VULNERABILITY ASSESSMENT OF EASTERN CRETAN BEACHES (GREECE) TO SEA LEVEL RISE

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Abstract

Purpose. Beaches are considered both valuable economic resources for the Mediterranean countries and vulnerable to climate changes. The purpose of this study is the vulnerability assessment of the beaches along East coast of Crete in relation to the anticipated sea level rise.

Methods. Morphological and sedimentological data have been collected/analyzed for 71 beaches, while wave regime has been based on INTERIM data. This information has been used in conjunction with an ensemble of 5 coastal morphodynamic models to assess the range of reduction of beach width under various rates of sea level rise.

Results. In the case of a sea level rise of 0.82 m, the analysis showed that the effects will be devastating since up to ~93% of the beaches will be inundated to more than 50% of their widths. In the case of a sea level rise of 1.86 m, the results suggest that the impact will be detrimental since up to ~94% of the beaches will be completely inundated.

Conclusions. It appears that sea level rise would considerably affect the 'pocket beaches' of Eastern Crete and, therefore, the impact of sea level rise should be taken into account in any future coastal management plans.

Keywords: Ensemble Modeling, Beach Retreat, Sea Level Rise, East Crete

Introduction

Beaches are the most morphologically dynamic coastal environments, being controlled by complex process-response mechanisms that operate in several temporal and spatial scales. Beaches provide dynamic protection to the coastal environments as they front e.g. back-barrier systems and cliffs (e.g. [21]), and protect coastal human infrastructure and other economic assets. In addition, beaches provide important recreational facilities and are a mainstay of tourism, which is of particular economic importance to Mediterranean countries.

Climate change and particularly sea level rise (SLR) (long-term and short-term) represents, probably, one of the most significant beach threats since beaches respond to the rising sea level with retreat. The latest forecasts [9] suggest that mean sea level rise, in 2100, will be between 0.26 and 0.82 m higher than that of period 1986-2005. Nevertheless, other recent studies that are based on alternative approaches, suggest much higher rises for the same period (e.g. [10,19]), thus Mori et al. [19] suggest a mean sea level rise of 0.87-1.86 m. In addition, changes in the frequency/intensity and destructiveness of the extreme storm waves/surges have been observed [7,22]. It is thought that this trend is going to continue under a warming climate, with devastating effects on the beaches, particularly if this trend is combined with the expected mean sea level rise [23].

The projected mean sea level rise will likely exacerbate the already significant beach erosion (e.g. [20]) and severely impact coastal populations, activities, infrastructure and assets (e.g. [18]). However, the most devastating impacts are likely to be associated with storms and storm-induced extreme sea levels (e.g. [5]) that will be superimposed upon the long-term sea level rise (e.g. [8]). As the physical impacts on the beaches (and other coastal areas) of the projected mean sea level and storm surge changes are likely to increase, the ever increasing coastal populations, activities and infrastructure will face growing exposure to coastal flooding, which can be devastating for the global economy (e.g. [14]). Coastal housing will be severely affected by climate change-driven extremes (e.g. [17]). A study by Lloyd's [15], has found that unless adaptation measures are taken, a 0.3 m sea level rise could increase very significantly the average loss exposure of high-risk coastal properties at several locations around the world, even in coastal areas with well-maintained flood-defenses.

Beach erosion is particularly devastating in the case of the Eastern Cretan beaches; these beaches are particularly vulnerable, due to their small size, climatic characteristics and negative sediment balance and the high relief and deforestation of their upstream drainage basins [25]. At the same time, beaches represent the most valuable natural resource of Greece, as they are the main focus of the "sun and beach" tourism (e.g. [16]).

The objective of the present contribution is to assess the vulnerability of the 71 highly touristic Eastern Cretan beaches in relation to the anticipated sea level rise. For this reason, topographic, hydrodynamic and sediment dynamic data were collected and analyzed, while the use of an ensemble of 5 beach morphodynamic models provides a quantitative assessment of the range of reduction of beach width under various rates of sea level rise.

