PHYSICAL AND ECONOMIC IMPACTS OF SEA LEVEL CHANGES ON THE ISLAND BEACHES OF THE AEGEAN ARCHIPELAGO (ISLA); CONCEPTS AND PRELIMINARY RESULTS

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ABSTRACT

Beach erosion, which is already significant along the global coastline, is likely to be exacerbated due to mean sea level rise (SLR) and changes in the wind/wave regimes and coastal sediment supply. Erosion is already alarming at the Aegean Archipelago beaches that form the pillar of the Greek ‘sun and sea’ tourist industry. The objectives of the ISLA project (2012-2015) are to: (i) create an inventory of the spatial characteristics of the Aegean Archipelago beaches, using readily available remote sensing information and web-GIS tools; (ii) assess the range of their potential retreat under sea level rise scenarios, through morphodynamic model ensembles; (iii) develop/evaluate low cost, optical systems to monitor beach morphology; (iv) assess the accuracy/sensitivity of satellite coastal images using appropriate ground truthing; (v) study the river sediment supply dynamics at representative island beaches; and (vi) assess erosion-driven socio-economic impacts. Preliminary results show that the Aegean Archipelago island beaches are generally small (64% of all beaches show maximum widths < 20 m) and mostly composed of sand (~ 49%) and coarse-grained (~25%) sediments. Comparison between their maximum widths and the projected beach retreats (from morphodynamic modeling) shows that sea level rise will have devastating impacts: almost 20% of all beaches will be inundated to about 50% of their maximum width under 0.6 m storm surges, whereas in the case of a 1 m mean SLR, ~90% of all beaches may retreat/lose more than 50% of their maximum width and ~68% will be entirely lost. Regarding the development of the beach monitoring system, automation of the shoreline detection from SIGMA images has advanced considerably, with the accuracy of the method being also significantly improved by the employment of RBF neural networks.

Keywords: beach erosion, sea level changes, risk assessment, Aegean Archipelago
1. INTRODUCTION

Coastal erosion emerges as a particularly serious environmental threat, since large tracts of the global coastline are already under irreversible retreat and recent projections indicate that the situation will, probably, worsen significantly in the future (IPCC SREX, 2012), due to (a) the projected rise in mean sea levels (SLR), (b) potential intensification/change of the wind/wave climate and (c) reductions in the river sediment supply to coasts, resulting from changes in precipitation and/or the further expansion of river management schemes (Nicholls et al., 2007). At the same time, coasts are characterized by rapid economic development, increasing populations and, thus, by considerable exposure of the coastal infrastructure, assets and activities to damages/flooding (Lenton et al., 2009). Beaches (i.e. the low-lying coasts built on unconsolidated sediments) are the most morphologically dynamic and vulnerable to erosion coastal environments. Beach erosion is particularly alarming for the Aegean Archipelago beaches, which are considered particularly vulnerable due to their limited size and sediment supply (Velegrakis et al., 2008). At the same time, these beaches are valuable natural and economic resources (Velegrakis et al., 2005); however, to date, there have been no detailed studies to assess their current state as well as their future evolution under the projected climatic changes.

The main objectives of the THALES-ISLA research project (2012-2015) are to: (i) assemble a dynamic and user-friendly database (Aegean Archipelago Beach Inventory) that will incorporate the spatial characteristics of the island beaches of the Aegean Archipelago, using readily available (web-based) remote sensing information; (ii) assess the potential beach retreat under different scenarios of sea level rise through the use of suitable ensembles of parametric and numerical morphodynamic models; (iii) develop/evaluate a low-cost, automated system of monitoring beach morphodynamics on a long-term basis and in high frequency; (iv) assess the accuracy/sensitivity of remote-sensed images that provide information on beach spatial characteristics (e.g. beach width), through specifically targeted and detailed ground truth experiments; (v) study the dynamics and assess the impacts of the riverine sediment supply at representative coastal drainage basins and beaches of the Aegean Archipelago; and (vi) assess the socio-economic impacts of coastal erosion due to storm surges and long-term SLR on representative beaches of the Aegean Archipelago and suggest effective beach protection policies/measures. The present contribution details the methodologies/approaches that will be employed in the ISLA research project and provides some preliminary results.

