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Mini Review

Sea Level Rise Impacts in Coastal Areas and Possible Mitigation Engineering Approaches

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

[1]Department of Physical Sciences, Earth and Environment, Università di Siena, Via P.A. Mattioli, 4-53100 Siena, Italy

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

Abstract

Coastal areas are subjected to both natural and man-made actions, leading to a deterioration of coastal structures. Climate change has had a heavy impact on these areas in recent years. An important consequence of these actions is sea level rise. This phenomenon is the most important cause of coastal erosion, a serious problem with ecological, economic, and human health consequences. The countermeasures to contrast this phenomenon and the degradation of the entire coastal system, are represented by engineering interventions. These basically consist of approaches for adaptation to sea level rise, namely protection, retreat, and accommodation. Variations and site adaptation of these actions can involve procedures of no intervention; advancement; protection; retreat; accommodation; and ecosystem-based adaptation. While these procedures have provided coastal benefits and protection, in the long run, they may cause further coastal disruption and further aggravate the situation. Such interventions, therefore, require an accurate assessment of the advantages and disadvantages. However, it is certainly necessary to proceed with actions aimed at mitigating climate change, respecting the rules in a sustainable way.

More Information

***Address for correspondence:** Milva Pepi, Stazione Zoologica Anton Dohrn, Fano Marine Centre, Viale Adriatico, 1-N-61032 Fano, Italy, Email: milva.pepi@szn.it

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Introduction

Coasts present high biological and ecological productivity and allow different activities including fishing, aquaculture, and tourism. Coastal areas are exposed to the continuous action of several natural factors including wave action, wind, tide, sediment transport, sediment supply from rivers to sea, soil subsidence, relative sea level change, rainfall, frequency, and intensity of extreme climate events, including storms [1]. Other factors impacting coastal levels comprehend an increase in population, urbanization, tourism, industrialization, and other development activities that, complexively, have introduced changes in coastal features and processes [2,3]. Additional agents acting on coasts include maritime constructions and coastal defense such as ports and barriers, which interfere with the dynamics of sediments [4]. Furthermore, the construction of residential, industrial, and recreational infrastructures, the management of river basins, and the regulation of watercourses to provide water resources for drinking, irrigation, and industrial use, can induce alterations in vegetation and forest drainage, influencing ultimately the balance of the coasts [5].

Coastal areas have changed considerably during the last century, mainly due to the action of climate change. In particular, coasts are exposed to the impacts of sea level rise, of which climate change is the main cause. Climate change affects coastal processes and dynamics through changes in winds, storm surges, or wave action. Variations in wind intensity, wave energy, and sea level cause major effects on coastlines, triggering major local impacts such as flooding and erosion [6,7]. The damage to the coasts, combined with the development and concentration of the population in the coastal areas, requires urgent adaptations and interventions [8].

In this mini-review, the causes and consequences of sea level rise have been described. Possible engineering interventions aimed at restoring the coastal features have also been described, thus favoring populations living in the coastal areas.

Climate change and other agents influencing sea level rise

Sea level rise is the result of the activity of various agents, such as climate change, structural factors, and human factors [9]. Climate change is the main cause of sea level rise and includes occasional changes and increases in the concentrations of greenhouse gases. Climate change can promote the thermal expansion of the oceans, one of the main agents involved in sea level rise (Figure 1). In fact, greenhouse gas emissions cause an increase in the temperature of the oceans, with variations in the density of seawater, with the mass of seawater remaining at a constant value [10]. As a consequence of rising temperatures, the volume of seawater gradually becomes larger, leading to sea level rise up to a certain level. Particularly in recent years, the seawater surface temperature has shown a definite growth pathway [11,12]. Since 1960, thermal expansion has contributed to about 25% of sea level rise [13]. In the period from 1993 to 2009, approximately 30% of global sea level rise was attributed to this phenomenon [14]. It has also been hypothesized that by 2100, sea level rise values above 12 cm will be caused by thermal expansion [12,15].

Climate change can promote the melting of glaciers and small ice sheets, along with the melting of the Greenland and Antarctic ice sheets, leading to sea level rise. The melting of glaciers and ice caps strongly influences sea level rise. In fact, global climate change has affected the melting of glaciers and ice caps, which could cause sea levels to rise by more than 2 m. From 2003 to 2010, ice and ice sheet mass decreased by about 148 ± 30 Gt yr^{-1} as continental glacier melt increased and this contributed about 0.41 ± 0.08 mm yr^{-1} to sea level rise [16]. During the period from 1992 to 2018, the average sea-level rise was about 10.8 mm due to the melting of Antarctic glaciers [17] To date, as greenhouse gas emissions increase, the melting of glaciers and ice sheets caused by climate change has become the main factor of sea-level rise, contributing about 50% [18,19]. This condition is likely to persist or increase in the future [20-22].