Physico-geographical setting

Crete, with a population of approximately 603,000 inhabitants, is the largest Greek island and the fifth largest in the Mediterranean. Its coastline totals 1300 km, 15 per cent of which consists of sandy beaches [1]. The climate in Crete is of the "Mediterranean" type with four distinct seasons. Furthermore, from November to March, the climate is cool and rainy, while from May to September it is hot and rather dry. The annual variation of the wind field is dominated by the persistence of northerly winds, which present a double maximum: the first during the winter period (Dec-Feb) and the second (also known as the "Etesians") during the summer period (especially July and August). Astronomical tides are of the order of a few tens of centimeters. The wave climate is primarily wind-driven with average offshore wave heights <1.5 m, which may exceed 6 m during storms. The present investigation concerns the East Crete Coast (Fig. 1).

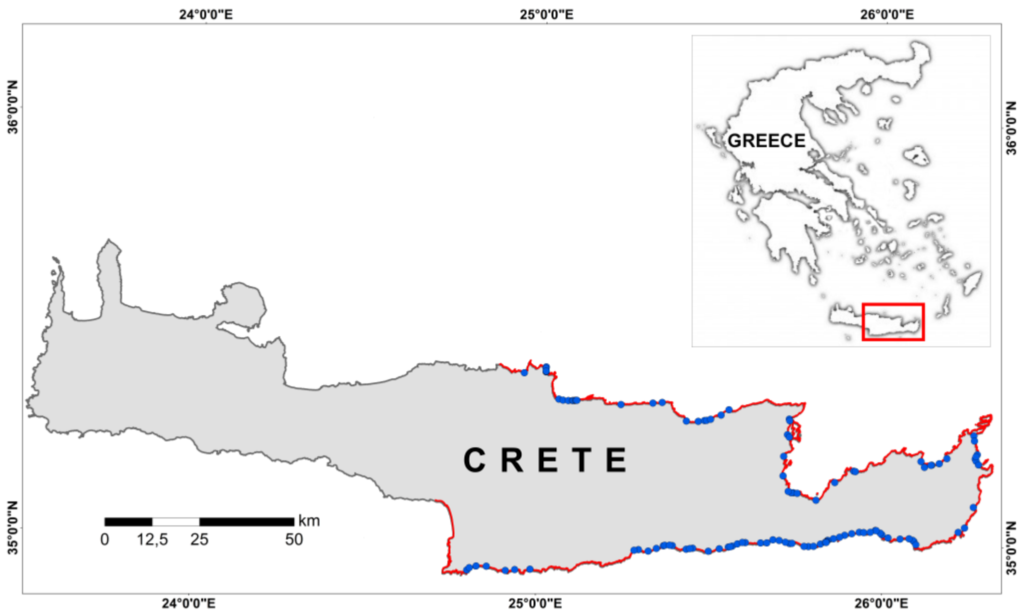

Fig. 1: Location map of the study area.

Data collection and methodology

Data collection

Topographic mapping in each of the 71 beaches are based in topographic sections record and shoreline measurement with the use of a leiser distant meter and a Differential GPS (DGPS) Top Con system, respectively. The inner boundaries of the beaches were the (seaward margin of vegetated dunes, anthropogenic structures (seawalls, roads, permanent buildings) and the feet of coastal cliffs.

Sediment samples were collected from each topographic section in the shoreline front. All sediments were subjected to grain size analysis and all grain size parameters were calculated (Mz, Md, Sk, σ) and classified, granulometrically, according to Folk's nomenclature.

The wave regime was investigated utilizing the ERA-INTERIM database of ECMWF that included timeseries of 6hourly data (with gridding of 0.25*0.25), of oceanographic parameters such as wave period, wave height and wave direction on pre-specified locations. In addition, from the total count of 50036 waves, mean wave heights and periods were estimated for bins of chosen wave directionalities.

