Recording of and technical responses to coastal erosion of touristic Aegean island beaches – The ERABEACH project

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Abstract

Beaches, which form the most significant natural resource of the Aegean Archipelago, are under increasing erosion risk due to projected mean sea level rise (MSLR) and changes in the magnitude/frequency of extreme sea levels (ESLS). In the framework of the ERABEACH project, the erosion risk of all beaches of 6 Aegean islands (Lesvos, Chios, Thira, Kalymnos, Chalki and Agathonisi) under different scenarios of SLR has been modeled, in order to select critical and vulnerable beaches in each island for further study. Then, different innovative approaches were developed/tested at different pilot beaches to establish the present and model the future erosion risk and design effective and cost-efficient technical responses. Our results advance our knowledge on the diagnosis/prognosis of the beach erosion and flood risk at island settings, provide detailed assessments of the erosion risk and designs of effective technical responses under SLR to the partner municipalities, improve our understanding of the interactions between beaches and their back-basins and develop our capability to monitor (in high frequency) beach erosion using cost-efficient optical systems. The ERABEACH project provides a structured approach to assess and respond to the current and future island beach erosion, according to the emerging international/European legal framework.

Keywords: beach erosion, coastal protection measures, sea level rise, management protocols, Aegean Archipelago

1. Introduction

Beaches are critical components of the coastal system as they buffer the backshore coastal ecosystems and valuable assets against marine flooding (e.g. Neumann *et al.*, 2015) and, at the same time, have a high earning potential; tourism, an economic sector contributing about 5 % of the Global Gross Product, has been increasingly associated with beach recreational activities according to the 'Sun-Sea-Sand-3S' tourism model (Phillips and Jones, 2006). At the time of their growing environmental and socio-economic significance, beaches face increasing erosion that may be differentiated into: (a) irreversible shoreline retreat due to mean sea level rise (MSLR) and/or negative coastal sedimentary budgets; and (b) short-term erosion, caused by storm surges/waves which may, or may not, result in permanent shoreline retreats but can nevertheless be devastating (Seneviratne *et al*., 2012). The projected MSLR coupled with potential changes in the intensity/frequency of energetic events (e.g. Vousdoukas *et al*., 2017) will exacerbate beach erosion with severe impacts on coastal ecosystems, infrastructure/assets and the beach carrying capacity for recreation/tourism, particularly in island settings. Island beaches, which are major tourist destinations, are particularly erosion-prone due to their small dimensions, diminishing sediment supply and increasing densities of backshore development. Thus, beach erosion must be amongst the first issues to consider when planning for the sustainable development of islands under the Climate Variability and Change (CV & C). Against this background, the aim of the ERABEACH research project has been to provide a structured approach (Figure 1) to (a) assess the beach erosion risk at different Aegean islands (Lesvos, Chios, Santorini, Kalymnos, Agathonisi and Chalki) under different scenarios of SLR; and (b) design/test an integrated approach for the assessment of erosion of individual beaches and the design of effective and cost-efficient technical responses.

