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Beach erosion due to climate change: evaluation and best mitigation practices in touristic beaches of North Aegean Islands and Cyprus – The methodological structure of BEACHTECH project

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Abstract The expected relative sea level rise (RSLR) and changes in the intensity/ frequency of extreme sea levels pose a growing erosion threat to beaches, the most important natural resources of touristic islands. In the framework of the BEACHTECH project, the beaches of Lesvos and Chios Islands (NE Aegean) and Cyprus have been digitized and modeled under different scenarios of sea level rise to assess their erosion. Four pilot beaches were selected for further study aiming to determine the present and model the future erosion risk and design effective technical adaptation measures. The results are envisaged to advance knowledge on the assessment of the anticipated coastal erosion and flood risk at island settings, offer options of technical measures (involving prospection for potential marine aggregate deposits) to the partner regional authorities, advance our understanding of the interactions between beaches and their backshore hydrological basins, and promote our capability to observe beach erosion using high frequency coastal monitoring systems.

Keywords: beach erosion, coastal protection measures, sea level rise, eastern Mediterranean

1. Introduction

Beaches are important coastal habitats since they (i) are themselves significant ecosystems, (ii) protect significant backshore human assets/infrastructure and ecosystems from marine flooding (i.e., Neumann et al., 2015) and (iii) have a high economic potential. According to the Sun-Sea-Sand- '3S' tourism model, the rapidly expanding tourism sector has focused on beach recreational activities (Monioudi and Velegrakis, 2022). However, beaches are experiencing significant and escalating erosion at a time when their environmental and socioeconomic significance is growing. According to several studies, erosion is a persistent issue on open coasts (e.g., Vousdoukas et al., 2020) and it can be divided into two categories: (a) irreversible shoreline retreat caused by the relative mean sea level rise (RSLR) and/or negative coastal sedimentary budgets, and (b) short-term erosion brought on by storm surges and waves (Seneviratne et al., 2012).

In the case of island beaches, their small (in general) size, the declining sediment supply, the deteriorating nearshore ecosystems that protect against marine erosion, and the growing backshore development, all make them particularly vulnerable to beach erosion (e.g., Peduzzi et al., 2022). Mediterranean island beaches are considered among the most popular 3S tourist destinations, and as a result, they have been evolving into the backbone of island economies.

The projected RSLR and potential changes in the frequency/intensity of energetic events will exacerbate beach erosion, with severe effects on coastal ecosystems, infrastructure and assets, as well as the beach hedonic value and carrying capacity for recreation and tourism (e.g., Bellard et al., 2014; Monioudi et al., 2017; Toimil et al., 2018). This may have negative economic impacts on the islands' economies. Therefore, beach erosion must be among the primary considerations in coastal management and climate change adaptation plans in island settings. In order to combat beach erosion and mitigate its negative effects on the coastal socioeconomic development, effective adaptation, including technical protection measures, will become increasingly necessary. The international community has acknowledged this, and related rules and regulations are now being increasingly introduced (i.e., UNEP, 2017).

In this context, the purpose of the current contribution is to present an integrated methodological framework that deals with (a) the assessment of the beach erosion risk at island scale under sea level rise, (b) the design/testing of methods to assess erosion and (c) the consideration of suitable adaptation measures (for selected beaches).

2. Methodological Framework

A methodological framework is suggested within the "INTERREG V-A Greece-Cyprus 2014-2020" Research Project BEACHTECH (http://beachtech.eu), whose main objective has been to highlight the urgent need for adaptation to climatic risks (coastal floods and erosion) and their dynamics under Climate Change. This is achieved through the risk assessment and the evaluation of effective protection measures, which will contribute to the resilience and sustainable development of beach tourism, a most critical sector of the Greek and Cypriot economies. Complementary and comprehensive activities were designed and implemented through the close cooperation between the University of the Aegean, the Cyprus University of Technology, the Regional Development Fund of North Aegean and the Municipality of Pegeia (Cyprus) - the beaches of which are already under significant erosion. The methodological framework involves four steps and has been applied to four diverse (in terms of size and other environmental and socio-economic characteristics) touristic beaches: 2 beaches in Lesvos, 1 in Chios and 1 in Cyprus.

