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Drivers and impacts of beach erosion in Eastern Mediterranean Islands

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Abstract This short contribution provides a brief overview of the drivers and impacts of beach erosion at the Greek islands and Cyprus, which are under an increasing risk of erosion. The most significant beach erosion drivers have been found to be the mean and extreme sea level rise, as well as various geological (e.g., the geological setting and the diminishing beach sediment supply) and anthropogenic factors (e.g. river dams that starve beaches of their terrestrial sediment supply, degradation of wave-attenuating coastal ecosystems and badly designed/implemented coastal works). Under climate change, beach erosion is projected to have very significant (even devastating) impacts on the populations, assets/infrastructure and socio-economic activities of the islands' beaches, the exposure of which is already very significant and increasing.

Keywords: Beach erosion, Climate change, Eastern Mediterranean, Sea level rise

1. Introduction

Beaches, i.e., the low-lying coasts built on unconsolidated sediments, form a large part of the global coastline and have a high environmental and socio-economic value associated with recreation, tourism and various other ecosystem services. At the same time, many beaches are already under erosion, (mostly) manifested by a 'long-term' retreat of the shoreline, which will be exacerbated by climate change; the complex shoreline dynamics, combined with the coastal retreat driven by rising mean and extreme levels and waves, might result in the near disappearance of almost half of the world's beaches by 2100 (Vousdoukas et al., 2020). There is and (will be) spatial variability in beach erosion dynamics, as this is controlled by various factors, such as hydrometeorological, geological and anthropogenic factors.

The objective of this short contribution is to provide a brief overview of the drivers and impacts of beach erosion focusing at the Greek islands and Cyprus), the beaches of which are vulnerable to erosion and major tourist destinations (e.g. Monioudi et al., 2017; 2023).

2. Beach erosion main drivers and impacts

2.1 Sea level changes

Beach erosion can be differentiated into long- and short-term erosion. Long-term erosion, i.e., the irreversible retreat of the shoreline, can be due to the (relative) mean sea level rise (RSLR) and/or negative coastal sediment budgets that force either beach landward migration or, in the case of lacking appropriate backshore accommodation space, beach 'drowning'. Short-term erosion takes place under extreme sea levels (ESLs) and high wave energy caused by storm surges and waves. Such events can result in large rates of erosion which, in many cases, can be transient; the beaches may recover after the extreme events. It should be noted, however, that in addition to the potential devastating impacts that short-term erosion may have on the backshore natural and human environment, extreme storm events could pull large quantities of beach sediments offshore to water depths from where the (mild) constructive waves cannot drive them back to the beach (i.e. beyond the closure depth of the beach sediment reservoir). It follows that if the lost beach sediments are not replenished by fresh inputs (from e.g. the rivers), successive short-term erosion events could eventually result to long term beach erosion.

Both the relative mean sea levels and extreme sea levels are expected to rise along the coasts of Greek islands and Cyprus due to the projected climate change. Mean sea level rise projections for different climatic (RCP4.5 and RCP8.5) and ice mass (ice-melt) change scenarios, based on Hinkel et al (2014) combined with those of land vertical movements (Peltier, 2004) are used to assess the future relative sea level rise (RSLR) in the Greek islands and Cyprus (see also Vousdoukas et al., 2017). By 2050, the RSLR at the Greek islands has been projected to be up to 0.35 m under the RCP4.5 and high ice-melt scenario (Figure 1). By 2100 under a medium ice-melt scenario, the RLSR is projected to be > 0.5 m and > 0.75 m along the Greek island and Cyprus coasts under the RCPs 4.5 and 8.5, respectively. In all cases, higher RSLRs are projected for some Crete and Cyprus beaches (Figure 1).