The increase in sea level due to structural factors mainly includes the decrease in ocean volume and land subsidence caused by tectonic movement. Their contribution to sea level rise is about 10% in addition to contributions from thermal expansion of the oceans, melting glaciers, and human activities. However, from a local perspective, the relative sea level rise caused by vertical geological movement may far exceed the impact of melting glaciers and the thermal expansion of the oceans [23-26] (Figure 1).

Human-related factors also contribute to sea level rise, such as groundwater and oil extraction, deforestation, and damming along rivers, although the impact on sea level rise is not as big as that of glaciers and ice caps [27]. Some anthropogenic activities can cause subsidence in some coastal cities, resulting in land elevation lower than sea level elevation [28-30]. Variations in inland waters are another factor related to sea level rise, including the aforementioned groundwater extraction and other human activities, such as irrigation and deforestation. The mechanism of their effect on sea level rise is almost the same as that of groundwater extraction, that is, the jump of freshwater areas in the coastal zone is significantly less than that of seawater. Furthermore, the intense damming along the rivers during the second half of the last century also influenced the sea level change, lowering overall levels by 0.5 mm yr^{-1} [31]. Dam building has also reduced the sediment input to river deltas, increasing the effect of sea level rise in these areas.

Although all these factors have an impact on the rise of

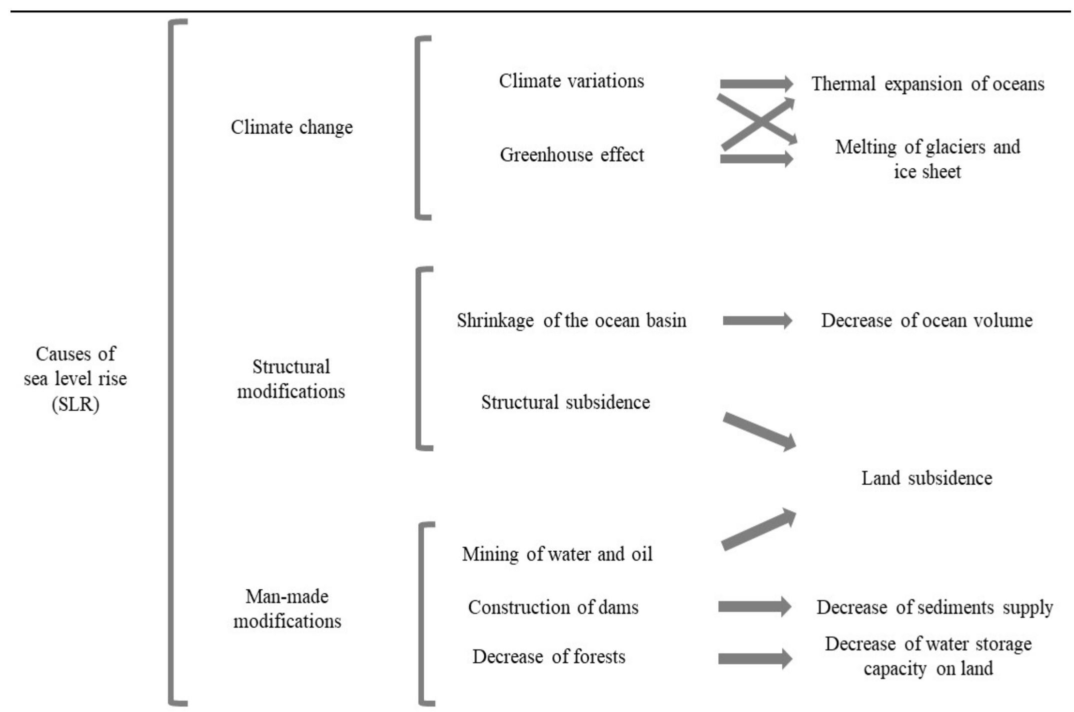

Figure 1: Agents affecting sea level rise and their mechanisms (modified from [12]).

sea level, the degree of impact is not easy to determine. Until recently, it has only been possible to detect that about 30%, 50%, 10%, and 10% of the contribution to sea level rise could be attributed to the thermal expansion of the oceans, the melting of glaciers, humans activities, and geological movements, respectively [12] (Figure 1).