Ensemble modeling

Beach retreat (erosion) due to sea level changes is assessed mostly through the development/application of parametric and/or process-response models (e.g. [24]); the former are based on the principle of the ‘equilibrium profile’ (e.g. [28]), while the latter on the coupling of hydro- and sediment dynamic numerical models. The principal advantage of the parametric models is their simplicity, although they cannot successfully describe beach changes due to high frequency events and/or longshore sediment transport. Process-response models, using either linear wave theory (e.g. [13]), or, non-linear Boussinesq type equations (e.g. [27]) are better express hydrodynamic conditions. Both parametric and process-response morphodynamic models are used to form suitable model ensembles in order to simulate (long- and short-term) beach retreats and assess their range under different morphological (beach slopes), sedimentological (grain size), wave conditions [26] and realistic scenarios of mean sea level changes and/or storm surges. This approach is based on the idea that as different models have differential sensitivity to the controlling factors, their common (ensemble) application is likely to provide more realistic prediction ranges; the aim of the exercise is not to replace detailed modeling studies, but to provide more realistic, basin-wide ranges of beach retreats. These ranges are then combined with the spatial characteristics (e.g. beach width) of the beaches in order to assess their vulnerability.

For the present study, the evaluation of shoreline retreat was based on the application of an ensemble of 3 parametric/analytical (Edelman, Bruun and Dean) and 2 process-response/numerical (Leont’yev and SBEACH) 1-D morphodynamic models. ***Bruun model*** [2] concerns long-term sediment budget based on the concept of equilibrium profile [28]. The ***Edelman model*** [6] is more appropriate for larger values of increased water levels and for time-varying storm surges. The ***Dean model*** [4] was developed for the diagnosis/prediction of storm-driven beach retreat and is also based on the concept of equilibrium profile. The ***SBEACH model*** [12] contains detailed descriptions of the wave transformation in the nearshore zone. The wave height distribution across the shore is calculated by linear wave theory and a model proposed by Dally [3] is used for the description of wave height decay in the surf zone. Sediment transport is computed by the wave energy flux and the beach slope. The ***Leont’yev model*** [13] uses the energetic approach, with the cross-shore changes of the wave energy flux being computed by the wave energy dissipation due to breaking. Sediment transport rates are predicted separately for the refraction, surf and swash zones. Two types of sediment transport are distinguished: (i) the transport due to wave/current interaction and (ii) the run-up induced transport.

The ensemble modeling was applied for all the range of the environmental conditions (slope, sediment size, waves) observed in the study area. The means of the lower and upper limits of all the model estimates were calculated. The low and high means of the beach retreat/inundation predictions of the model ensemble (i.e. the best fit of the lowest predictions from all models) were compared with the widths of the beaches. Also a more detailed analysis has been conducted for 2 highly touristic and natural/economic valuable beaches, Ammoudara and Koutsounari located at North and South Crete respectively.

Results and Discussion

Morphodynamic characteristics

Beach typology (i.e. dissipative, intermediate or reflective,[11]) was assessed by estimating the Iribarren number ξ ($\xi = \beta/(H_o/L_o)^{1/2}$, where β is the beach slope and H_o and L_o the offshore wave height and length, respectively. It was found that the examined beaches are dissipative ($\xi < 0.4 - 0.5$) and intermediate ($0.5 < \xi < 3.3$) and that the slopes of the swash zone section of the measured profiles ranges between ~1/10 and ~1/30.

Beach widths were found to be quite limited, as all beaches showed widths less than 80 m (except 1). More specific, 20% of the beaches showed maximum widths ≤ 20 m (~7% in North, ~3% in East and ~10% in South Crete), whereas up to ~ 90% of all beaches (~21% in North, ~13% in East and ~55% in South Crete) showed maximum widths < 50 m; very few beaches (North, ~6%, South, ~4%) showed closed to moderate widths (50-100 m); and only 1 beach had a width of more than 100 m (Fig 2).

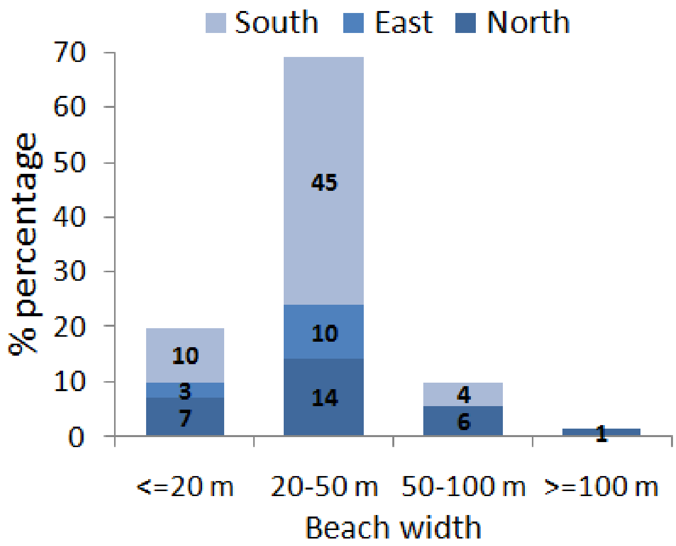

Fig. 2: Categories of the Eastern Cretan beaches according to their width.