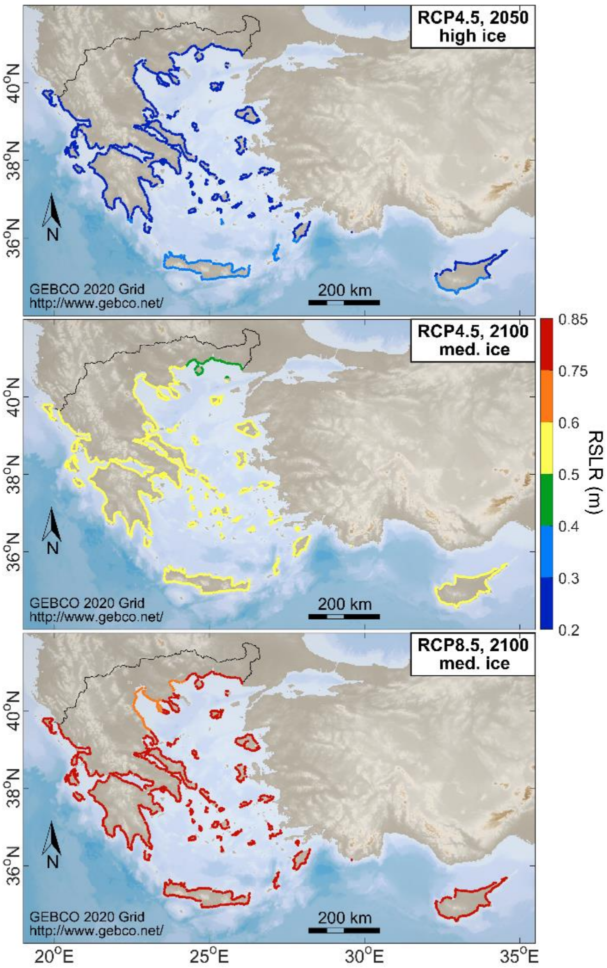

Figure 1. Projections of the relative sea level rise (RSLR) along the Greek and Cyprus coasts in 2050 and 2100 under RCP4.5 and RCP8.5 and for different ice-melt scenarios. Projections relative to the mean of the 1986-2005 period.

Concerning the ESLs that can drive large short-term beach erosion, the baseline values and projections for 2050 and 2100 are shown in Figure 2. Extreme sea-levels (ESLs) integrate the mean sea level, the tide and the episodic sea level rise due to storm surges and wave set-ups. The above RSLR projections were combined with tidal elevations (considering also their potential changes under the mean sea level rise), whereas storm surge levels and waves (offshore significant wave heights (H_s), periods (T) and directions) were hindcasted for the period 1980-2014 and projected for 2050 and 2100 (Vousdoukas et al., 2017). Wave set-ups were estimated using a generic approximation (0.2 x the offshore H_s , whereas non-stationary extreme value analysis was used to obtain values for the return periods of extreme events, such as the 1 in a 100-year event - ESL_{100} (for more details, see Velegrakis et al. (2023a)).

For the Greek islands, the baseline 1 in a 100 years extreme sea level- ESL_{100} (mean of the period 1980-2014) varies, with the highest values found along the northern Aegean islands and Crete (up to 1.7 m above the mean sea level). By 2050, $ESLs_{100}$ will increase by up to 0.45 m under RCP8.5 (high ice-melt scenario). By 2100, the increases of $ESLs_{100}$ relative to the baseline will be close to 0.9 m for some Greek island and Cyprian coasts under RCP8.5, even under a median ice-melt scenario (Figure 2), whereas higher $ESLs_{100}$ increases are projected under the high-end scenario. A recent, Cyprus-scaled study has also found that the baseline (2000) ESL_{100}, which ranged between 0.8 and 1.3 m above the mean sea level (MSL), will increase to up to 2.05 m by 2100 (Monioudi et al., 2023). Regarding the waves, these have been projected not to increase, or even slightly decrease during in the 21^{st} century (Velegrakis et al, 2023a; Monioudi et al., 2023).