2. Geographical scope and Methodology

Aegean islands form very significant 3S tourism destinations. In 2015, 43 % of the foreign arrivals to Greece arrived at the 11 international Aegean island airports, with tourism accounting for about 60 % of the GDP of the Cyclades and Dodecanese island complexes. Aegean island beaches, the pillars of the 3S tourism, are under erosion. Eurosion (2004) had suggested that the Aegean island coastline was already under severe erosion; recent projections show that, under a moderate MSLR scenario (0.5 m, RCP4.5, 2100), at least 31 % of all Aegean island beaches will be completely eroded under an extreme storm surge/wave event (Monioudi *et al*., 2017). In terms of forcing, northerly winds/waves prevail at the Aegean archipelago, with highly energetic events of short duration occurring along island straits. Mean significant wave heights (Hs) of about 1 m and mean maximum heights of about 2.4 m are estimated for the Aegean, with relatively small increases projected for the 21st century. MSLR rates of 4.3 - 4.6 mm yr^{-1} have been recorded in recent years (Mamoutos *et al*., 2014), whereas Hinkel *et al*. (2014) have suggested for 2050 sea levels of about 0.15 m and for 2100 0.5 (RCP 4.5) and 0.7 m (RCP 8.5) higher than that of the 1985 – 2005 reference period, respectively. Extreme sea levels (ESLs) due to storm surges/waves, which can effect severe beach erosion (at least temporarily) when combined with increasing MSLs, presently have a seasonal footprint with positive extremes (of up to 0.5 m) occurring in winter (Tsimplis and Shaw, 2010). ESLs in the area are projected to somewhat increase in the 21st century (Vousdoukas *et al*., 2017). Implementation of the project has been carried out in two major steps. First, as beach erosion is projected to affect all island beaches requiring very high adaptation costs, there should be risk assessments at regional and/or island level in order to identify erosion 'hot spots' and plan for efficient allocation of resources. Towards this objective, the spatial characteristics (e.g. area, length, maximum width, orientation, sediments and the presence of coastal works and the density of the backshore development) of all beaches of the 6 Aegean islands studied were recorded, using all available remote-sensed information (from Google Earth Pro and archived imagery). Retreat/erosion of the pocket beaches was projected for different scenarios of long- and short-term SLRs, using suitable ensembles of analytical and numerical morphodynamic models. Seven cross-shore (1-D) morphodynamic models were used (5500 experiments): the Bruun (1988), Edelman (1972) and Dean (1991) analytical models (long-term ensemble), and the numerical models SBEACH (1989), Leont'yev (1996), XBeach (2010) and a Boussinesq model (Karambas and Koutitas, 2002) whose hydrodynamic module involves high-order Boussinesq equations (short-term ensemble) (for more details on the models, their validation and the procedure used to assess temporary maximum wave-run up inundation, see Monioudi *et al*. (2017)). The mean high and low projections of the model ensembles under different long- and short-term and combined scenarios were then compared with the (recorded) maximum widths of the 6 island beaches to assess their exposure (and of their backshore assets) under mean and extreme SLRs. The findings, together a stakeholder consultation process drove the prioritization/selection of individual beaches in each island for further study. 8 beaches were selected (Fig, 2): Eresos and Tsamakia (Lesvos), Kataraktis and Agia Ermioni (Chios), Kamari (Santorini), Masouri (Kalymnos), Pontamos (Chalki) and Agios Georgios (Agathonisi). The second step involved several approaches. Due to time and logistics constraints, some approaches were tested in only some of the pilot beaches. Thus, high frequency optical monitoring of the shoreline, climate index for tourism (CIT) projections and cost-benefit analysis were carried out only in Kamari (Santorini), whereas riverine sediment supply modeling was carried out in the dammed Eresos basin (Lesvos) where the necessary information was available. In all the beaches, detailed topographic / bathymetric information was collected, using dense survey lines, an RTK-DGPS positioning system and a single beam echosounder. Side-scan sonar (SSS) surveys were simultaneously undertaken using a SSS system able to

