity of the water selects for the more resistant species among these plants [34]. Coastal erosion can cause damage to infrastructure such as outages in power plants, fuel lines and other facilities located in coastal areas, thus causing increases in energy and infrastructure costs. Wave energy can reach and damage both the base of coastal cliffs and dunes, causing increased rates of erosion. Coastal threats will have economic impacts such as passive erosion and gradual beach loss [28].

4. Mediterranean Sea coastal areas

Coastal areas of the Mediterranean Sea are subject to important climate change impacts, with resulting extreme weather events, and to human-induced pressures such as building houses along the coasts, with an increasingly high vulnerability. The coastal areas of the Mediterranean basin are affected by climate change which includes rising sea levels with the resulting risks, storms, droughts and coastal erosion. Furthermore, these phenomena are expected to continue into the future as well. The level of sea in the Mediterranean will likely rise by values ranging from 7 cm to 12 cm by 2050 and the greatest sea level rise will occur on the eastern and southern coasts of the Mediterranean [36]. In the Mediterranean region, coastal areas will be subjected to sea level rise and possible storm-related flooding. These phenomena will put low-lying areas in serious danger of submersion with damage to coastal activities and the beaches will also be more vulnerable to erosion. Marine habitats and coastal ecosystems in the Mediterranean region are also threatened by the risk of loss. Sea level rise is a concern for some regions of the Mediterranean basin and regarding 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 cm by 2100, with severe impacts on the southern Mediterranean region [37] and a future increase in storms in the Adriatic and Aegean seas [38]. In the coastal region of the Mediterranean Sea there is about 46% of low sedimentary coasts such as beaches, dunes, reefs, lagoons, estuaries and deltas. 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, so as to determine the growth of the coast, or its erosion or stability [39]. The stability of the coasts can be influenced by the presence of artificial interventions in the coastal areas. In the Northern Mediterranean, the 25% of coast is affected by erosion and along the same Northern Mediterranean coast there is 10% of marine defenses [39]. The northern coast of the Mediterranean was transformed by artificial interventions during the twentieth century, with an extension of 1,500 km. The current increase in sea level rise will accelerate coastal erosion causing higher waves and inducing changes in current dynamics, thus affecting sediment balances. These sea level rise effects depend on wave and current action, coastline type and geomorphology, and will cause coastal erosion to increase.Furthermore, increased frequency of storms and moderate winds may further contribute to coastal erosion [40]. In the period between 1960 and 1989, information on sea level rise in the Mediterranean Sea, obtained by combining tide gauge and altimetry data with sea level fingerprints of contemporary land mass

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changes, showed that sea level in the Mediterranean fell at an average rate of -0.3 ± 0.5 mm yr^{-1}, due to an increase in atmospheric pressure over the Mediterranean Sea basin and land inputs. Level of sea water in the Mediterranean started to accelerate rapidly after 1989, and in the period from 2000 to 2018, due to currents changes and ice melting, values stabilized at an average rate of 3.6 ± 0.3 mm yr^{-1}. The rate of sea level rise showed significant modifications in the Mediterranean Sea, mainly due to changes in the large-scale circulation of the Mediterranean basin. Since 2000, the higher levels of sea level rise have been evidenced in the Adriatic, Aegean and Levantine seas as respect to values detected in other parts of the Mediterranean Sea [41].

It is noteworthy to highlight that over the past three decades, in the Mediterranean Sea the global mean sea level has risen to a value of ~3.3 mm yr^{-1} faster than twice the values recorded during the twentieth century. This increase is due to enhanced melting rates of land glaciers and thermal expansion of the oceans [42]. These processes cause highly variable behaviors of sea level change, due to the fact that the local rate of sea level change can be modified by global modifications. The high variability in the sources of global sea level rise highlighted the need for accurate investigations at a local level [41]. In the period from 1960 to 2000, sea level in the Mediterranean remained at constant values or showed a slight decrease, while in the same period, in the eastern North Atlantic sea level has risen by more than 1 mm yr^{-1} [43]. During the period 1960-2000, 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) [44]. Since the 1990s, in the Mediterranean Sea it has been detected an important increase in the rate of sea level rise, with an average rate of 2.7 mm yr^{-1} over the period 1993-2017 [45], in line with global average rate. Sterodynamic changes, including ocean density and circulation, along with melting of land ice could have originated the increase of sea level rise in the Mediterranean [41].

The Mediterranean 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% [39]. In the Mediterranean countries, the pressure exerted by these elements is further amplified by the effects of tourism which has been registered in continuous growth and mainly along the coast. Other agents affecting the Mediterranean coastal area are represented by climate change. As a consequence, sea level rise and associated hazards are expected to have significant increases in the Mediterranean basin during the twentyfirst century [46]. 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 patways at level of the Mediterranean coastal area [47]. Risks associated to climate change, including sea level rise, storms and droughts, can heavily affect Mediterranean coastal areas [48], with the highest evidence in Eastern and Southern Mediterranean coasts. Sea level rise and flooding will represent serious challenges in the Mediterranean basin, along with losses of coastal and marine habitats and related ecosystems. The primary risk during the coastal-level assessment is the management of hazards related to future impacts of marine storms [48]. Moreover, climate change has a role in inducing drying trends, with droughts mainly centered in countries of the western 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. Effects of droughts coupled with those triggered by sea level rise and storms represent serious concerns for estimation of coastal erosion [36]. Several Mediterranean coastal hotspots were reported in Table 1.

4.1. Mediterranean Sea monitoring

The Mediterranean coasts are affected by extreme climate change episodes, coupled with human-induced pressures, increasing vulnerability. Monitoring is thus of extreme importance in this area and an example is the method of Coastal Risk Index allows risk assessment in the Mediterranean

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region (CRI-MED). Through this methodology it is possible to achieve the integrated assessment of risk and vulnerability as 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 at coasts of the Mediterranean Sea [36] (Table 1). Identification of coastal hotspots in Mediterranean area is finalized to highlight interventions by policy makers and administrators by taking into account the the evaluations based on Integrated Coastal Zone Management (ICZM). This approach enables identification of convenient coastal sites to be allocated for urban settlements and for others economic and social actions [36]. Another approach for monitoring the Mediterranean basin, defined as 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 regionalcontext. 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 socio-economic development. Moreover, the method of Mediterranean Coastal Database allows to obtain advices on risk and impact assessment [47]. 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 sediments 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. The collected data represent an important support to policy makers and to the socio-economic actors for planning interventions for remediating altered Mediterranean coasts [49]. The Mediterranean Sea is among the most important global biodiversity hotspots (Table 1). With this in mind and 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 advices to decision-makers and to improve the quality of life, thus contributing to the defence of the environment, to the maintenance and reconstruction of the Mediterranean Sea and to make their contribution for a sustainable blue economy. Mediterranean Sea Literacy can help development of the Mediterranean Sea aimed to achieve an innovative and sustainable blue economy and thus to the accomplishment of Sustainable Development Goal 14 in the Mediterranean region [50].