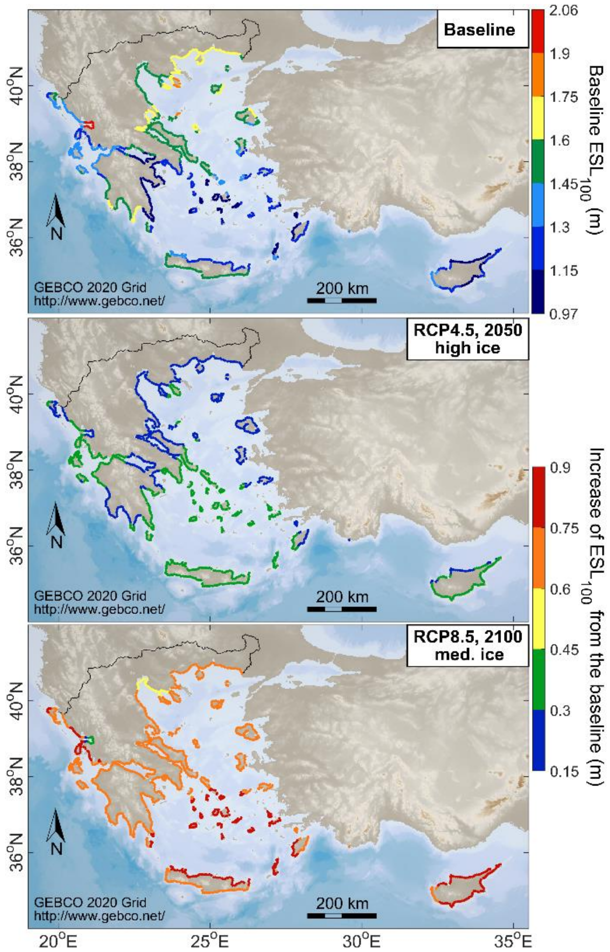

Figure 2. Baseline (1980-2014) extreme sea levels $ESLs_{100}$ (1 in 100-year events) and their projections at the Greek and Cyprus coasts, for 2050 and 2100 under the RCP 4.5 high ice-melt scenario and RCP8.5 median melt scenario. Original data from: http://data.jrc.ec.europa.eu/collection/liscoast#datasets

Although the above hazard increases may appear moderate, their impacts on the island beaches can be devastating due to their generally small dimensions; about 59 % of Aegean island beaches have had recorded maximum ‘dry’ widths - BMWs of < 20 m and 92 % < 50 m, whereas, in Cyprus, almost 42 % of beaches were recorded having BMWs of < 20 m and 91 % < 50 m. Consequently, both the long- and short-term beach erosion can be very impactful to the backshore human and natural environment. A RSLR of 0.7 m can drive beach retreat/drowning of up to 68 % of the Aegean archipelago beaches, affecting back shore assets at about 1730 beaches; under extreme sea levels, an extreme sea level of 1.1 m has been projected to result in short-term full erosion of up to 88 % of all beaches affecting backshore assets in at 2270 beaches (Monioudi et al., 2017). For Cyprus, on the basis of the median projected erosion, a RSLR of about 0.8 m about 30 % of all beaches will be fully eroded, whereas by 2100 up 70 % of all beaches will under full short-term erosion by 2100 (Monioudi et al, 2023).

2.2 Geological controls

As stated earlier, beach erosion is also controlled by the 'budgets' of the beach sediment reservoirs; beach erosion forced by RSLR and ESLs may be mitigated, or exacerbated by positive or negative 'external sediment supply' budgets. Unfortunately, in the case of the Eastern Mediterranean and its islands, these budgets are already mostly negative and expected to deteriorate in the future if the situation is not specifically mitigated. There have been changes in the riverine water and sediment fluxes to the coast due to the construction of many water dams, which have reduced significantly the terrestrial sediment supply to the islands' beaches (e.g., Velegrakis et al.. 2008). The situation is expected to deteriorate further in the future, as decreases in precipitation and increases in dry periods will probably increase the needs for water capture exacerbating the decreases in water/sediment fluxes to the beaches.

Other geological controls affecting the dynamics of the beach sedimentary deposits are, among others: the antecedent basement morphology/geology that controls the wider topographic setting, orientation, sediment producing capacity and seabed slopes and, thus, the beach sediment dynamics and morphodynamics; and shoreline lithification (i.e., beachrock formation) (Cooper et al., 2018).

Regarding the former, the tectonically active area setting has resulted in the development of mostly narrow pocket beaches. These are backed by small drainage basins of high relief with intermittent water and sediment flows (which is many cases are now choked by dams), and fronted by relatively narrow (inner) continental shelves with relatively high seabed slopes that allow limited wave attenuation and promote net offshore sediment transport. The basement geological formations also control beach development/evolution; for example, Cyprus beaches associated with the geological formations of the Troodos and Kyreneia terranes are generally narrower than the rest of the Cyprus beaches (Monioudi et al. 2023). Concerning the latter beachrocks, which are quite prevalent in Eastern Mediterranean, can affect beach morphodynamics by: 'locking' the beach profile, modifying the nearshore hydrodynamics, changing the porous character of the beach and, thus, its response to wave forcing; and differential seabed erosion at the margins of the beachrock outcrops that can alter significantly the long- and, particularly, the cross-shore sediment transport (Vousdoukas et al., 2007). Therefore, although (relict) submerged beachrock outcrops may provide coastal protection by reducing the wave energy impinging onto the coastline (Velegrakis et al., 2016), modern beachrocks may promote offshore loss of unconsolidated beach sediments and buried beachrock outcropping.