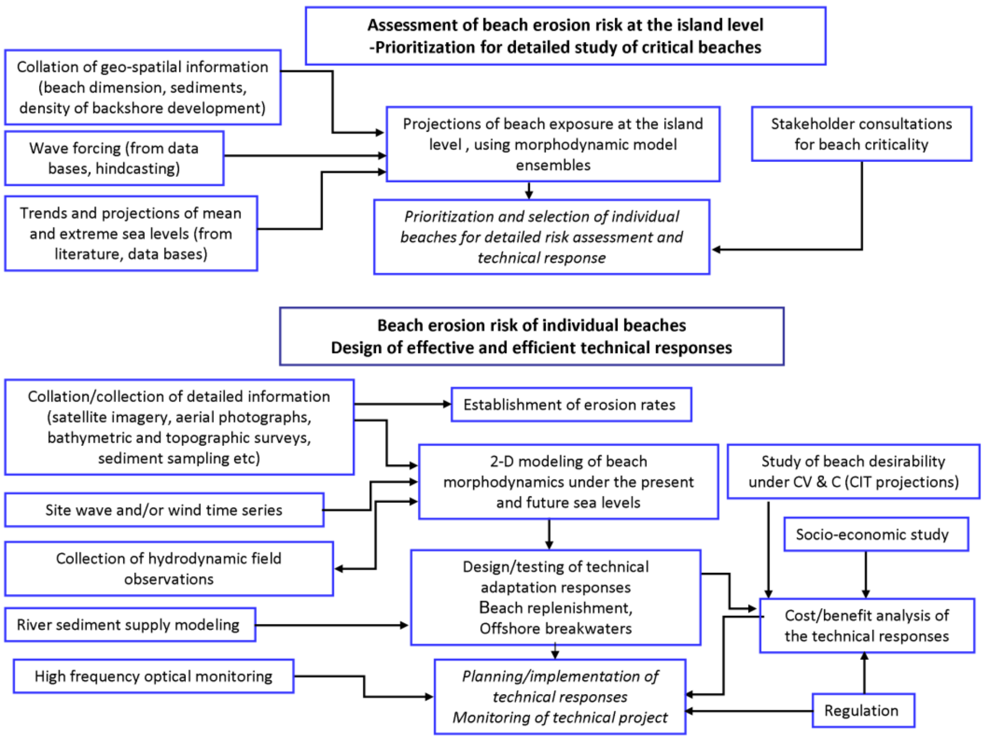

Figure 1. Methodological flow chart, showing the major components of the implementation of the study.

collect information in very shallow waters; this information, 'ground-truthed' by underwater camera imagery and sediment samples was used to map the nearshore sedimentary environments. High frequency hydrodynamic observations (waves and currents) were also collected, using Acoustic Doppler Velocimeters-ADVs and wave recorders-RBRs deployed nearshore; however, energetic events were recorded only in some pilot beaches (Kamari and Eresos). The above information, together with wave information hindcasted from Greek Meteorological Service wind records was then used to set up and force the 2-D models used to model beach erosion under the current and projected sea levels, and design the 'hard' coastal protection works and study their effects on the adjacent coast. The 2-D model ALS (Karambas *et al.*, 2013) was used in all beaches but Eresos, where a 2-D Boussinesq model was used. Replenishment scheme design followed Dean (2002). There were experiments to test the efficiency of the 'hard' (offshore breakwaters) and 'soft' (replenishment) adaptation measures (and their combination), under both current and projected SLRs. An approach developed to study terrestrial sediment supply to island beaches was tested in Eresos. In this approach, different methodologies are used depending on the dimensions, characteristics and data availability: empirical/analytical tools (e.g. the Universal Soil Erosion Equation USLE) and numerical simulations using the hydraulic HEC-RAS and the hydrological SWAT models. A methodology was also developed/applied to project the desirability of beaches as environments of leisure under CV & C. A questionnaire survey of tourists of Kamari beach (summer 2016) was used to identify the preferred ranges/ideal values of climatic conditions (e.g. temperature, precipitation/cloudiness, nearshore waves). These preferences, calibrated by simultaneous meteorological records, were then compared to regional projections of the relevant climatic factors under CC. A methodology for the analysis of costs and benefits of the different technical adaptation options was developed/applied on the proposed technical adaptation responses (replenishment and offshore breakwaters) for Kamari beach. The current (and emerging) legal/regulatory regime pertaining to beach erosion and the relevant technical responses was collated/analysed at the international, European and national levels.