4.2. Mediterranean Sea and migrations

Climate change affects people living in poverty unequally, 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 [51]. The serious problem of migration in the Mediterranean was dramatically revealed in 2015, when an unprecedented ingress of migrants from the regions of Middle East, Maghreb and sub-Saharan Africa has involved Europe [52]. As consequences of inundations and of increase of hazards due to sea level rise, large proportions of communities will move and migration responses will increase. A direct inundation forces migrations, after that, socioeconomic and demographic inequalities can interact with climate change effects, augmenting migration responses [53]. Nowadays, a large number of people live near the coasts, that evidence serious situations caused by sea level rise, with consequences for the increase in the number of migrants. Processes of migration triggered by sea level rise also depend from other aspects as the economic, social and cultural, with families that initially oppose to migration caused by sea level rise, until migration remains the only possible option. An assessment of the number of migrants is not simple because it involves various reasons including quantification derived by climate change effects and possible interventions on the coasts. In case that coasts are not protected, sea level rise and flooding phenomena will lead to important migration episodes [54]. 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 [53]. Migration as consequence of climate change could represent a growing phenomenon of the twentyfirst century,as population that is exposed to environmental factors effects will probably significantly augment [55]. Phenomena 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 [56]. As a measure to contain the migration process, protection of coasts represents a way to reduce this phenomenon and to maintain stable the populations living along coastal areas [57].

4.3. 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 represents a famous sea, cradle of glorious civilizations and source of great changes, theater of exchanges and economic activities. The institution named United Nations Educational, Scientific and Cultural Organisation (UNESCO) includes the heritages under the World Heritage Convention [58]. Coasts host a large portion of unities included in the cultural World Heritage Convention are located 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 (WHs) already located in this area at risk from flooding and coastal erosion [59]. 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 civilisations that developed in this region [60]. In the Meditarranean 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 [59]. From 2000 to 2100 there will be the vast majority of World Heritage Convention at risk, and in particular 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. Decision-makers will detect the areas with higher probabilities to be damaged [59] (Table 1).

Table 1. Mediterranean coastal highlighted hotspots.

Mediterranean coastal hotspots	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	[61,62]
Algeria, Gulf of Oran	Alien jellyfish species will threaten native Mediterranean species in the Gulf of Oran	Vulnerability of coastal areas to erosion, flooding and salt intrusion	[63]
Croatia, Cres-Lolinj		Increased salinization of Lake Vrana	[61,64]
Croatia, Kaštela Bay	Flooding of Pantana spring and Zrnovnica estuary	Increased salinisation of estuaries and groundwater resulting in problems for coastal services and infrastructure. More evident deterioration of historic buildings and increased water needs in homes, industries and agriculture	[61,64]
Egypt, Delta of Nile	Dramatic increases in migration rates mainly from coastal areas	Increased coastal erosion and outgrown coastal defences. Increase in floods with damage to port and city infrastructures, with the retreat of the barrier dunes, the decrease in soil humidity, the increase in water salinity in the soils and in lagoon areas and decrease in fish production. Major coastal retreats and alterations to coastal activities are also anticipated	[61,65–69]
Egypt, FukaMatrouh		Increase in evapotranspiration and decrease in rainfall, with extension of aridity levels in the summer period and increase in coastal erosion phenomena and decrease in soil fertility.	[61,70]
France, Delta of Rhône	Extraordinary tourism	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	[61,71]
Greece, wetland delta environments formed by the Axios and Aliakmonas rivers	The particular conformation of the dynamics of the Mediterranean river delta and their behaviors require the use of Earth Observation technologies and GIS as tools to collect information		[72]
Greece, Island of Rhodes	Soil erosion in the Maltese Islands and groundwater salinisation 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	[61,73]
South Greece	Geomorphological conformations, erosion of the coast, morphology of coastal slope		[74]
Greece, Thermaikos Gulf		Coastal lowland flooding, saline water intrusion into rivers, marsh flooding, increased seawater stratification and bottom anoxia, decreased river runoff levels, groundwater salinization, decreased soil fertility, damage to coastal protection structures, changes in the tourist season	[61,75]
Italy, Apulian Coastline	Geomorphological conformations, erosion of the coast, aspects of the coastal slope, width of beaches and dunesand of vegetation behind the beach		[76]
Italy, Delta of Po		Increased flood events and coastal erosion, dune retreat, damage to coastal infrastructure, soil salinization, altered water distribution regimes, reduced	[61,77,78]

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		nearshore water mixing and primary production, increased anoxia in deep waters	
Italy, Italian coast	Shoreline pathways changes, distance from shoreline, elevation, coastal slope, geological coastal type, land roughness, conservation designation, coastal protection structures		[79]
Spain, Delta of Ebro		Increases in coastal erosion rates and coastal reshaping, inundation and loss of wetlands, reductions in fisheries	[61,80]
Spain, Delta of Tordera	Very high "hotspotness" condition, with extensive and frequent damage to the site in recent decades		[81]
Spain, Delta of Ebro	Flooding and erosion phenomena have been detected in the urban area of the study area		[82]
Spain, Gulf of Valencia		Major alterations of the marine environment with sea water level rises, storms and wave surges, coastal vulnerability to erosion, flooding and saline intrusion, marine pollution, biodiversity decrease and spread of invasive species with impacts on fisheries, on industry and tourism	[83]
Syria, Syrian coast		Increase in soil erosion phenomena, groundwater salinization, exceptional storm surges with consequent beach erosion and damage to coastal structures and human settlements	[61]
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	[83,84]
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	[69]
Tunisia, IchkeulBizerte		Increase in evapotranspiration and consequent decrease in soil moisture, decrease in lake fertility and increase in salinity, increase in lake salinity, decrease in wetlands and loss of habitats	[61]
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}	The most significant impacts may be groundwater salinization, erosion and possible flooding	[61,85]

5. Engineering approaches for coasts protection

The management of coasts must consider the physical processes responsible of erosion and the aggravating anthropogenic influences. Relevant strategies facing to these damages at coasts include defence, accommodation and retreat. Accelerated coastal erosion due to human pressure is prevalent. Standard defense techniques have been adopted to combat erosion, with the addition of a further new final point which consists in intervening on the causes of these damages and on human pressure [86]. Cities in coastal areas suffer from problems related to sea level rise, such as storm surges, erosion, flooding and the resulting rapid degradation of natural coastal systems [28,87]. Sea level rise causes flooding, increased rates of coastal erosion, saltwater intrusion, and land subsidence. In the long term, the most significant problems can be represented by coastal erosion. Sea level rise and coastal erosion have serious impacts such as disruption of economic activities, degradation of natural ecosystems and alteration of biodiversity [88].

The Coastal Management Subgroup and Response Strategies Working Group has identified three measures to address sea level rise, namely protection, retreat and accommodation [89]. In Europe, risk reduction in coastal zones has included additional specific strategies [34], which have been described in various studies [90,91]. 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 [34].