2. METHODOLOGY

The project duration is 42 months, involves 3 Research Groups (RGs), is organised into 6 Work Packages (WPs) and is managed (WP1) by the Department of Marine Sciences of the University of Aegean. WP2 (Aegean Island Beach Inventory-AIBI) concerns the development of a database of the spatial (length, width, area and orientation) and -where such information is available- of the geological, wave and hydrological characteristics of all the Aegean island beaches. Beach spatial characteristics will be recorded/analysed using widely available remote sensing information (Google Earth Pro) and web-GIS tools (Velegrakis et al, 2009); the accuracy/sensitivity of the remote sensing information will be assessed at 2 representative-case study beaches. As the mean SLR and the frequency/intensity of storm surges are expected to be variable in the Aegean Archipelago (e.g. Tsimplis and Shaw 2010), an assessment of the current status and future dynamics of the sea level will also be carried out.
In the WP3 (Morphodynamic modeling), beach retreat/erosion in the Aegean Archipelago due to the long- and short-term sea level rise will be assessed through the development/application of parametric (e.g. Bruun, 1988) and/or process-response models. The advantage of the former models is their simplicity; however, they cannot describe very successfully beach morphodynamics under associated with high frequency level changes, as is the case with process-response models that are based on the coupling of hydro- and sediment dynamic numerical models (e.g. Larson and Kraus, 1989; Leont’yev, 1996). A ‘pool’ of both parametric and process-response morphodynamic models will be created, from which suitable (1-D) model ensembles will be formed to simulate long- and short-term beach retreats and assess their range under different morphological (beach slopes), sedimentological and hydrodynamic conditions (Velegrakis et al., 2009) and scenarios of mean SLR and/or storm surges. This approach is based on the premise that, since different models have different sensitivity to the environmental controls, their common (ensemble) application may provide more realistic predictions. It must be also noted, that the aim of this exercise is not to replace detailed modeling studies, but to provide realistic ranges of beach retreats. These ranges will be then compared to the spatial characteristics of the Aegean island beaches (e.g. beach width maxima) recorded at the AIBI, to project retreats assess the vulnerability of all Aegean island beaches; short-term modeling predictions will be validated at the case study beaches, through high frequency hydrodynamic/morphodynamic observations. In addition, the short-term hydrodynamics and morphodynamics of these case study beaches will be studied through the development/application of 2-D and pseudo 3-D models that are based on non-linear Boussinesq type equations (e.g. Vousdoukas et al., 2009a).

Within the THALES-ISLA project a low cost, automated, high frequency beach monitoring system (AOMS) will be developed (WP4). The system will consist of integrated video cameras suitably located, calibrated and geo-referenced, which will record (in 2-D) the long-term shoreline locations, wave breaking zones and wave run-ups (e.g. Vousdoukas et al., 2009b). New algorithms/techniques will be developed, whereas the system will record the initial ‘raw’ optical data as well as final morphological time series (meta-data) at suitable temporal scales. The system is planned to be fully automated, i.e. it will be able to provide automatically long time-series of beach morphology such as shoreline positions and wave run up excursions. Following trials, the system will be deployed at the (2) case study beaches where, following repeated geo-referencing, its performance will be assessed on the basis of the various ground-truth information (e.g. morphological and hydrodynamic) that will be collected during dedicated beach experiments.