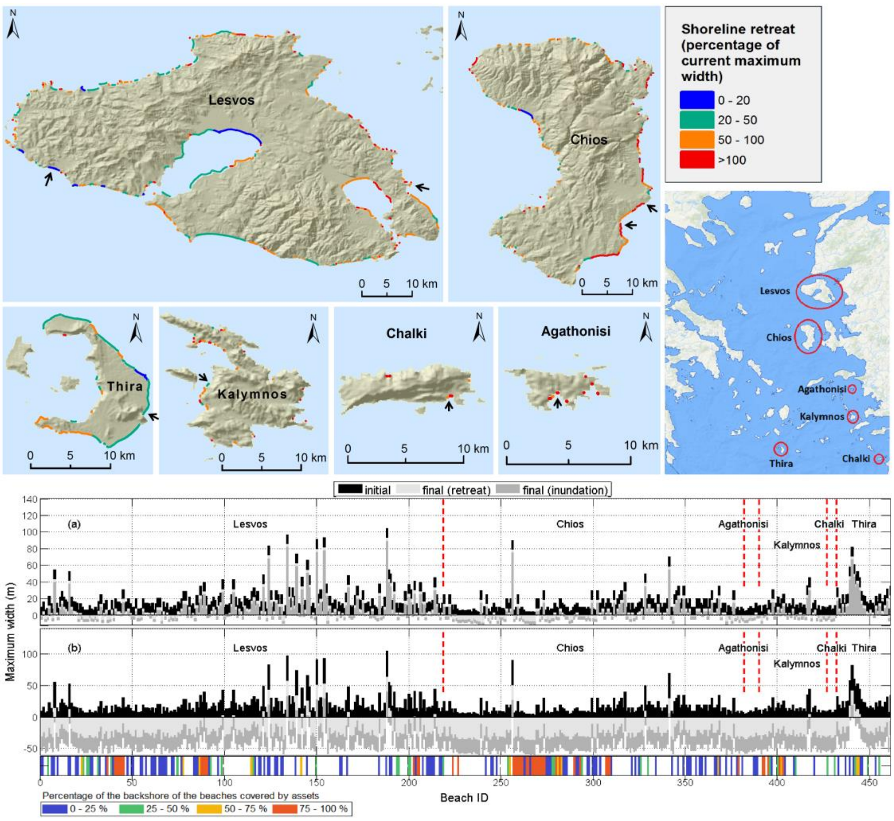

Figure 2. Beach retreat estimations under a combined SLR of 1.1 m (0.5 m MSLR and an ESL of 0.6 m). In the maps, the retreat shown is the minimum retreat as percentage of the maximum recorded width. In the lower panels, the minimum (e) and maximum (f) retreat and inundation (from wave run-up) of all beaches are shown together with the recorded density of backshore assets (as a percentage of the beach length). The location of detailed beach studies is also shown.

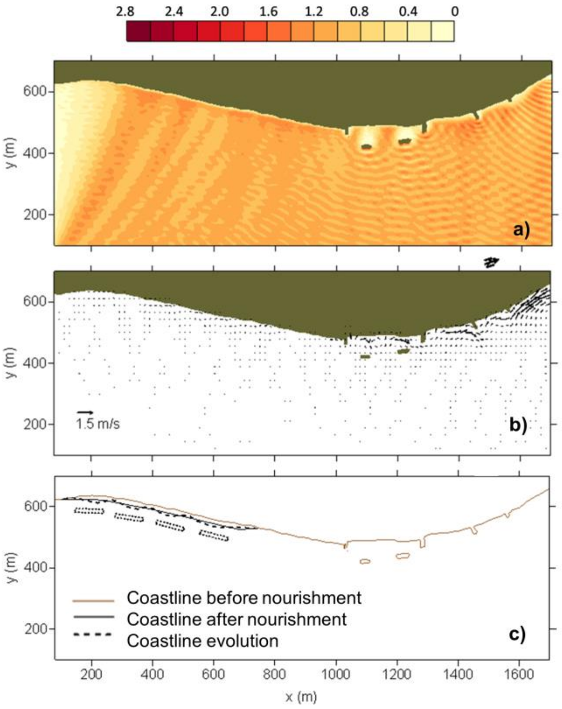

Figure 3. Kamari, Santorini. (a) and (b) modeled waves and wave-induced currents following construction of the offshore breakwaters (equivalent extreme mean waves from the eastern sector). (c) The response of the nourished beach is also shown.

Finally, new methodologies have been developed to monitor beach erosion at different spatio-temporal scales using (a) high resolution satellite imagery and (b) a novel optical (video) monitoring system that provides high frequency information on the shoreline position (e.g. Velegrakis et al., 2016); these methodologies were tested at Kamari, where time series of satellite imagery were available and a land-based coastal optical monitoring system was installed. It must be noted, that monitoring of beach erosion before (and particularly after) implementation of technical adaptation responses is a legal requirement under European Directive 2014/52/EE. In the following section, only selected results are presented due to space limitations.