Defence interventions against sea level rise and erosion include: a) "do nothing", a procedure without action, meaning do not make any changes. In this kind of approach, free areas and wetlands without physical and economic impacts are sacrificed to suffer the impact of downstream flooding or erosion; b) "seaward movement" which consists of advancement interventions, with the construction of structures above sea level, using sand or other materials, with the aim of reducing the risk of flooding for the coasts. This strategy leads to compression and increased susceptibility of coasts and for adjacent ecosystems, wetlands, salt marshes and mangroves; c) "line maintenance strategy" an intervention that consists in the introduction of elements capable of reducing the impact of sea water, to avoid flooding of the coasts and coastal cities. These elements include rigid protections such as dykes, dams, sea walls, barriers and weirs, while also preventing erosion at coasts and intrusion of water into the soil. Other protections include sediments and dunes. When these measures are implemented in combination, they are called hybrid measures. They are usually expensive due to the construction of rigid structures, such as dams, revetments, sea walls. In case of coast control, hard structures such as breakwaters and revetments are the most effective, fastest and easiest. As for perpendicular structures such as breakwaters or sea walls, they promote normal deposition of sediment and beach aggregation, however downward erosion is expected; d) "managed realignment" intervention consists of an adaptation strategy that includes moving, displacement and relocation. Moving involves the permanent or semi-permanent movement 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, usually by providing incentives for families. This type of intervention involves the relocation of critical structures or land use inland. The costs of this intervention must include the purchase of land, the reconstruction of infrastructure and the transfer of existing assets; e) "adaptation or accommodation" which represents the continued use of a land at risk with interventions such as raising the platform level, an elevated structure, floating houses, contingency planning and retreat areas.This intervention aims to reduce coastal risks by reducing impacts on human lives, livestock, ecosystems and human activities; f) "limited intervention" consists of adaptation interventions that provide combinations of protection and enhanced advantages, preserving and restoring coastal ecosystems. The system acts as a barrier reducing the waves energy and the speed of storms. This intervention can counteracts soil erosion by stabilizing sediments at coasts, but can be expensive to maintain and take longer to deliver results [34,92].

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5.1. Hard engineering interventions at coasts

Engineering interventions offer adaptation solutions for the resilience of coastal areas. The continuous increase in the population at coasts, underlines the attention to their protection [93]. One type of coastal intervention is the hard engineering, defined also as "grey infrastructure". This technique can protect coasts due to absorption of waves energy and diminishing probabilities of coastal erosion and flooding anduses man-made structures with a high visiblity [94]. Structures of hard engineering are frequent in northwestern Europe, eastern Asia and deltas of rivers or in coastal cities with high density of population [95]. 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 in the meantime, can trigger erosion and destabilize beaches. These structures also include groins able to stop sand transport along the coast and are successful in beach development but can induce erosion phenomena. Finally, detached sea walls and artificial reefs which reduce wave energy and that are effective in beach construction, again can cause erosion downstream [91].

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 flows, overturns, slides, and falls [96]. Erosion at the base of cliffs is caused by waves, 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 that can be conducted by inserting metal bars into cliffs conferring cliff reinforcement and shorelines protection from erosion [97] (Table 2). Coastal barrage is another hard-engineering procedure using dam-like structures in partly submerged, that have the role to control tidal flow (Table 2). This intervention can control storm surges changing water levels and may provide protection against coastal flooding [98]. Moreover, coastal barrage can originate consistent water levels that can be exploited for hydroelectricity production. Energy in marine and tidal currents can be also converted to electricity as well [99]. Gabions are structures that reduce the impact of waves and consist of bundles of wire mesh or bare boulders placed overhanging [100] (Table 2). Gabions are anti-erosion devices that protect the piers and abutments 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 [100]. Groynes consist of wooden fence-like barriers built at right angles to the beach. These hard engineering devices partially or completely block shoreline drift (Table 2). 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 [101]. Revetments are structures placed along a cliff and consists of inclined concrete, wooden, or rock structures preventing cliff erosion by absorbing wave energy (Table 2). These structures require maintenance work and can therefore be quite expensive [102]. Rock armor 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 (Table 2). Rock reinforcements are rigid engineering structures whose stability must be controlled. In particular, a control is required in the presence of high, non-linear waves which can damage such structures [103]. 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 (Table 2). 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 and is built to protect a port or beach from the force of the waves [104]. Hard engineered coastal protection devices can have disadvantages because they can be expensive, or 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 frequent monitoring activities.

5.2. Soft engineering interventions at coasts

The soft engineering protection approach to face with coastal erosion is gaining a growing recognition of the benefits in coasts protection. This kind of engineering approach allows the coast to respond dynamically to change respecting environmental equilibra. Such applications were therefore defined as "building with Nature", and consist in strategies that provides an effective response to protect beaches and coastal areas. These responses to coastal erosion offer economic and social benefits. Soft adaptation is considered an environmentally friendly protection response in coastal ecosystems [105]. The principles of conservation, restoration and use of vegetated coastal habitats in eco-engineering processes for coastal protection, provide a promising strategy, giving important insights for climate change mitigation and adaptation [106]. Coping with the problems of coastal erosion with the use of vegetation allows to dissipate the energy of the waves whose flow is separated and the friction given by their presence makes the bottom more jagged, 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 [106]. 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*' [107,108].

One way to stabilize the coasts and in particular the dunes, while respecting the natural principles of the vegetation, is represented by the planting of trees, with the method defined afforestation of the coastal dunes (Table 2). 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 [109,110]. Beach nourishment is a soft engineering approach that allows increasing the path that the wave must travel, diminishing wave energy and preventing erosion (Table 2). Beach nourishment procedure aims to maximize the time of sand permanence on the beach, in order to promote human safety, recreation of aquatic environments, groundwater dynamics, and ecosystem resilience [111]. In approaches of beach stabilization dead trees are added to the sand with the aim is to stabilize 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 [112]. Beach stabilization strongly sustains the use of eco-friendly approaches for coastal protection [113]. 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 (Table 2). Coral reefs reduce the energy of waves, thus protecting coasts against erosion [114]. Studies on innovative techniques and new ecological engineering approaches in processes of coral reef restoration are in progress [115]. Dune regeneration is a soft engineering approach that allow for setting up barriers and for absorbption of wave energy, finally reducing coastal erosion and protecting against flooding. Dune regeneration procedure is finalized to the establishment of new sand dunes or the restoration of the existing ones (Table 2). These nature-based solutions can have an important role in responding to the challenges of climate change in coastal areas [116]. Managed retreat is a soft engineering procedure (Table 2) where certain coastal areas have been identified on the basis of their low value, to become naturally subjected to erosion and flooding. The approach of naturally eroded and flooded coasts therefore favor the development of beaches and salt marshes with a low-cost and sustainable procedures [117]. Mangrove preservation and planting are soft engineering procedures requiring the planting of mangrove trees along the coast

(Table 2). These restored mangrove ecosystems have important ecological, economic and social values for the coast [118]. Roots of mangrove trees hold the ground prevent erosion and allow wave energy to be dissipated. 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 considered a widely applicable type of intervention to enhance coastal safety [119]. Soft engineering to be used in implementing and maintaining coasts can provide 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 [120].

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Table 2. Types of hard and soft 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	[97,121]
Coastal barrage	A partly submerged dam-like structures 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 maintaintenance	[98,122,123]
Gabion	Rocks and boulders encased in a wired mesh	Absorbption of the energy from waves	It can be not very effective or attractive	[124,125]
Groyne	Insertion of barriers similar to 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 erosion further downstream and, in addition, the need for high maintenance costs	[101,126,127]
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	[102,128]
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 maintaintenance	[103,129]
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	[104,130,131]
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	[110,132]
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	[111,133,134]
Beach stabilization	Introducing dead trees in the sand, stabilizing beaches	Beaches widening waves slowing and erosion prevention	Intervention trees need to be sourced and can their maintenence can be costly	[113,135]
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 wave length 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	[115,136,137]
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	[138]
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	[117,139,140]
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	[118,141]

6. Conclusions

The coasts are the border area between land and sea and are of fundamental importance. Their monitoring is strategic and can be conducted by adopting different approaches, from laboratory analyzes to remote sensing investigations. The latter can dispose of technologies such as unmanned aerial vehicles that allow improvements in monitoring procedures, together with mathematical models. Sea level rise and coastal erosion seriously affect ecology and economy of coasts and can have consequences for human health. In particular, the inhabitants of agricultural areas and people living in islands can be more damaged and need a support to combat climate change.