With regard to sediments textures, Eastern Cretan beaches were found to consist mostly of medium and coarse sands with the ~41% to be composed of coarse/very coarse sand and the ~31% of fine/medium sands (Fig. 3). The remainder ~28% of beaches are composed of fine and coarse gravels. Medium-grained (sandy) sediments were found to dominate the northern (fine to medium sands: ~55% and coarse sands: ~35%) and the eastern (fine to medium sand: 33% and coarse sands: ~67%) Cretan beaches. The southern sector is dominated by coarse-grained sediments (i.e. coarse sand to fine gravels: ~67%, coarse gravels: ~14%), whereas the remainder (~19%) are fine to medium sands.

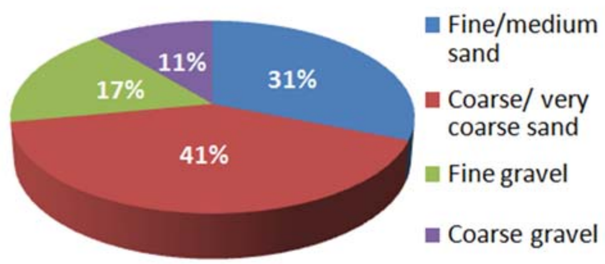

Fig. 3: Percentages of beaches, according to their sediment texture.

The wave state of the northern beaches is characterized by W to NW waves (57.39%) with heights of approximately 0.92 m and periods of 4.7 sec. Waves with large heights (1.35 m) and periods (5.28 sec) are Northerly with11.54% of occurrence. The southern beaches are mostly affected by waves with NNW directions (28.96%) and have heights of 1.26 m and periods of 5.11 sec. It should be noted here that higher waves are also from the same direction. The wave regime of the eastern beaches is as well characterized by NW-NNW waves (48%) with mean periods of 4.94 sec and heights of 1.15 m. The highest waves are of NNW directions with 1.31 m height and 5.19 sec period.

Beach retreat projections

Vulnerability assessment

The models were applied using linear profiles with slopes of 1/10, 1/15, 1/20, 1/25 and 1/30. Experiments were carried out using varying wave conditions, i.e. wave heights (H) of 0.5, 1, 1.5 m, wave periods (T) 4-5 sec, and

10 different identified sediment grain sizes (d_{50} of 0.2, 0.33, 0.50, 0.80, 1, 2, 5, 10, 20 and 30 mm). For all cases, 12 sea level rise scenarios (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. Totally 5500 experiments were carried out. The models of the ensemble displayed differential behavior for almost all tested conditions, showing, as expected, significant ranges of results (Fig. 4), since varying initial conditions and forcing have been used. It was also shown that beach retreats are higher for the dissipative than for the intermediate beaches.