3. Results and discussion

In order to implement the first step, the geo-spatial characteristics of all beaches of the 6 islands were used in conjunction with projections from the cross-shore morphodynamic model ensembles. It appears that both the present and, particularly, the projected island exposure to beach erosion are worrying. Even as early as 2050, a modest ESL of 0.4 m combined with a MSLR of 0.15 m, will result (*at minimum*) in the, at least temporary, erosion of about 20 % of all island beaches to the half of their *maximum* width. In 2100, beach erosion is projected to be devastating; 36% (at minimum) of all beaches will be completely eroded during the combined effect of a 0.5 m MSLR (RCP 4.5) and a projected for the area ESL of 0.6 m, with devastating effects on the backshore infrastructure/assets (Figure 2). Such high exposure of the primary natural resource and coastal assets of the islands suggest that technical adaptation measures will be necessary. Concerning the studies of the individual selected beaches (second step), major findings are as follows. The different approaches used to study the riverine sediment supply at Eresos beach, have shown that: (a) the Eresos dam traps > 50 % of the basin's sediment production; (b) sediments are also trapped in the coastal downstream river section (NATURA site); (c) there is increased flood risk, requiring river restoration schemes; and (d) riverine sediments are flushed out only during extreme flow events. Regarding the establishment of erosion rates, the method developed for coastline classification in high resolution satellite imagery was well validated by the 'ground' high frequency optical imagery; results showed significant erosion in Kamari beach; however, the high spatio-temporal variability of the shoreline position (identified from the high frequency optical monitoring, see also Hasiotis *et al*, these proceedings) and the short length of the time series (2013-2016) may have influenced these results. Concerning the desirability of the beach under CV & C, the CIT index analysis has shown minimal impacts for Kamari; a short lengthening of the tourist season may be discerned in the results. When the need to maintain the carrying capacity of touristic beaches is considered together with the protection of the backshore assets/ecosystems, effective response to SLR should involve, in most cases, both soft (beach replenishment) and hard technical responses. Beaches must be raised through sediment nourishment to avoid drowning, whereas offshore breakwaters should be constructed to reduce the effects of energetic wave events. Consequently, beach nourishment schemes were designed/tested so to raise and extend seawards the beaches, with the objective being to obtain final increases (after re-arrangement by the local hydrodynamics) of the current beach widths of 15 - 18 m. Morphodynamic model tests, have been carried out in order to select the most effective design of the additional 'hard' technical responses (offshore breakwaters). In Figure 3, the proposed design for the Kamari beach is shown for wave transmission coefficient Kt of 0.4 (i.e. decreasing the wave height to 40 %). 4 offshore breakwaters are proposed with the following characteristics: freeboard, sea level; side slope, 1/2.5; width at sea level, 8 m; breakwater length, water depth and distance from the present coastline, 80, 4-5 and 50 m, respectively; breakwater spacing, 50 m. Regarding beach nourishment different options are proposed depending on the grain size of the replenishing material; for sediment size (d50) of 0.6 mm, the required volume to extend seawards the beach by 33 m (so to obtain a 15 m final additional width) with the optimal slope of 0.25 has been estimated as 136 m^3/m. Cost benefit analysis of the proposed scheme has shown that even when using only the direct income from the beach (i.e. public revenues from umbrella renting on the beach), the cost of 'doing nothing' is much higher that the proposed technical scheme (nourishment and offshore breakwaters). Finally, analysis of the legal/regulatory regime pertaining to beach erosion and protection, revealed very complex and time-consuming administrative procedures; these certainly should be optimized and streamlined in a manner that will take also into consideration emerging legal obligations regarding the construction and monitoring of technical adaptation responses (see e.g. the European Directive 2014/52/EE).

4. Conclusions

The ERABEACH project has provided a structured approach for the assessment of beach erosion risk and the design of effective technical responses under SLR at different Aegean island settings. Our projections show a very significant erosion risk, which will have devastating impacts on the Aegean island beaches by the end of the century. Different innovative approaches have been developed/tested and their results: advance our knowledge on the diagnosis/prognosis of the beach erosion risk at island settings; provide detailed assessments of the current/future beach erosion risk as well as designs of effective technical responses; improve our understanding of the interactions between beaches and their back-basins; and improve our capability to monitor beach erosion in high frequency, using cost-efficient optical systems. The study has also shown that the administrative procedures relevant to coastal protection require an urgent and substantial overhaul/streamlining to become more cost and time effective and take into consideration the emerging international and European legal framework.

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