Engineering interventions can counter the threats of sea level rise and coastal erosion. Hard engineering, also called "grey infrastructure" and soft engineering, also called "Nature-based solutions", are important interventions that can be used to address coastal problems by improving the environmental and socio-economic conditions of these areas. In any case, an important and detailed local assessment of the advantages and disadvantages of these interventions is needed. In fact, some solutions that may be considered effective in some regions may be ignored or perceived negatively in others. For example, low-rise and submerged structures widely used in Europe with very good results for the environment, can be perceived negatively in tropical regions. To improve adaptation to these innovations it is therefore necessary to fill any technological gaps and provide the necessary economic resources, accelerating adaptation.

The determination of the effectiveness of coastal engineering interventions must be carried out in order to obtain a better evaluation of the outcomes of such engineering approaches. The proposed engineering approaches should be technically feasible, economically feasible, environmentally friendly and socially acceptable. What would be important is to have a multidisciplinary approach to coastal problems, with new solutions and collaborations with agencies related to the field of coastal management, engineering and marine sciences for effective planning and evaluation of interventions. Future insights and research should include further investigations of coastal-level engineering approaches, combined with an important monitoring activity both before and after each engineering intervention.

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References

1. Toure, S.; Diop, O.; Kpalma, K.; Maiga, A.S. Shoreline Detection using Optical Remote Sensing: A Review. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 75. doi:10.3390/ijgi8020075.
2. Cantasano, N.; Pellicone, G.; Ietto, F. Integrated coastal zone management in Italy: A gap between science and policy. *J. Coast. Conserv.* **2017**, *21*, 317–325.
3. González-Dueñas, C.; Padgett, J.E. Performance-Based Coastal Engineering Framework. *Front. Built Environ.* **2021**, *7*, 690715. doi: 10.3389/fbuil.2021.690715.
4. Bruno, M.F.; Molfetta, M.G.; Pratola, L.; Mossa, M.; Nutricato, R.; Morea, A.; Nitti, D.O. Chiaradia, M.T. A combined approach of field data and earth observation for coastal risk assessment. *Sensors* **2019**, *19*, 1399.
5. Nicholls, R.J.; Lincke, D.; Hinkel, J.; Brown, S.; Vafeidis, A.T.; Meyssignac, B.; Hanson, S.E.; Merkens, J.L.; Fang, J. A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nat. Clim. Change* **2021**, *11*, 338–342.
6. Sarkar, N.; Rizzo, A.; Vandelli, V.; Soldati, M. A Literature Review of Climate-Related Coastal Risks in the Mediterranean, a Climate Change Hotspot. *Sustainability* **2022**, *14*, 15994. https://doi.org/10.3390/su142315994.
7. Toimil, A.; Camus, P.; Losada, I.J.; Le Cozannet, G.; Nicholls, R.J.; Idier, D.; Maspataud, A. Climate change-driven coastal erosion modelling in temperate sandy beaches: Methods and uncertainty treatment. *Earth-Sci. Rev.* **2020**, *202*, 103110.

8. Vousdoukas, M.I.; Mentaschi, L.; Voukouvalas, E.; Verlaan, M.; Jevrejeva, S.; Jackson, L.P.; Feyen, L. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nat. Commun.* **2018**, *9*, 2360. DOI: 10.1038/s41467-018-04692-w.
9. De Serio, F.; Armenio, E.; Mossa, M.; Petrillo, A.F. How to Define Priorities in Coastal Vulnerability Assessment. *Geosci*. **2018**, *8*, 415. doi:10.3390/geosciences8110415.
10. Zanchettin, D.; Bruni, S.; Raicich, F.; Lionello, P.; Adloff, F.; Androsov, A.; Antonioli, F.; et al. Sea-level rise in Venice: historic and future trends (review article). *Nat. Hazards Earth Syst. Sci.* **2021**, *21*, 2643–2678. https://doi.org/10.5194/nhess-21-2643-2021.
11. CMRC-Coastal & Marine Resource Centre. Methodology for Coastal Monitoring Programme at Portrane; Technical Report for Fingal County Council; Rush Beaches, Co.: Dublin, Ireland. **2009**.
12. NOAA-National Oceanic and Atmospheric Administration What Is Remote Sensing? National Ocean Service Website. Available online: https://oceanservice. noaa.gov/facts/remotesensing.html (accessed on 24 July 2023). **2023**.
13. Faye, B.N. Dynamique du trait de côte sur les littoraux sableux de la Mauritanie à la Guinée-Bissau (Afrique de l'Ouest): Approches régionale et locale par photo-interprétation, traitement d'images et analyse de cartes anciennes, These de l'universite de Bretagne occidentale. soutenue le 15 février 2010. Available online: https://tel.archives-ouvertes.fr/tel-00472200/PDF/DYNAMIQUE-DU-TRAIT-DE-COTEEN-AFRIQUE-DE-L_OUEST-MAURITANIE-GUINEE-BISSAU-VOLUME1.pdf (accessed on 26 June 2023). **2010**.
14. Minervino Amodio, A.; Di Paola, G.; Rosskopf, C.M. Monitoring Coastal Vulnerability by Using DEMs Based on UAV Spatial Data. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 155.
15. Isha, I.B.; Adib, M.R.M. Shoreline monitoring using Unmanned Aerial Vehicle (UAV) at Regency Beach, Port Dickson. *IOP Conf. Ser.: Mater. Sci.* **2021**, *1144*. doi:10.1088/1757-899X/1144/1/012060
16. Qi, L.; Wang, M.; Hu, C.; Holt, B. On the capacity of Sentinel-1 synthetic aperture radar in detecting floating macroalgae and other floating matters. *Remote Sens. Environ.* **2022**, *280*, 113188.
17. Agharroud, K.; Puddu, M.; Ivčević, A.; Satta, A.; Kolker, A.S.; Snoussi, M. Climate risk assessment of the Tangier-Tetouan-Al Hoceima coastal Region (Morocco). *Front. Mar. Sci.* **2023**, *10*, 1176350. doi: 10.3389/fmars.2023.1176350.
18. Renzi, M.; Provenza, F.; Pignattelli, S.; Cilenti, L.; Specchiulli, A.; Pepi, M. Mediterranean Coastal Lagoons: The Importance of Monitoring in Sediments the Biochemical Composition of Organic Matter. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3466; doi:10.3390/ijerph16183466.
19. Hansen, J.; Sato, M.; Hearty, P.; Ruedy, R.; Kelley, M.; Masson-Delmotte, V.; Russell, G.; Tselioudis, G.; et al. 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.* **2016**, *16*, 3761–3812.
20. Domingues, C.M.; Church, J.A.; White, N.J.; Gleckler, P.J.; Wijffels, S.E.; Barker, P.M.; Dunn, J.R. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* **2008**, *453*, 1090–1093.
21. Micheal, O.; Bruce, G.; Hinkel, J.; Roderik, V.; Frederikse, T. 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. **2019**.
22. Kopp, R.E.; DeConto, R.M.; Bader, D.A.; Hay, C.C.; Horton, R.M.; Kulp, S.; Oppenheimer, M.; Pollard, D.; Strauss, B.H. Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections. *Earth's Future* **2017**, *5*, 1217–1233.
23. Shepherd, A.; Ivins, E.; Rignot, E.; Smith, B.; van den Broeke, M.; Velicogna, I.; Whitehouse, P.; et al. Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature* **2020**, *579*, 233–239.
24. Edwards, T.L.; Nowicki, S.; Marzeion, B.; Hock, R.; Goelzer, H.; Seroussi, H.; et al. Projected land ice contributions to twenty-first-century sea level rise. *Nature* **2021**, *593*, 74–82.
25. Antonioli, F.; De Falco, G.; Lo Presti, V.; Moretti, L.; Scardino, G.; Anzidei, M.; et al. Relative Sea-Level Rise and Potential Submersion Risk for 2100 on 16 Coastal Plains of the Mediterranean Sea. *Water* **2020**, *12*, 2173.
26. Chao, B.F.; Wu, Y.H.; Li, Y.S. Impact of artificial reservoir water impoundment on global sea level. *Science* **2008**, *320*, 212–214.
27. Dong, L.; Cao, J.; Liu, X. Recent Developments in Sea-Level Rise and Its Related Geological Disasters Mitigation: A Review. *J. Mar. Sci. Eng.* **2022**, *10*, 355. https://doi.org/10.3390/jmse10030355.
28. Griggs, G.; Reguero, B.G. Coastal Adaptation to Climate Change and Sea-Level Rise. *Water* **2021**, *13*, 2151. https://doi.org/10.3390/w13162151.