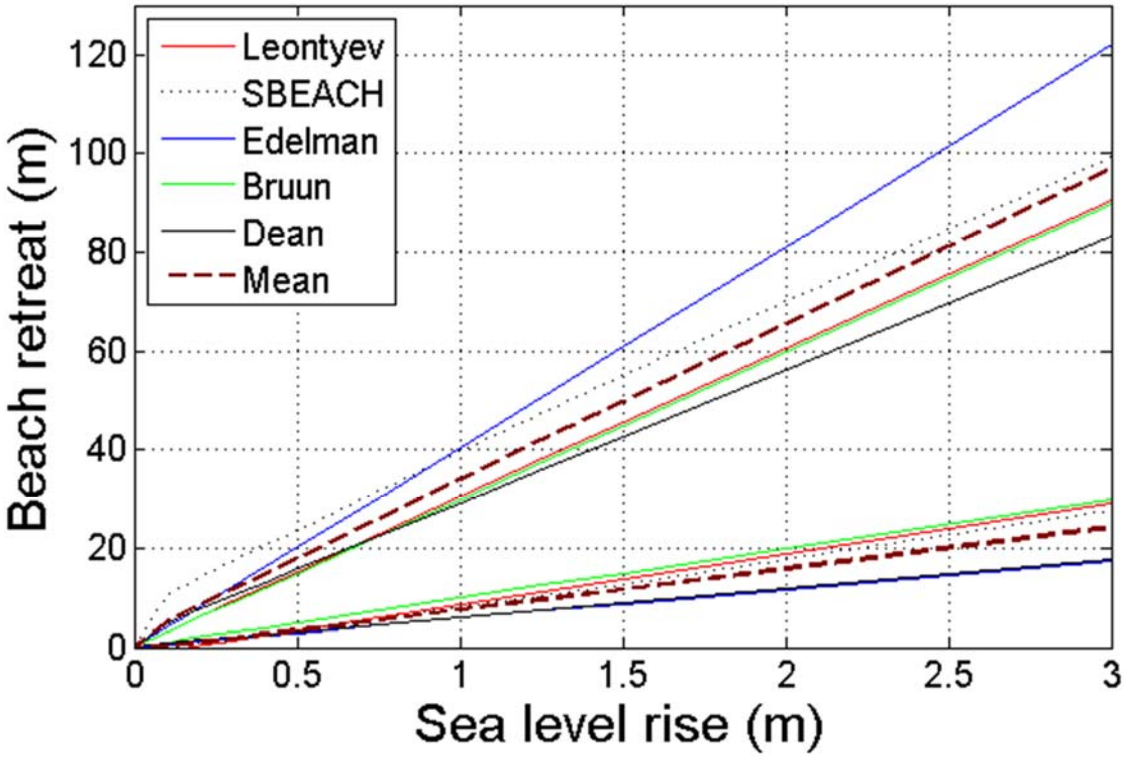

Fig. 4: Range of modeling predictions for 71 beaches located along the east coast of Crete. The means for the high and low prediction ranges of the model ensemble (brown stippled lines) are also shown.

The means of the lower and upper limits of all the model estimates were calculated; it was found that the low prediction mean of the ensemble (i.e. the best fit of the lowest predictions from all models) is given by $S = 0.05\ \alpha^2 + 8.12\ \alpha - 0.46\ (R^2 = 0.99)$ and the high prediction mean by $S = -0.16\ \alpha^2 + 32.19\ \alpha + 1.95\ (R^2 = 0.99)$, where S is the beach retreat and α the sea level rise (Fig. 4). On the basis of these results, the exercise suggests that sea level rises of 0.26, 0.82 (i.e. the low and high estimates for the average sea level rise expected for 2100, according with the latest report of IPCC [9]), 0.87 and 1.86 m (another study, for the same period, based on alternative approaches, see [19]) will result in beach retreats of 1.7 – 10.3 m, 6.2 – 28.2 m, 6.6 – 29.8 m and 14.8 – 61.3 respectively, being depend on the initial conditions and wave forcing.

The comparison between the beach widths with the ensemble modeling results showed that sea level rise will have considerable impacts on Eastern Cretan beaches. In the case of a sea level rise of 0.26 m (the low estimate for 2100,[9]), the analysis showed that, on the basis of the low mean predicted by the ensemble modeling (Table 1), the effects will not be significant, but they will be, on the basis of the high mean predicted by the model output as ~75% of North, 100% of East and ~93% of South beaches will lose more than 20% of their width and ~23% more than 50%. The loss of more than 20 and 50% of the width of the narrow Cretan (and Greek generally) beaches is not at all insignificant, since beach sections with smaller widths may be entirely lost.

Table 1. Projections of the maximum and minimum cross-shore beach retreats (in m) on the basis of the best fits for the lowest and highest predictions from all five models of the ensemble (see also Fig. 5 and its caption). Beach width loss percentages have been estimated through the comparison of minimum and maximum retreat projections with the maximum beach width of all Eastern Cretan beaches.