River sediment supply (and its extremes) and the flood curves of the drainage basins associated with the 2 case study beaches will be assessed, through flow/sediment discharge modeling (e.g. Velegrakis et al., 2008; Lekkas, 2008), calibrated/validated by short-term flow/sediment discharge observations. High resolution remote sensing information (e.g. IKONOS, Quickbird, WorldView) will be used to define the shoreline at the 2 case study beaches; this information will be then compared to that provided by the AOMS and accurate (RTK-DGPS) topographic surveys, considering also the high frequency hydrodynamic/sediment dynamic observations and swash zone pore pressure measurements (e.g. Karambas, 2003) that will be collected concurrently. It is envisaged that the study will improve the assessment of the satellite information accuracy.

The flood-induced economic vulnerability of the 2 case study beaches will be also assessed (WP5). Coastal capital and activities at risk (e.g. Callaway 2004) will be evaluated together with their sustainability under different mean SLR and storm surge-induced coastal inundation scenarios, using the projections from the work packages WP2
and WP3 and appropriate technical adaptation responses will be proposed. Finally, the synthesis of the results and their dissemination will take place in WP6.

3. PRELIMINARY RESULTS

To date the results of the study are mostly related to the development of the AlIBI, the development/application of the 1-D model ensembles and research/development of the low cost, automated, high frequency beach monitoring system (AOMS). The two case study beaches have been also selected (Eresos beach, Lesbos and a Mykonos beach), on the basis of their history of erosion and their geo-environmental and socio-economic characteristics, as well as logistics considerations.

3.1. Characteristics of the Aegean Archipelago beaches

The Aegean Archipelago beaches were found to be quite limited in size, with > 64% and 94% of all beaches showing maximum widths < 20 and < 50 m, respectively. Very few beaches (< 7%) have been found to have moderate widths (> 50 m), and only ~0.7% and ~0.3% of all beaches have maximum widths in excess of 100 and 200 m, respectively. With regard to the beach sediments, Aegean Archipelago beaches are mostly associated with medium-grained sediments: ~49% of beaches are composed of sandy sediments, ~13% of pebbles, ~12% of gravels/sandy gravels and ~2% of fine-grained sediments), whereas for ~24% of beaches, there is no information available on their sediment type.

3.2. Modeling

Two model ensembles were created: a long-term sea level change ensemble, consisting of the Bruun (1988) and Dean (1991) models, and a short-term consisting of the Leont’yev (1996), SBEACH (Larson and Kraus, 1989) and Edelman (1972) models. The models were applied for linear profiles (bed slopes of 1/10, 1/15, 1/20, 1/25 and 1/30) and experiments were carried out using varying wave conditions (offshore wave heights (H) of 0.5, 1, 1.5, 2, 3, 4, 5 and 6 m and periods (T) 3-14 s) and 7 sediment grain sizes (d$_{50}$ of 0.2, 0.33, 0.50, 0.80, 1, 2 and 5 mm). For all cases, 14 sea level rise scenarios (0.038, 0.05, 0.10, 0.15, 0.22, 0.30, 0.40, 0.50, 0.75, 1, 1.25, 1.50, 2 and 3 m) were tested.

![Figure 1](image)

**Figure 1.** Beach retreat/inundation predictions due to short-term and long-term sea level rise for different environmental forcing. The means for the high and low prediction ranges of the model ensembles are also shown.
The means of the lower and upper limits of the model projections have been estimated on the basis of the results of 16744 experiments. It was found that the low prediction mean of the short-term ensemble (i.e. the best fit of the lowest predictions from Leont’yev, SBEACH and Edelman models) is given by \( s = 0.54 \alpha^2 + 7.08 \alpha - 0.31 \) \( (R^2 = 0.998) \) and the high prediction mean by \( s = 1.23 \alpha^2 + 29.52 \alpha + 4.71 \) \( (R^2 = 0.996) \) (Figure 1), where \( s \) is the beach retreat/inundation and \( \alpha \) is the sea level rise. It was also found that low prediction mean of the long-term ensemble (i.e. the best fit of the lowest predictions from Bruun and Dean models) is given by \( s = -0.001 \alpha^2 + 7.9 \alpha + 0.1 \) \( (R^2 = 1) \) and the high prediction mean by \( s = 5E-05 \alpha^2 + 28 \alpha + 5.2 \) \( (R^2 = 1) \) (Figure 1). On the basis of these results, a storm surge of 0.6 m (i.e. maximum value recorded in the Aegean Sea, see Tsimpis and Shaw (2010)) will result in beach inundations of 4.1 – 22.9 m, whereas according with the long-term ensemble a SLR of 1 m (projection for 2100, see Grinsted et al., 2010) will result in beach inundations of 8 – 33.2 m.