29. Lievin, M.; Kocha, C.; Courcol, B.; Philipps, S.; Denis, I.; Guinle, T.; et al. Reprocessing of Sea Level L2P Products for 28 Years of Altimetry Missions. OSTST. **2020**. Available online at: https://www.aviso.altimetry.fr/en/data/ucts/ocean indicator products/mean sea level.html (accessed on 19 June 2023).
30. DeConto, R.M.; Pollard, D. Contribution of Antarctica to past and future sea-level rise. *Nature* **2016**, *531*, 591–597.
31. Focardi, S.; Pepi, M. Sea Level Rise Impacts in Coastal Areas and Possible Mitigation Engineering Approaches. *Ann. Civil Environ. Eng.* **2023**; *7*, 030-036
32. Enríquez, A.R.; Marcos, M.; Álvarez-Ellacuría, A.; Orfila, A.; Gomis, D. 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.* **2016**, *361*. doi:10.5194/nhess-2016-361.
33. Li, S.; Wahl, T.; Talke, S.A.; Jay, D.A.; Orton, P.M.; Liang, X.; Wang, G.; Liu, L. Evolving tides aggravate nuisance flooding along the U.S. coastline. *Sci. Adv.* **2021**, *7*, eabe2412.
34. Rashidi, M.A.H.; Jamal, M.H.; Hassan, M.Z.; Mohd, S.S.; Mohd, S.L.; Abd Hamid, M.R. Coastal Structures as Beach Erosion Control and Sea Level Rise Adaptation in Malaysia: A Review. *Water* **2021**; *13*, 1741. https://doi.org/10.3390/w13131741.
35. Sundar, V.; Sannasiraj, S.A.; Babu, S.R. Sustainable hard and soft measures for coastal protection – Case studies along the Indian Coast. *Mar. Georesources Geotechnol.* **2022**, *40(5)*, 600-615. DOI: 10.1080/1064119X.2021.1920650.
36. Satta, A.; Puddua, M.; Venturini, S.; Giupponi, C. Assessment of coastal risks to climate change related impacts at the regional scale: The case of the Mediterranean region. *Int. J. Disaster Risk Reduct*. **2017**, *24*, 284–296.
37. IPCC. Climate change 2013: the physical science basis, in: T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen. J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley (eds.), 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. **2013**.
38. Guedes Soares, C.; Carretero-Albiach, J.; Weisse, R.; Alvarez-Fanjul, E. 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, **2002**, pp. 669–675.
39. UNEP/MAP. Mediterranean Strategy for Sustainable Development 2016-2025. Plan Bleu, Regional Activity Centre, Valbonne, **2016**.
40. Sánchez-Arcilla, A.; Mösso, C.; Sierra, J.P.; Mestres, M.; Harzallah, A.; Senouci, M.; El Raey, M. Climatic drivers of potential hazards in Mediterranean coasts. *Reg. Environ. Change* **2011**, *11*, 617–636.
41. Calafat, F.M.; Frederikse, T.; Horsburgh, K. The sources of sea-level changes in the Mediterranean Sea since 1960. *J. Geophys. Res. Oceans* **2022**, *127*, e2022JC019061. https://doi.org/10.1029/2022JC019061.
42. Frederikse, T.; Landerer, F.; Caron, L.; Adhikari, S.; Parkes, D.; Humphrey, V.W.; et al. The causes of sea-level rise since 1900. *Nature* **2020**, *584(7821)*, 393–397. https://doi.org/10.1038/s41586-020-2591-3.
43. Tsimplis, M.N.; Baker, T.F. Sea level drop in the Mediterranean sea: An indicator of deep water salinity and temperature changes? *Geophys. Res. Lett.* **2000**, *27(12)*, 1731–1734. https://doi.org/10.1029/1999GL007004.
44. Tsimplis, M.N.; Josey, S. Forcing the Mediterranean sea by atmospheric oscillations over the North Atlantic. *Geophys. Res. Lett.* **2001**, *28(5)*, 803–806. https://doi.org/10.1029/2000GL012098.
45. Mohamed, B.; Abdallah, A.M.; Alam El-Din, K.; Nagy, H.; Shaltout, M. Inter-annual variability and trends of sea level and sea surface temperature in the Mediterranean sea over the last 25 years. *Pure Appl. Geophys.* **2019**, *176*, 3787–3810. https://doi.org/10.1007/s00024-019-02156-w.
46. Vousdoukas, M.I.; Mentaschi, L.; Voukouvalas, E.; Verlaan, M.; Feyen, L. Extreme sea levels on the rise along Europe’s coasts. *Earths Future* **2017**, *5*, 304–323. https://doi.org/10.1002/2016ef000505.
47. Wolff, C.; Vafeidis, A.T.; Muis, S.; Lincke, D.; Satta, A.; Lionello, P.; Jimenez, J.A.; Conte, D.; Hinkel, J. Data Descriptor: A Mediterranean coastal database for assessing the impacts of sea-level rise and associated hazards. *Sci. Data* **2018**, *5*, 180044. DOI: 10.1038/sdata.2018.44
48. Gualdi, S.; Somot, S.; May, W.; Castellari, S.; Déqué, M.; Adani, M.; Artale, V.; Bellucci, A.; Breitgand, J.S.; Carillo, A.; Cornes, R.; Dell’Aquila, A.; et al. 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, **2013**.
49. Amrouni, O.; Abderraouf Hzami, A.; Heggy, E. Photogrammetric assessment of shoreline retreat in North Africa: Anthropogenic and natural drivers. *ISPRS J. Photogramm. Remote Sens.* **2019**, **157**, 73–92.