SLR scenarios (m)	Ensemble prediction	Beach retreat (m)	Beaches loosing 20% surface (%)	Beaches loosing half surface (%)	Beaches loosing all surface (%)
0.26	Min	1.7	0	0	0
	Max	10.3	88.7	22.5	1.4
0.82	Min	6.2	53.5	1.4	0
	Max	28.2	100	93	40.9
0.87	Min	6.6	56.3	2.8	0
	Max	29.8	100	93	47.9
1.86	Min	14.8	97.2	47.9	4.2
	Max	61.3	100	100	94.4

Similarly, for a 0.82 m sea level rise (the high estimate of IPCC for 2100), if the high mean of the modeling predictions is used (Table 1, Fig. 5a), the effects will be devastating since all the beaches will lose more 20% of their width, ~93% more than 50% and ~41% (~40% of North, ~56% of East and ~38% of South Crete) will be entirely lost/inundated (see negative values of beach widths, in Fig. 5a). The negative values of beach widths suggest that not only the beaches will be entirely lost, but also that human infrastructure/activities will be likely seriously affected. In the case of a sea level rise of 0.87 m (low estimate for 2100 by Mori et al.[19]) the effects will be similar with the previous examined scenario. The East and South beaches are the most vulnerable since they will lose more than 50% of their width, while 50-56% will be entirely lost/inundated. The losses of the North sector are not less important, since 80% of the beaches will lose more than 50% of their width and 40% will be entirely lost/inundated.

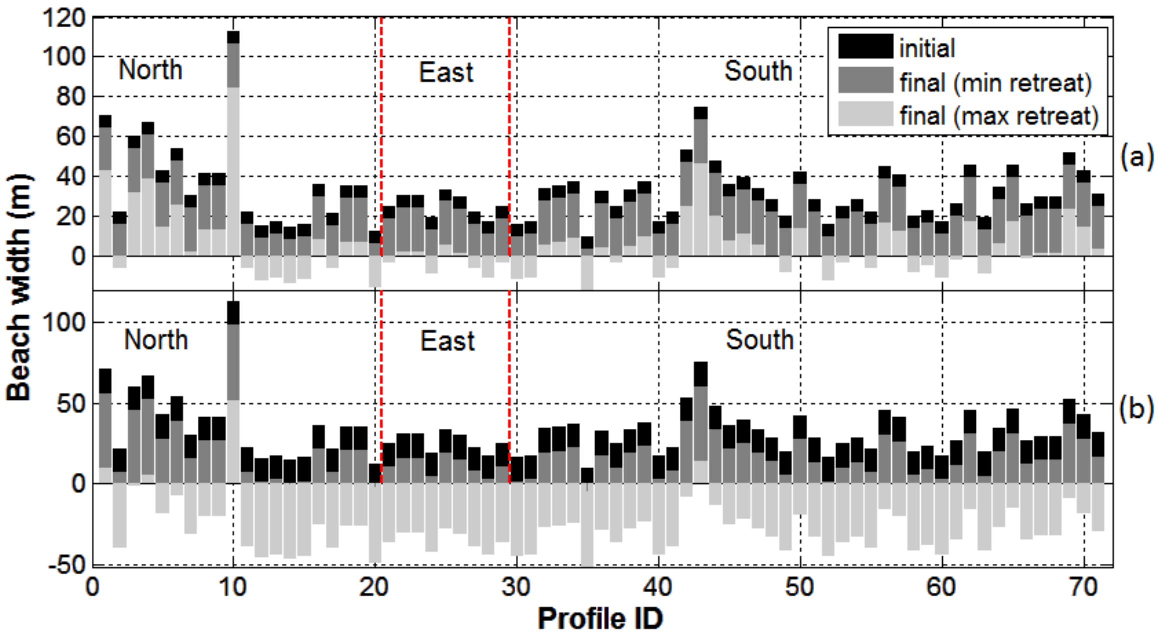

Fig. 5: Minimum and maximum retreats of Eastern Cretan beaches for sea level rises of (a) 0.82 m and (b) 1.86 m estimated on the basis of the low and high mean of the model ensemble projections. Final widths values less than zero show beaches that will be entirely lost. Beach ID progresses clockwise.