Step I objectives aim to evaluate beach erosion (and flooding) at island level. Its implementation entails (a) a beach register for each island that collates the available geospatial environmental and socio-economic characteristics of the beaches (i.e., area, length, maximum width, orientation, sediment type, presence of coastal works, density of backshore development) from freely accessible remote sensing information (Google Earth Pro), and (b) the assessment of the risk of beach retreat/erosion under various scenarios of long- and short-term sea level rise using suitable ensembles of cross-shore morphodynamic models that consider different ranges of cross-shore seabed profiles, sediment sizes (median (d50), and plausible energetic wave conditions (for details, see Monioudi et al., 2017). This procedure helps to address the lack of precise information on these factors over the different island beaches.

Mean sea level rise projections for different climatic (RCP4.5 and RCP8.5) and ice mass (ice-melt) change scenarios (Hinkel et al, 2014), combined with land vertical movements (Peltier, 2004) were used to assess the future relative sea level rise (RSLR). These RSLR projections were then combined with tidal elevations, storm surge levels and coastal wave set-ups (to obtain extreme sea level (ESL) projections under extreme events, such as the 1 in a 100-year event - ESL_{100} (i.e., Vousdoukas et al., 2017).

By comparing the mean high and low predictions of the model ensembles with the maximum 'dry' beach widths recorded under various mean and severe sea levels, ranges of beach erosion (decrease in 'dry' beach width) have been forecasted. This information can then support other actions such as the prioritization of beaches according to their need for adaptation responses.

Step II is focused on a holistic approach for the assessment of beach erosion along pre-selected pilot beaches as case studies. This includes the following activities.

(i) Hydrological modeling of the upstream catchments of the pilot beaches in order to estimate the volume of sediment that might be trapped in upstream dams which will affect negatively the beach sediment reservoirs. The assessment can be made through detailed and high-precision recording of the dam bathymetry-morphology before and after major flooding events and with the analytical study of the hydrological diet and the sediment supply of the dam catchments. Model predictions can be validated by appropriate field data (river level, flow intensity, suspended solids concentration, determination of sediment volume in dams) as well as from remote sensing data (e.g., dam water turbidity after heavy rainfall). Using extreme value stochastic methods, flood events will be identified (Tzoraki et al., 2013) and sediment volumes corresponding to certain flood return periods under Climate Change conditions are estimated. The results of this action will be used to evaluate the current and future sediment balance in the dams and in the catchment beds.

(ii) Detailed mapping and description of the hydrodynamic conditions at the pilot beaches. Field measurements are carried out at each beach for the acquisition of coastal topo-bathymetric, morphological and sedimentological information, which is necessary to set up the coastal hydrodynamic/morphodynamic simulation models. The hydrodynamic experiments include sensor deployment for high resolution measurements of current speed and wave height/period.

(iii) Monitoring of the morphological evolution of the pilot beaches with remote sensing methods. This is expected to address a large challenge for erosion risk assessments, which is the incomplete spatio-temporal information that constrains the analysis of the evolution of coastal morphology and the shoreline positions. This information, although essential for effective coastal zone planning and management, is very rarely available. The results are anticipated to contribute decisively to the development/testing of Climate Change adaptation measures for the prevention/management of coastal erosion. The activities include the following. (a) Repeated topographic mapping of the pilot beaches using visual information from Unmanned Aerial Vehicles (UAVs) of high spatial resolution and accuracy. (b) Installation of optical monitoring systems for the long-term beach observation, consisting of network cameras, meteorological stations and high-resolution wave sensors (Velegrakis et al., 2016; Chatzipavlis et al., 2019). The camera records images at a 5Hz sampling rate for 10 minutes at the beginning of each hour with natural light. Pre-processing of the images on the field computer automatically generates metadata, i.e., TIMEX and SIGMA images. The cameras are calibrated for lens distortion, and the images are geo-referenced using Ground Control Points-GCPs from RTK-DGPS. The results of the image processing together with the records of the weather stations that are installed next to the optical systems are uploaded to the BEACHTECH website and they are available to the public. TIMEX and SIGMA metadata from fixed optical tracking systems can be further analyzed by innovative automated processes (e.g., Rigos et al., 2016; Chatzipavlis et al., 2019) for the production of time series of the coastline of the 4 beaches with a high resolution. These results together with those from the wave sensors provide long-term records of large spatio-temporal resolution of the response of the beach to the wave regime. (c) Geo-referenced satellite information available for pilot beaches in order to estimate their long-term historical erosion trends. An assessment of the range of uncertainty characterizing temporally satellite records of the coastline in relation to the 'average positions' of the temporally variable coastline can be made, comparing satellite information and records from the optical monitoring system.