50. Mokos, M.; Cheimonopoulou, M.Th.; Koulouri, P.; Previati, M.; Realdon, G.; Santoro, F.; Mogias, A.; Boubonari, T.; Gazo, M.; Satta, A.; et al. Mediterranean Sea Literacy: When Ocean Literacy becomes region-specific. *Medit. Mar. Sci.* **2020**, *21(3)*, 001-607. DOI: http://dx.doi.org/10.12681/mms.23400.
51. Global Commission Report. Work for a brighter future – Global Commission on the Future of Work International Labour Office – Geneva ILO, **2019**.
52. Werz, M.; Hoffman, M. Climate Change and Migration in the Mediterranean: Challenges for the Future. Strategic Sectors, Economy & Territory IEM ed. Mediterranean Yearbook. **2017**.
53. Hauer, M.E.; Fussell, E.; Mueller, V.; Maxine Burkett, M.; Call, M.; Abel, K.; McLeman, R.; Wrathall, D. Sea-level rise and human migration. *Nat. Rev. Earth Environ.* **2020**, *1*, 28–39.
54. Lincke, D.; Hinkel, J. Coastal migration due to 21st century sea-level rise. *Earth's Future* **2021**, *9*, e2020EF001965. https://doi.org/10.1029/2020EF001965.
55. IPCC. Intergovernmental Panel on Climate Change; 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. **2018**.
56. Cattaneo, C.; Beine, M.; Fröhlich, C.J.; Kniveton, D.; Martinez-Zarzoso, I.; Mastrorillo, M.; et al. Human migration in the era of climate change. *Rev. Environ. Econ. Policy* **2019**, *13(2)*, 189–206. https://doi.org/10.1093/reep/rez008.
57. Oppenheimer, M.; Glavovic, B.C. Chapter 4: Sea level rise and implications for low lying islands, coasts and communities. In The ocean and cryosphere in a changing climate. IPCC **2019**.
58. UNESCO. Convention Concerning the Protection of the World Cultural and Natural Heritage http://whc.unesco.org/archive/convention-en.pdf. UNESCO, Paris, **1972**.
59. Reimann, L.; Vafeidis, A.T.; Brown, S.; Hinkel, J.; Tol, R.S.J. Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nat. Commun.* **2018**, *9*, 4161. https://doi.org/10.1038/s41467-018-06645-9.
60. Cazenave, A. Anthropogenic global warming threatens world cultural heritage. *Environ. Res. Lett.* **2014**, *9*, 51001.
61. UNEP/EEA. State and pressures of the marine and coastal Mediterranean environment. **1999**.
62. World Bank. Adapting vulnerable energy infrastructure to climate change. Climate change projections for Albania **2009**, pp 30.
63. Sahabi-Abed, S. Future Climate Projections in Algeria Using Statistical DownScaling Model. *Res. Sq.* **2021**, https://doi.org/10.21203/rs.3.rs-627355/v1.
64. Baric, A.; Grbec, B.; Bogner, D. Potential Implications of Sea-Level Rise for Croatia. *J. Coast. Res.* **2008**, *24(2)*, 299-305.
65. El-Raey, M.; Dewidar, Kr.; El-Hattab, M. Adaptation to the impacts of sea level rise in Egypt. *Mitig. Adapt. Strateg. Glob. Chang.* **1999**, *4*, 343–361.
66. Frihy, O.E. The Nile Delta-Alexandria coast: Vulnerability to Sea-Level Rise, consequences and Adaptation. *Mitig. Adapt. Strateg. Glob. Chang.* **2003**, *8*, 115–138.
67. Hereher, M.E. Vulnerability of the Nile Delta to sea level rise: an assessment using remote sensing. *Geomat. Nat. Hazards Risk* **2010**, *1(4)*, 315–321.
68. Hassaan, M.A.; Abdrabo, M.A. Vulnerability of the Nile Delta coastal areas to inundation by sea level rise. *Environ. Monit. Assess.* **2013**, *185(8)*, 6607-6616.
69. Hzami, A.; Heggy, E.; Amrouni, O.; Mahé, G.; Maanan, M.; Abdeljaouad, S. Alarming coastal vulnerability of the deltaic and sandy beaches of North Africa. *Sci. Rep*. **2021**, *11*, 2320. | https://doi.org/10.1038/s41598-020-77926-x.
70. Yousif, M.; Bubenzer, O. Perched groundwater at the northwestern coast of Egypt: a case study of the Fuka Basin. *Appl. Water Sci.* **2012**, *2*, 15–28.
71. Tol, R.J.; Bohn, M.; Downing, T.E.; Guillerminet, M.L.; Hizsnyik, E.; Kasperson, R.; Lonsdale, K.; Mays, C.; Nicholls, R.J.; Olsthoorn, A.A.; Pfeifle, G.; Poumadere, M.; Toth, F.L.; Vafeidis, A.T.; Van Der Werff, P.E.; Yetkiner, H.I. Adaptation to Five Metres of Sea Level Rise. *J. Risk Res.* **2006**, *9(5)*, 467–482.
72. Petropoulos, G.P.; Kalivas, D.P.; Griffiths, H.M.; Dimoub, P.P. 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.* **2015**, *35*, 217–228.