Sea level rise

Sea level rise was reported to be less than 1 mm yr^{-1} until about the mid-1800s. Due to the development of the industrial age and the increase in the burning of fossil fuels including coal, oil, and natural gas, the concentration of greenhouse gases in the atmosphere has gradually increased. Since the beginning of the industrial revolution, the carbon dioxide (CO_2) content in the atmosphere has increased. Quantification of these values showed variations of approximately 50%, from 175-275 μg ml^{-1} to 419 μg ml^{-1} today. This has caused the Earth to warm up by about 1 °C over the past 100 years. As previously reported, rising temperatures, ice sheets, and melting continental glaciers have caused seawater to warm and expand. In response to these changes, the global sea level has risen at a faster rate than in the previous 7000-8000 years [32]. Tide gauges have highlighted the global average of documented historical record sea level rise values ranging from ~1.2 to ~1.7 mm yr^{-1} for much of the twentieth century [33-35].

Satellite-based observations allow us to measure the average acceleration of sea-level rise. The average rate of rise of 3.4 mm yr^{-1} over the past 27 years has now increased to about 4.8 mm yr^{-1}, based on observations of the past 10 years [36].

Sea level measurements need to take into account aspects such as tide gauges and satellite observations, as they provide a good understanding of past and present sea levels. However, the challenge for coastal regions around the globe is projecting sea level rise and its impact into the future. This is an important goal of the Intergovernmental Panel on Climate Change (IPCC), but individual geographic entities (from local governments to national governments) are simultaneously involved in developing future sea level rise projections for their regions [27]. Future climate projections are developed through global climate models, which include uncertainties and assumptions about future greenhouse gas emissions and model the inputs or factors that will affect global climate, including ice melt and consequently sea level rise [32]. Today, predictions or projections for the next few decades are generally consistent, but estimates for the end of the century vary across models and depend on representative concentration pathways, with uncertainties and ever-widening ranges by 2100. The most recent studies indicate that the values for the end of the century (2100) vary from a minimum of ~50 cm to a maximum of ~310 cm, depending on the scenarios of greenhouse gas emissions and various probabilities or uncertainties, in particular regarding the extent of the melting of the Greenland and Antarctic ice sheets [37].

In this century alone, a sea level rise of just 1 m will create substantial problems for developed coastlines around the globe. A recent global assessment determined that approximately 110 million people live below current high water levels and 250 million occupy land below current annual flood levels [38]. For the first few meters of sea level rise, more than 3 million additional people are at risk for every 2.5 cm of rise. One billion people today, about 13% of the entire world population, live less than 10 m above high tide.

Frequent and extreme climate change risks have been recorded in the twenty-first century, compared to previous years. Sea level rise is likely to continue to increase even after reductions in greenhouse gas emissions, as stated in the Paris Agreement on climate change. Several studies have shown that sea level rise will develop unevenly across the world, with people living on coasts most exposed to the risk of coastal flooding by 2050 [35].

Engineering interventions to counteract sea level rise

The threat of future sea level rise to coastal cities and low-lying areas around the world, combined with storm surges, erosion, and flooding, and the rapid degradation of natural coastal systems, will be a major societal and infrastructure challenge of this century [35,39-44].

Potential negative impacts of sea level rise are coastal flooding, accelerated coastal erosion, saltwater intrusion, and land subsidence [45]. Globally, sea level rise is also held ultimately responsible for long-term coastal erosion problems [46]. The impacts of coastal erosion and sea level rise include loss of life, disruption of economic sectors, and degradation of natural ecosystems and biodiversity [47].

The first study by the Intergovernmental Panel on Climate Change (IPCC): Coastal Management Subgroup and Response Strategies Working Group proposed three approaches for sea level rise adaptation, namely protection, retreat, and accommodation [48]. Discussions about available methods have evolved and, based on a recent management guide for disaster risk reduction in the European coastal zone, several strategies have been adopted [49]. Possible intervention strategies have been described and proposed in various studies [50-52]. Adaptation measures could improve the socio-economic conditions and natural resources of the country. Adaptation policies should ensure that vulnerabilities to climate change risks decrease and also help reduce greenhouse gas emissions [49].