For the worst case scenario studied, (1.86 m sea level rise, the high estimate for 2100 by Mori et al.[19]) and even if the low mean of the modeling predictions is considered, the effects will be severe, as ~97% of the beaches will lose >20%, some ~48% will lose > 50% of their width, while few beaches will be entirely lost/inundated. According to the high mean of the ensemble predictions (Fig.5b), the effects will be detrimental, as all the tested beaches will lose > 50% of their width, and about the ~94% will be entirely lost/inundated. This scenario could be catastrophic for the East Cretan coast since almost all beaches showed negative final widths in Fig. 5b. Finally, it is worth mentioning that the beach erosion predicted by the present analysis is likely to be an underestimation, as other significant beach erosion factors have not been considered, as for example human-induced decreases in coastal sediment supply (e.g. [25]).

Detailed study to specific beaches

The analysis of the beach retreat estimation in the 2 touristic beaches of high economic value was based on the application of the 5 models of the ensemble using the specific values of the predominant environmental conditions. The initial profiles and the sediment grain-sizes used were obtain by in situ measurements during the field campaigns. The process-response models (Leont'yev and SBEACH) have been applied first to the topographic profiles, with wave regime and sediment grain-size being the only forcing factors. The resulting profiles were then used as initial profiles during the application of the same models for successive sea level rise scenarios (0.26, 0.82 and 1.86 m). The resulted beach retreat projections are shown in Table 2, and the resulted beach profiles are depicted in Fig. 6 .

Table 2. Shoreline retreats for 1 topographic profile of Ammoudara and 1of Koutsounari, under 3 SLR scenarios, given by the 5 models of the ensemble. The mean values of the 5 models are also shown.

SLR scenarios (m)	**Beach retreat (m)**					
	Leont'yev	**SBEACH**	**Edelman**	**Bruun**	**Dean**	**Mean**
			AMMOYDARA			
0.26	3.2	2.4	7.5	7.2	10.4	6.1
0.82	8.8	5.3	23.7	22.6	26.6	17.4
1.86	19.4	14.5	55.0	52.5	57.9	39.9
			KOUTSOUNARI			
0.26	6.4	4.3	1.9	2.3	2.3	3.4
0.82	14.8	13.6	5.9	7.3	6.3	9.6
1.86	32.8	30.0	13.6	16.9	14.0	21.5

For the case of Ammoudara beach, the north wave conditions used (H=1.4 m, T=5.3 sec), and for the case of Koutsounari the south wave conditions (H=1.05 m, T=4.8 sec). Both models showed that sea level rise induces significant beach retreat/inundation, accompanied by significant morphological changes with sediment been eroded from the upper shoreface and deposited on the lower shoreface. The Leont'yev model showed significant profile changes in the breaking and surf zone and also the creation of bars at the depth of ~1.5 m (Fig. 6). The profile changes extend to a distance of 70-80 m from the coastline, in the case of Ammoudara beach and to a distance of ~40 m, in the case of Koutsounari beach. The morphological changes resulted by SBEACH model extend to a distance of ~50 m from the coastline, in the case of Ammoudara beach and to a distance of ~35 m, in the case of Koutsounari beach (Fig. 6).

With regard to the shoreline retreat projections the analytical/parametric models suggest significant values of beach retreat for the 3 examined SLR scenarios in the case of Ammoudara beach, being less significant in the case of Koutsounari beach, while the numerical/process-response models displayed an opposite behavior (Table 2). This is the result of the different sensitivity of the models to the controlling factors (beach morphology, wave regime, grain- size). As the maximum width of Koutsounari beach is about 75 m, in the case of a sea level rise scenario of 1.86 m the impact will be significant, as 28% of its width will be lost ((according with the mean of the 5 models (Table 2)). The impact will be much worse in the case of the Ammoudara beach (maximum width about 60 m) and in the case of the worst sea level rise scenario of 1.86 (according with the mean of the 5 models (Table 2)) as about the 67% of its maximum width will be lost. Moreover, beach sections with width < 8 m will be totally lost/inundated, with catastrophic consequences to the human infrastructure/activities that they front.