73. IEEP (Institute for European Environmental Policy). Impacts of Climate Change on all European Islands: FinalReport **2012**, pp 47.
74. Tragaki, A.; Gallousi, C.; Karymbalis, E. Coastal Hazard Vulnerability Assessment Based on Geomorphic, Oceanographic and Demographic Parameters: The Case of the Peloponnese (Southern Greece). *Land* **2018**, *7*, 56.
75. Poulos, S.E.; Ghionis, G.; Maroukian, H. 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* **2009**, *107(1–2)*, 18–24.
76. Pantusa, D.; D'Alessandro, F.; Riefolo, L.; Principato, F.; Tomasicchio, G. Application of a Coastal Vulnerability Index. A Case Study along the Apulian Coastline, Italy. *Water* **2018**, *10*, 1218.
77. Torresan, S.; Critto, A.; Rizzi, J.; Marcomini, A. Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. *Nat. Hazards Earth Syst. Sci*. **2012**, *12*, 2347–2368.
78. Taramelli, A.; Valentini, E; Righini, M.; Filipponi, F.; Geraldini, S.; Nguyen Xuan A. Assessing Po River Deltaic Vulnerability Using Earth Observation and a Bayesian Belief Network Model. Water 2020, 12, 2830; doi:10.3390/w12102830.
79. Furlan, E.; Pozza, P.D.; Michetti, M.; Torresan, S.; Critto, A.; Marcomini, A. Development of a Multi-Dimensional Coastal Vulnerability Index: Assessing vulnerability to inundation scenarios in the Italian coast. *Sci. Total Environ.* **2021**, *772*, 144650.
80. Sánchez-Arcilla, A.; Jiménez, J.A.; Valdemoro, H.I.; Gracia, V. Implications of Climatic Change on Spanish Mediterranean Low-Lying Coasts: The Ebro Delta Case. *J. Coast. Res.* **2008**, *24(2)*, 306–316.
81. Jimenez, J.A.; Sanuy, M.; Ballesteros, C.; Valdemoro, H.I. The Tordera Delta, a hotspot to storm impacts in the coast northwards of Barcelona (NW Mediterranean). *Coast. Eng*. **2018**, *134*, 148–158.
82. Grases, A.; Gracia, V.; García-León, M.; Lin-Ye, J.; Pau Sierra J. Coastal Flooding and Erosion under a Changing Climate: Implications at a Low-Lying Coast (Ebro Delta). *Water* **2020**, *12*, 346. doi:10.3390/w12020346.
83. Navarra, A.; Tubiana, L. Regional Assessment of Climate Change in the Mediterranean (RACCM). *Adv. Glob. Chang. Res*. **2013**, *50*, *51* and *52*.
84. Gzam, M.; Moncef, S.M.; Ouaja, M.; Jedoui, Y. Coastal progradation in response to the recent sea level rise: a case study of El Grine coast, Gulf of Gabes (Southeastern Tunisia). *Arab. J. Geosci.* **2013**, *6(12)*, 5007-5016.
85. Saidani, L.V.N. Rapport du Centre Hydrographique et Océanographique de la Marine Nationale de la Tunisie. Analysis of the tidal data in the port of Sfax **2007**, *1-5*.
86. Williams, A.T.; Rangel-Buitrago, N.; Pranzini, E.; Giorgio Anfuso, G. The management of coastal erosion. *Ocean Coast. Manag.* **2018**, *156*, 4-20.
87. Reguero, B.G.; Storlazzi, C.D.; Gibbs, A.E.; Shope, J.B.; Cole, A.D.; Cumming, K.A.; Beck, M.W. The value of US coral reefs for flood risk reduction. *Nat. Sustain.* **2021**, *1*, 11.
88. Ghazali, N.H.M.; Awang, N.A.; Mahmud, M.; Mokhtar, A. Impact of Sea Level Rise and Tsunami on Coastal Areas of North-West Peninsular Malaysia. *Irrig. Drain.* **2018**, *67*, 119–129.
89. IPCC. Intergovernmental Panel on Climate Change; Coastal Zone Management Subgroup; Dronkers, J.J.; Misdorp, R.; Spradley, J.R. Strategies for Adaptation to Sea Level Rise. Ministry of Transport and Public Works, Rijkswaterstaat, Tidal Waters Division: Geneva, Switzerland. **1990**.
90. Sarkar, M.S.K.; Begum, R.; Pereira, J.; Jaafar, A.; Saari, M.Y. Impacts of and Adaptations to Sea Level Rise in Malaysia. *Asian J. Water Environ. Pollut.* **2014**, *11*, 29–36.
91. Gracia, A.; Rangel-Buitrago, N.; Oakley, J.A.; Williams, A.T. Use of ecosystems in coastal erosion management. *Ocean. Coast Manag.* **2018**, *156*, 277–289. doi: 10.1016/j.ocecoaman.2017.07.009.
92. Focardi, S.; Pepi, M. Monitoring of Coastal Areas by Remote Sensing and Engineering Approaches. *Current Trends in Eng. Sci.* **2023**, *3*, 1033.
93. Armenio, E.; Mossa, M. On the Need for an Integrated Large-Scale Methodology of Coastal Management: A Methodological Proposal. *J. Mar. Sci. Eng.* **2020**, *8*, 385. doi:10.3390/jmse8060385.
94. Singhvi, A.; Luijendijk, A.P.; van Oudenhoven, A.P.E. The grey - green spectrum: A review of coastal protection interventions. J. *Environ. Manage.* **2022**, *311*, 114824.
95. IPCC. Intergovernmental Panel on Clmate Change; IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. eds H.-O. Po'lrtner, D. Roberts C, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, et al. **2019**.

96. Sunamura, T. Geomorphology of Rocky Coasts. John Wiley & Sons, Chichester, **1992**.
97. Kogure, T. Rocky coastal cliffs reinforced by vegetation roots and potential collapse risk caused by sea-level rise. *Catena* **2022**, *217*, 106457.
98. Ma, Q.; Marcondes Moreira, T.; Adcock, T.A.A. The impact of a tidal barrage on coastal flooding due to storm surge in the Severn Estuary. *J. Ocean Eng. Mar. Energy* **2019**, *5*, 217–226.
99. Etemadi, A.; Emami, Y.; AsefAfshar, O.; Emdadi, A. Electricity Generation by the Tidal Barrages. Energy *Procedia* **2011**, *12*, 928 – 935.
100. Ramli, M.; Karasu, T.Jr.; Dawood. E.T. The stability of gabion walls for earth retaining structures. *Alex. Eng. J.* **2013**, *52*, 705–710.
101. Kristensen, S.E.; Drønen, N.; Deigaard, R.; Fredso, J. Impact of groyne fields on the littoral drift: A hybrid morphological modelling study. *Coast. Eng.* **2016**, *111*, 13–22.
102. Abd-Elmonem, I.; Abedio, T.I.; Kheireldin, K.A.; Soliman, M.R. Assessment of Coastal Revetment: Case study of Rosetta Revetment. *Ain Shams Eng. J.* **2022**, *13(3)*, 101623.
103. Eldrup, M.R.; Lykke Andersen, T. Extension of shallow water rock armour stability formulae to nonlinear waves. *Coast. Eng.* **2019**, *153*, 103536.
104. Salauddin, M.; O'Sullivan, J.J.; Abolfathi, S.; Pearson, J.M. Eco-Engineering of Seawalls—An Opportunity for Enhanced Climate Resilience From Increased Topographic Complexity. *Front. Mar. Sci.* **2021**, *8*, 674630. doi: 10.3389/fmars.2021.674630.
105. Bongarts Lebbe, T.; Rey-Valette, H.; Chaumillon, É.; Camus, G.; Almar, R.; Cazenave, A.; Claudet, J.; Rocle, N.; Meur-Férec, C.; et al. Designing Coastal Adaptation Strategies to Tackle Sea Level Rise. *Front. Mar. Sci.* **2021**, *8*, 740602. doi: 10.3389/fmars.2021.740602.
106. Duarte, C.M.; Losada, I.J.; Hendriks, I.E.; Mazarrasa, I.; Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change.* **2013**, *3*, 961-802.
107. European Commission 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'. **2015**.
108. Cohen-Shacham, E.; Walters, G.; Janzen, C.; Maginnis, S. Nature-based solutions to address global societal challenges. IUCN International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2016.13.en. **2016**.
109. Akça, E.; Kapur, S.; Tanaka, Y.; Kaya, Z.; Bedestenci, H.C.; Yaktı, S. Afforestation Effect on Soil Quality of Sand Dunes. *Pol. J. Environ. Stud.* **2010**, *19(6)*, 1109-1116.
110. Jackson, D.W.T.; Costas, S.; González-Villanueva, R.; Cooper, A. A global 'greening' of coastal dunes: An integrated consequence of climate change? *Glob. Planet. Change* **2019**, *182*, 103026.
111. de Schipper, M.A.; Ludka, B.C.; Raubenheimer, B.; Luijendijk, A.P.; Schlacher, T.A. Beach nourishment has complex implications for the future of sandy shores. *Nat. Rev. Earth Environ.* **2021**, *2*, 71.
112. Corral, L.R.; Schling, M. The impact of shoreline stabilization on economic growth in small island developing states. *J. Environ. Econ. Manage.* **2017**, *86*, 210–228.
113. Escudero, M.; Mendoza, E.; Silva, R. Micro Sand Engine Beach Stabilization Strategy at Puerto Morelos, Mexico. *J. Mar. Sci. Eng.* **2020**, *8*, 247. doi:10.3390/jmse8040247.
114. Hein, M.Y.; Vardi, T.; Shaver, E.C.; Pioch, S.; Boström-Einarsson, L.; Ahmed, M.; Grimsditch, G.; McLeod, I.M. Perspectives on the Use of Coral Reef Restoration as a Strategy to Support and Improve Reef Ecosystem Services. *Front. Mar. Sci.* **2021**, *8*, 618303. doi: 10.3389/fmars.2021.618303.
115. Arias-González, J.E.; Baums, I.B.; Banaszak, A.T.; Prada, C.; Rossi, S.; Hernández-Delgado, E.A.; Rinkevich, B. Editorial: Coral Reef Restoration in a Changing World: Science-Based Solutions. *Front. Mar. Sci.* **2022**, *9*, 919603. doi: 10.3389/fmars.2022.919603.
116. Lawlor, P.; Jackson, D.W.T. 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. **2022**. https://doi.org/10.1007/978-3-031-01980-7.
117. Tubridy, F.; Scott, M.; Lennon, M. Managed retreat in response to flooding: lessons from the past for contemporary climate change adaptation. *Plan. Perspect.* **2021**, *36(6)*, 1249-1268. DOI: 10.1080/02665433.2021.1939115.
118. Ellison, A.M.; Felson, A.J.; Friess, D.A. Mangrove Rehabilitation and Restoration as Experimental Adaptive Management. *Front. Mar. Sci.* **2020**, *7*, 327. doi: 10.3389/fmars.2020.00327.