Several coastal defense strategies to protect against threats from erosion and sea level rise include i) a no-action procedure, which means "do nothing" and leaving the situation as it is. This represents an inactive intervention, vacant land or available wetland that has insignificant physical and economic impacts that are selected as sacrificial areas for downstream flood or erosion impact areas (Figure 2); ii) advancement interventions, building structures above sea level, using sand

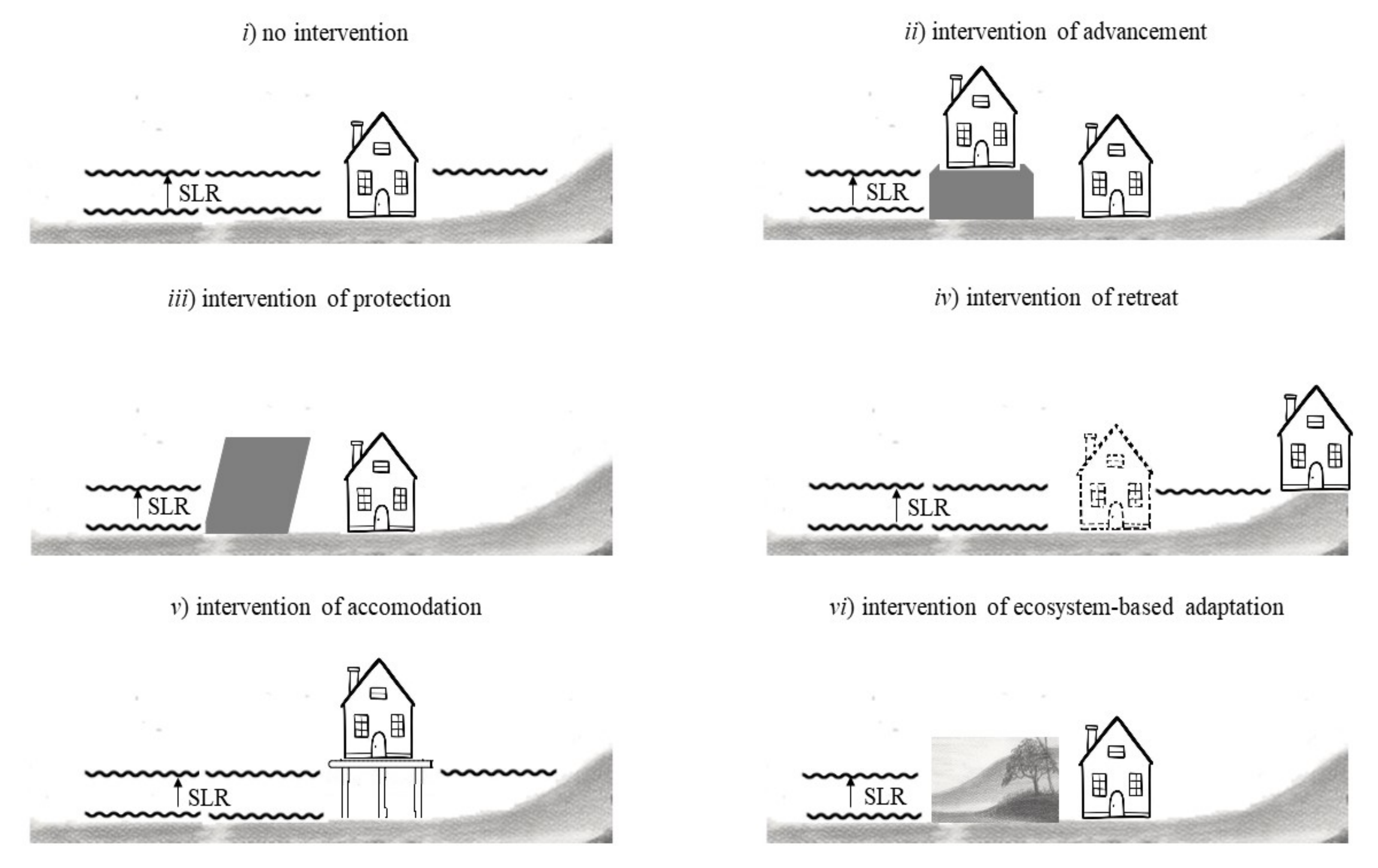

Figure 2: Different intervention strategies facing sea level rise at the coastal level.