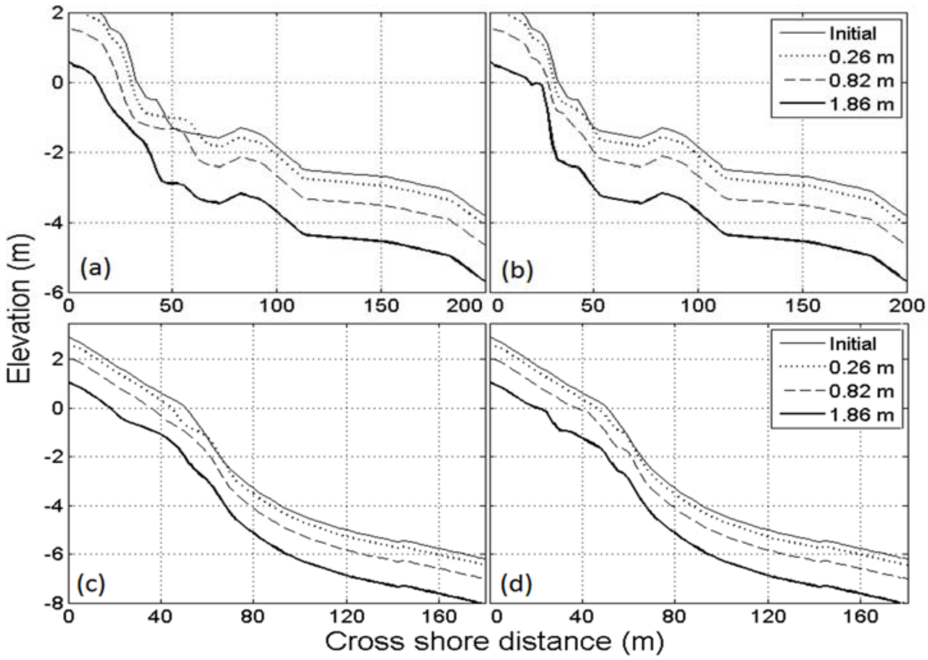

Fig. 6: Beach profile evolution along 1 transect in Ammoudara (a and b) and 1 in Koutsounari (c and d) under 3 SLR scenarios (0.26, 0.82, 1.86 m), given by Leont'yev (a and c) and SBEACH (b and d) models.

Conclusions

The analysis showed that sea level rise induces significant beach retreats/inundations and in the case of the numerical models they are accompanied by significant morphological changes of the profiles in most cases. The ensemble modeling showed that sea level rises of 0.82 (i.e. the high IPCC estimates for the average sea level rise expected for 2100) and 1.86 m (the high estimate by an alternative approach) will result in beach retreats of 6.2 – 28.2 m and 14.8 – 61.3 m respectively.

The application of the beach retreat projections by the ensemble modeling to beach widths shows that sea level rise may have highly significant impacts on the Eastern Cretan beaches, since they are characterized by generally small widths (69% of the beaches are showing widths between 20 and 50 m). Projections suggest that, based on the high IPCC estimate of 0.82 m sea level rise by 2100, effects will be severe, as 54-100% of the beaches will lose as much as 20% of their width, ~93% will lose >50%, while ~41% of the beaches will be entirely lost/inundated. If the prediction of 1.86 m sea level rise by 2100 is adopted, the results of the present analysis suggest detrimental impacts on Eastern Cretan beaches, as all the beaches will lose >50% of their width that leads to a complete loss of the ~94% of them. It is worth mentioning, that these results could be worse if other effects are taken into account such as the reduction of fluvial sediment influxes due to construction of dams and poorly-designed coastal infrastructure/protection schemes.

Beach dynamic predictions under a changing climate (due to mean sea level rise and extreme events) are essential for the development of effective, science-based coastal management plans. Nevertheless, while the approach adopted in the present study cannot replace detailed studies focusing on specific beaches, it can provide a rapid assessment of the beach retreat/inundation due to sea level rise and identify 'hot spots' of erosion.

Acknowledgements

The study is supported by the project “Cooperation 2007-2013” (09SYN- 31-711 “AKTAIA”) of the Operational Program "Competitiveness and Entrepreneurship” co-funded by the European Regional Development Fund (ERDF) and the General Secretariat for Research and Technology (Hellenic Ministry of Education). Some co-authors are also 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. Investing in knowledge society through the European Social Fund.

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