119. van Bijsterveldt, C.E.J.; Debrot, A.O.; Bouma, T.J.; Maulana, M.; Pribadi, R.; Schop, J.; Tonneijck, F.H.; van Wesenbeeck, B.K. To Plant or Not to Plant: When can Planting Facilitate Mangrove Restoration? *Front. Environ. Sci.* **2022**, *9*, 690011. doi: 10.3389/fenvs.2021.690011.
120. Jordan, P.; Fröhle, P. Bridging the gap between coastal engineering and nature conservation? *J. Coast. Conserv.* **2022**, *26*, 4.
121. Mancini, F.; Castagnetti, C.; Rossi, P.; Dubbini, M.; Fazio, N.L.; Perrotti, M.; Lollino P. An Integrated Procedure to Assess the Stability of Coastal Rocky Cliffs: From UAV Close-Range Photogrammetry to Geomechanical Finite Element Modeling. *Remote Sens.* **2017**, *9*, 1235; doi:10.3390/rs9121235.
122. Ringwood, J.V.; Faedo, N. Tidal barrage operational optimization using wave energy control techniiques. *IFAC PapersOnLine* **2022**, *55-31*, 148–153.
123. Vandercruyssen, D.; Baker, S.; Howard, D.; Aggidis, G. Tidal range electricity generation: A comparison between estuarine barrages and coastal lagoons. *Heliyon* **2022**, *8*, e11381.
124. Cherkasova, L. J. Application of gabions for strengthening marine coastal slopes. *Phys.: Conf. Ser.* **2019**, *1425*, 012206.
125. Adi, H.P.; Wahyudali, S.I.; Soebagyo, A. Gabion as a coastal protection structure: a case study in Panjang Island Indonesia. *IOP Conf. Ser.: Earth Environ. Sci.* **2022**, *955*, 012005.
126. Choufu, L.; Abbasi, S.; Pourshahbaz, H.; Taghvaei, P.; Tfwala, S. Investigation of Flow, Erosion, and Sedimentation Pattern around Varied Groynes under Different Hydraulic and Geometric Conditions: A Numerical Study. *Water* **2019**, *11*, 235. doi:10.3390/w11020235.
127. Valsamidis, A.; Reeve, D.E. A new approach to analytical modelling of groyne fields. *Cont. Shelf Res.* **2020**, *211*, 104288.
128. Crawford, T.W.; Islam, M.S.; Rahman, M.K.; Paul, B.K.; Curtis, S.; Miah, M.G.; Islam, M.R. Coastal Erosion and Human Perceptions of Revetment Protection in the Lower Meghna Estuary of Bangladesh. *Remote Sens.* **2020**, *12*, 3108. doi:10.3390/rs12183108.
129. Van der Meer, J.W. Rock Armour Slope Stability under Wave Attack; the Van der Meer Formula revisited. *JCHS* **2021**, *1*. https://doi.org/10.48438/jchs.2021.0008.
130. Dong, S.; Abolfathi, S.; Salauddin, M.; Tan, Z.H.; Pearson, J.M. Enhancing climate resilience of vertical seawall with retrofitting - A physical modelling study. *Appl. Ocean Res.* **2020**, *103*, 102331.
131. Wu, Y.-T. Breaking Solitary Wave Impact on a Vertical Seawall. *Water* **2022**, *14*, 583. https://doi.org/10.3390/w14040583.
132. Valcheva, M.; Sopotlieva, D.; Apostolova, I.; Tsvetkova, N. Vegetation Characteristics and Recent Successional Trends of Sand Dune Habitats at the Bulgarian Black Sea Coast. *Coasts* **2021**, *1*, 1–24. https://doi.org/10.3390/coasts1010001.
133. Staudt, F.; Gijsman, R.; Ganal, C.; Mielck, F.; Wolbring, J.; Hass, H.C.; Goseberg, N.; Schüttrumpf, H.; Schlurmann, T.; Schimmels, S. The sustainability of beach nourishments: a review of nourishment and environmental monitoring practice. *J. Coast. Conserv.* **2021**, *25*, 34. https://doi.org/10.1007/s11852-021-00801-y.
134. Chen, W.L.; Muller, P.; Grabowski, R.C.; Dodd, N. Green Nourishment: An Innovative Nature-Based Solution for Coastal Erosion. *Front. Mar. Sci.* **2022**, *8*, 814589. doi: 10.3389/fmars.2021.814589.
135. Manakul, C.; Mohanasundaram, S.; Weesakul, S.; Shrestha, S.; Ninsawat, S.; Chonwattana, S. Classifying Headland-Bay Beaches and Dynamic Coastal Stabilization. *J. Mar. Sci. Eng.* **2022**, *10*, 1363. https://doi.org/10.3390/jmse10101363.
136. Kleypas, J.; Allemand, D.; Anthony, K.; Baker, A.C.; Beck, M.W.; Hale, L.Z.; Hilmi, N.; Hoegh-Guldberg, O.; et al. Designing a blueprint for coral reef survival. *Biol. Conserv.* **2021**, *257*, 109107.
137. Hilmi, N.; Basu, R.; Crisóstomo, M.; Lebleu, L.; Claudet, J.; Seveso, D. The pressures and opportunities for coral reef preservation and restoration in the Maldives. *Front. Environ. Econ.* **2023**, *2*, 1110214. doi: 10.3389/frevc.2023.1110214.
138. Rinaldo, T.; Ramakrishnan, K.A.; Rodriguez-Iturbe, I.; Duran Vinent, O. Probabilistic structure of events controlling the after-storm recovery of coastal dunes. *Proc. Natl. Acad. Sci. U.S.A.* **2021**, *118(1)*, e2013254118.
139. Carey, J. Managed retreat increasingly seen as necessary in response to climate change's fury. *Proc. Natl. Acad. Sci. U.S.A.* **2020**, *117(24)*, 13182–13185.
140. O'Donnell, T. Managed retreat and planned retreat: a systematic literature review. *Phil. Trans. R. Soc. B* **2022**, *377*, 20210129. https://doi.org/10.1098/rstb.2021.0129.
141. Monga, E.; Mangora, M.M.; Trettin, C.C. Impact of mangrove planting on forest biomass carbon and other structural attributes in the Rufiji Delta, Tanzania. *Glob. Ecol. Conserv.* **2022**, *35*, e02100.