or other materials, with the aim of reducing the risk of flooding for the coasts. This can be termed a "seaward move" and is only performed if coastal land remediation is absolutely necessary, as the strategy leads to various negative impacts on the environment. Adjacent ecosystems, wetlands, salt marshes, and mangroves are in fact becoming more vulnerable to the effects of any coastal compression (Figure 2); iii) a protective intervention is carried out through the introduction of elements capable of reducing the impact of seawater, which would otherwise cause flooding of the coasts and coastal cities. These elements that can protect against floods include rigid protections such as dykes, embankments, breakwaters, barriers, and weirs, while also preventing coastal erosion and water intrusion into the soil. Other protections include sediments and dunes. All these measures are implemented in combination and are called hybrid measures. They can be defined as a "line maintenance strategy" that maintains the existing shoreline. They are usually expensive due to the construction of rigid structures, such as dams, revetments, and breakwaters. For shore control, hard structures such as breakwaters and revetments are the most effective, fastest, and easiest. Perpendicular structures such as groynes and breakwaters promote natural sediment deposition and beach accumulation. However, downward erosion is expected (Figure 2); iv) the retreat intervention, consisting of an adaptation strategy that includes within it three forms, namely migration, displacement, and relocation. Migration 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, while relocation involves government bodies helping people to relocate to a different location, usually by providing incentives for families. This type of intervention can be defined as "managed realignment" and involves the relocation of critical structures or land use inland. The costs of "managed realignment" consist of the purchase of land, the reconstruction of infrastructure, and the relocation of existing assets (Figure 2); v) the process of accommodation includes both biophysical and governmental adaptations, aimed at reducing coastal risks by reducing impacts on human lives, livestock, ecosystems and human activities. Switching to elevated or floating homes, switching to saltwater resistant or tolerant crop varieties, contingency plans, insurance plans, and setback zones by government institutions are some of the methods that come under the housing to deal with the elevation of sea level. This strategy can be defined as "adaptation or accommodation" representing the continued use of land at risk with interventions such as platform level rise and elevated buildings (Figure 2); vi) ecosystem-based adaptation interventions provide combinations of protection and advanced benefits by preserving and restoring coastal ecosystems. The system helps narrow the path of waves and reduce the speed of storms by acting as a barrier. They also reduce soil erosion by trapping coastal sediments. This strategy can be defined as a "limited intervention" that requires little cost, such as modifying existing land use, restoring wetlands, and replanting mangroves. Coastal protection system selection is site specific. Soft engineering techniques are environmentally friendly but are expensive for maintenance and take longer to produce significant impacts [49] (Figure 2).

Discussions and perspectives

Coastal adaptation is also a clear collective action problem: a group benefits from an intervention but no individual has sufficient incentive to act alone [53]. Social conflict barriers can arise whenever stakeholders hold conflicting interests that can be overcome through governance to develop norms, laws, or policies in order to resolve conflicts [54]. Formal institutions can help, but other informal means and community involvement are needed. Social barriers remain challenging and difficult to overcome and can be further exacerbated when local needs, contexts, and priorities are not adequately considered [55]. Solutions considered effective in some regions may be ignored or perceived negatively in other areas. A clear example is found in the low-crested and submerged structures that have been used extensively in Europe, including with environmental benefits [56], but it can be perceived as negative, for example, in tropical regions. Societal challenges to adaptation may also be driven by divergent interests among parties, including who benefits and who pays, which can be an important decision factor in adaptation planning. Other social barriers are related to conflicts over cultural and social priorities and constraints. Barriers to adaptation can be overcome through efforts to fill gaps in technology, economic and human resources, management, and institutional change. Understanding risk, planning, and financial adaptation are key to accelerating adaptation [57]. Furthermore, the process known as the "Paris alignment", which refers to the alignment of financial flows consistent with a path to low greenhouse gas emissions and climate-resilient development, also presents an opportunity to expand adaptation efforts among activities in global coastal zones [35].

Coastal protection measures are based on management strategy options as i) do nothing; ii) move seaward/advancement; iii) hold the line/protection; iv) managed realignment/retreat; v) limited intervention/accommodation; vi) ecosystem-based adaptation [49]. The intervention measures can be of hard and soft engineering or a combination of both. Determining the functionality and impacts of these coastal structures should be further carried out at specific sites with detailed scenarios by using advanced numerical modeling tools for better impact assessments. The proposed engineering approaches should be technically feasible, economically achievable, environmentally friendly, and socially acceptable. It is important to propose new solutions and collaborate with agencies related to the field of coastal management, engineering, and marine sciences for valuable planning and evaluation.

Conclusion

Sea level rise is a major coastal problem with serious ecological, economic, and human health consequences. The engineering interventions can alleviate the problems of the sea level rise and the consequent serious problem of coastal erosion. However, while on the one hand, the interventions improve the situation of the coasts, on the other hand, they can cause other complications and modify the original environment, adding further imbalances to the whole system. An important and detailed local assessment of the pros and cons is therefore required. Different adaptation strategies are effective to face the important damages caused by sea level rise on the level of the coast. The poorest sections of society, rural dwellers, and island communities are subject to serious vulnerabilities if immediate adaptation strategies and countermeasures to climate change are not provided.

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