Last, but not least, Eastern Mediterranean is a tectonically very active area, with major tectonic structures present, such as the Hellenides orogenic belt, the western margins of the Anatolian faults, the Aegean volcanic arc and the Hellenic trench; this setting has caused high and diachronic seismicity and volcanism (Le Pichon and Kreemer, 2010). Therefore, the tsunami hazard is high at the Eastern Mediterranean beaches (Papadopoulos et al., 2010). Karambas and Hasiotis (2012) simulated landslide tsunami generation and propagation in the Aegean Sea and found that the complicated physiography can alter the tsunami wave propagation patterns and result in extreme water elevations in many coastal settings. It is should be noted that the tsunami impacts (losses/damages) may be extremely high.

2.3 Anthropogenic controls

In Eastern Mediterranean islands there are also very significant anthropogenic drivers and impacts of beach erosion. In addition to the river management schemes (referred to above) that can starve beaches of their terrestrial sediment supplies, beach erosion can be also induced by: a) degradation of wave-attenuating and sediment trapping inshore ecosystems (e.g. seagrasses) due to pollution and/or ecological invasions (e.g. Peduzzi et al., 2022); b) allowing large vessels (e.g. ferries) to sail fast close to the shore and, thus, generate large and steep beach eroding waves (e.g. Velegrakis et al., 2007); and c) badly designed/implemented coastal works, e.g., groynes, seawalls, breakwaters and port facilities (Reeve et al., 2018). Concerning the latter, although their construction may well be, in some cases, necessary to protect coastal infrastructure/assets, this must be done carefully and after consideration of the projected hazard changes. Detailed, quality studies are needed at local level to assess the risk, and upgrade the old and design new protection measures, which should be also flexible and 'not 'over-engineered' (UNFCCC, 2020).

Coastal works at the Greek islands and Cyprus are, currently, quite sparse; 85 % of the Aegean Archipelago beaches do not contain any coastal works (Monioudi et al., 2017), whereas in Cyprus 76 % of all island beaches are not associated with coastal works (Monioudi et al., 2023).

It should be noted that that a most significant determinant of the current and future beach erosion risk is related to the exposure of populations, infrastructure/assets and socio-economic activities. Beach erosion can impact negatively on the beach carrying capacity for recreation and tourism (e.g. Monioudi and Velegrakis, 2022), thus affecting primary economic activities in the Greek islands and Cyprus. In addition, there many backshore assets and infrastructure that can be affected by beach erosion (see Section 2.1), which are also not evenly distributed over the island beaches (Monioudi et al., 2017; 2023). It follows that there should be dedicated efforts to decrease this exposure and the future exorbitant beach protection costs, probably through the introduction of set-back zones, such as those prescribed in the Art. 8 of the 2008 Integrated Coastal Zone Management (ICZM) Protocol to the Barcelona Convention which, however, Greece and Cyprus have not ratified (for details, see Velegrakis et al., 2023b).

3 Conclusions

This brief overview has found that the Greek island and Cyprus beaches face an increasing risk of erosion. The most significant beach erosion drivers have been found to be the mean and extreme sea level rise, as well as geological factors (e.g., the geological setting that constrains the development of large/wide beaches and the diminishing beach sediment supply) and various anthropogenic factors (e.g. river management schemes that starve beaches of their terrestrial sediment supply, degradation of wave-attenuating coastal ecosystems and badly designed/implemented coastal works). Under climate change, beach erosion can have very significant (even devastating) impacts on the populations, assets/infrastructure and socio-economic activities of the islands' beaches, the exposure of which is already very significant and increasing. It appears that substantial efforts should be made to mitigate and/or adapt to the beach erosion risk.

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