Step III focuses on the simulation of beach erosion under the current and projected sea levels, the design of "soft" and "hard" coastal protection measures, and the study of their effectiveness and potential effects on the adjacent coast under changing sea levels. A state-of-the-art (3-D Boussinesq) coastal hydro-morphodynamic model is used (Karambas, 2012; Velegrakis et al., 2016) for the diagnosis/prognosis of coastal morphodynamics in the pilot beaches under the existing conditions. The model simulates wave propagation and is applicable in compound wave fields where the waves are affected by shoaling, refraction, diffraction, reflection (total and partial reflection), and breaking. The depth-averaged circulation used to describe nearshore currents and the movement of sediment in the surf and swash zone is driven by radiation stress components. A subroutine that simulates the response of the beach morphology and in particular the displacement of the shoreline (erosion/sediment) is also included. The model is set up using the detailed topographical, bathymetric and sedimentological data that have been collected at the pilot beaches and its comprehensive calibration is based on (i) the hydrodynamic data collected with the current and wave meters, and (ii) the available optical system information for the shoreline position. Thus, it can be also used to diagnose current coastal erosion trends at the pilot beaches. The same model is utilized to examine the effectiveness of the "hard" (i.e., submerged breakwaters) and "soft" (beach replenishment) adaptation measures (and their combination) under both the present and projected sea levels. Beach replenishment schemes are designed in accordance with Dean (2002), taking into account different scenarios of beach width and elevation, as well as filling sediment size (Andreadis et al., 2021). To this end, the possibility of the potential availability of marine aggregate deposits, having similar characteristics with the native beach sediments, is also investigated in the wider offshore areas of the pilot beaches, taking also into account the local geology and marine spatial planning issues (e.g., territorial waters, fishing grounds, wrecks, cables, protected habitats, Hasiotis et al., 2020). This preliminary survey approach includes a bathy-morphological investigation and sediment grab sampling/analysis, considering commonly applied environmental terms for marine aggregate extraction (trailer dredging) to reduce consequences of seabed disturbance.

Step IV will provide a cost-benefit assessment of climate change adaptation options. Beach width decrease due to erosion will lead to a reduction in the available space and, thus, of the number of visitors that can accommodated (carrying capacity), creating overcrowding and unpleasant experiences, that could have negative implications for the economy. Carrying capacity assessments can be useful tools in beach management as they can facilitate the determination of acceptable development limits and, thus, maintaining the quality/quantity of natural coastal resources and ensuring environmental and socio-economic benefits. A cost-benefit analysis can estimate the economic viability of the various adaptation options, taking into account the cost of (i) beach loss due to erosion for different Climate Change scenarios, and (ii) the application of proposed suitable protection works, for which the construction, maintenance and monitoring costs is also estimated.

3. Concluding remarks

BEACHTECH project envisages to offer a structured methodology for the assessment of beach erosion risk and the construction of effective technical adaptation measures under sea level rise at North Aegean Islands and Cyprus. According to the project projections, by the end of the century the beaches of Lesvos, Chios and Cyprus will face a high erosion risk. Various research approaches are tested, and the preliminary results help to improve the diagnosis and prognosis of the beach erosion risk in island settings, provide detailed assessments of the current and future erosion risk aiding to the design of efficient technical responses, improve our understanding on the interactions between beaches and their backshore basins, and advance our capability to monitor beach erosion in high frequency using cost-effective operational tools. The outputs of the project are expected to be extremely useful not only for the involved local authorities but also for the Regional/National competent authorities, coastal managers and populations and the tourism industry of Greece and Cyprus.

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