3.3. Beach spatial characteristics versus modeling results

Comparison between the maximum beach widths and the projected beach retreats shows that sea level rise will devastate the Aegean Archipelago beaches. In the case of a storm surge of 0.6 m, the analysis showed that, on the basis of the low mean predicted by the short-term ensemble, ~64% and ~19% of all beaches will be inundated to > 20% and > 50% of their maximum width, respectively; ~3% of the beaches will be entirely inundated. On the basis of the projected high mean, the effects will be even worse, since ~99% and ~91% of all beaches will be inundated to > 20% and > 50% of their maximum width, respectively, whereas 68% of the beaches will be completely inundated (Figure 2a).

![Figure 2. Maximum inundation/retreat of the Aegean Archipelago beaches for sea level rises of (a) 0.6 m (short-term/storm surge) and (b) of 1 m (long-term). Final width values < 0 show beaches that will be entirely inundated.](image)

For a 1 m mean SLR and on the basis of the high mean of the long-term ensemble predictions, the effects will be very severe (Figure 2b), as ~97% of all beaches will be inundated to > 50% of their maximum width, and ~84% will be lost. In this case, infrastructure/activities associated with these beaches will be also very seriously affected.

3.4. Development of the AOMS system

To date, the development of the AOMS system has focused on the automatisation of the shoreline detection procedure, building on recent efforts that have shown that the
deployment of neural networks may improve substantially the performance of automatic shoreline extraction from SIGMA coastal imagery, i.e. from the gray-scale variance imagery that represents the standard deviation of pixel intensities along the image frame for a given period of image acquisition (e.g. Vousdoukas et al., 2011). A Radial Basis Function neural network (RBF-NN), trained in terms of fuzzy clustering has been used to improve shoreline detection performance (e.g. Rigos et al., 2013). The coastal images used have been obtained by a 2-video camera system installed at the reflective, sandy Faro Beach (S. Portugal) since 2009 (Vousdoukas et al., 2011). The system has been monitoring a 500 m long stretch of the beach and our analysis focused on a time-series (02/2009- 06/2010) of hourly SIGMA images; these images represent the sum of the absolute pixel intensity differences between consecutive images and can be considered as ‘accumulated motion images’ with high pixel intensities being related to wave-breaking and swash activity (Figure 3). Image rectification procedures, e.g. calibration of the camera's intrinsic parameters, translation the camera's view field into space coordinates and geo-rectification were utilised to generate appropriate plan view images.

Figure 3. Shoreline detection at the Faro Beach (S. Portugal). (a) A SIGMA image and extracted shorelines using Otsu's method (Otsu, 1979) and the proposed method (Rigos et al., 2013; Vousdoukas et al., 2011). (b) a TIMEX image, created by averaging a series of snapshots.

In order to accurately detect the shoreline in the geo-rectified image sequences an RBF-NN has been employed. To generate the input data, normalized SIGMA histograms were used, following a regression approach that employs a ‘steepest descent’ iterative optimization algorithm (Rigos et al., 2013); for the output data the Vousdoukas et al. (2011) approach was used, which utilises a thresholding procedure on SIGMA images. The RBF-NN was then applied on the input-output data sets to predict the corresponding threshold that yields shoreline position for each SIGMA image. The results of the analysis that was based on a splitting of a 1200 images data set into a training (comprising 60% of the SIGMA images) and a testing set (comprising the remainder 40 % of the images), have been very promising, as they have shown to be (after validation by ground truth data) much more accurate than procedures using previous approaches (Figure 3).

4. CONCLUSIONS

The ISLA project (2012-2015) has as principal objectives to develop management tools that (a) will assist in the assessment of the sea level change impacts on the Aegean Archipelago beaches and (b) help the competent authorities with regard to important legal obligations (e.g. the 2007 Flood Risk Directive and the ICZM Protocol to the Barcelona...
Convention). These tools are: (i) a beach inventory of the Aegean Archipelago (AIBI) containing spatial and –where available- other geo-environmental characteristics; (ii) a prognostic tool that can provide projections of the ranges of beach retreat under different SLR scenarios and/or extreme waves/surges; (iii) an automated, low cost monitoring system of the beach morphology; and (iv) improved approaches in the modeling of sediment loads/yields of small island drainage basins. In addition, methodologies to evaluate the coastal capital of economically important beaches of the Aegean Archipelago and assess potential losses due to sea level changes will be developed.

To date, the results of the study are mostly related to the development of the AIBI, the development/application of the 1-D model ensembles and research/development of the low cost, automated, high frequency beach monitoring system (AOMS). It has been found that the Aegean Archipelago beaches are limited in size (> 64 % of all beaches show maximum widths < 20 m, with only ~7 % of all beaches having maximum widths > 50 m), and are built mostly on sand (~ 49%) and coarse-grained (~25 %) sediments. With regard to the morphodynamic modeling, a 'long- and a 'short-term' model ensemble were applied for 5 different linear profiles, 7 different sediment sizes, varying wave conditions and 14 sea level rise scenarios; 16744 experiments were carried out and the means of the lower and upper limits of the model projections have been estimated.

The comparison between the recorded maximum beach widths and the projected beach retreats showed that the sea level rise will have devastating impacts on the Aegean beaches. Almost 20 % of all beaches will be inundated to about 50 % of their maximum width under a 0.6 m storm surge, whereas in the case of a mean SLR of 1 m ~90 % of all beaches may retreat/lose more than 50 % of their maximum width and ~68 % will be entirely lost. It must be noted that these projections may be under-estimates, as they refer only to the sea level rise effects, not taking into account other potent beach erosion forcings (e.g. the reductions in beach sediment supply). With regard to the beach monitoring system, preliminary results are encouraging. Automation of the shoreline detection procedure from SIGMA images has advanced considerably, with the accuracy of the method being significantly improved by the use of RBF neural networks.

In the following years, and according to the project timetable, the research will focus (amongst others) on: (a) the further development/application of the model ensembles in order to improve projections of beach retreat/erosion under different scenarios of sea level rise; (b) the development/application of a 2-D morphodynamic model, based on non linear, Boussinesq-type, wave equations and its field validation; (c) the development, installation and field testing of the autonomous optical monitoring system (AOMS) at 2 experimental sites through comparison of its meta-data (e.g. time series of shoreline positions) with morphological, hydro- and sediment-dynamic observations; (d) the comparison/calibration of shoreline positions obtained from high resolution satellite sensors with 'ground truth' data from the AOMS and high resolution (RTK-DGPS) topographic surveys; (e) integrated field experiments combined with modeling of e.g. the swash infiltration/exfiltration processes to improve our knowledge on the interactions between incident waves, beach morphology/sediments and the wave run-up and swash infiltration/exfiltration and (f) the advancement/testing of methodologies regarding the assessment of the socio-economic impacts of climate change in an Archipelago setting.

ACKNOWLEDGEMENTS

This research has been co-financed by the European Union (European Social Fund – ESF) AND Greek National funds through the Operational program ‘Education and Lifelong Learning’ of the National Strategic Reference Framework (NSRF)-Research Funding Program THALES.
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