RECENT AND FUTURE TRENDS OF BEACH ZONE EVOLUTION IN RELATION TO ITS PHYSICAL CHARACTERISTICS: THE CASE OF THE ALMIROS BAY (ISLAND OF CRETE, SOUTH AEGEAN SEA)

PETRAKIS S.[1, *]
ALEXANDRAKIS G.[1, 2]
POULOS S.[1]

[1]Department of Geography & Climatology
Faculty of Geology & Geoenvironment
National & Kapodistrian University of Athens
Panepistimioupolis – Zografou, 15784, Greece
[2]Institute of Applied & Computational Mathematics
Foundation for Research and Technology, Hellas, N. Plastira
100, Vassilika Vouton, 70013 Heraklion, Crete, Greece

ABSTRACT

The present study investigates recent and future evolution of the beach zone of Almiros Bay, one of the most touristic developed beaches of north Crete, in relation to its morphodynamic setting and the anticipated sea level rise. The beach zone is exposed to northerly winds, with maximum wave heights and periods of 4.3 m and 9 s, respectively.

The comparison of the aerial photographs (1982-1996) and a satellite image of 2007 have revealed an extended retreat of the beach zone, with its highest retreating rates (i.e. 0.6-0.8 m y^{-1} for the last 25 years) found at its central part. Moreover, an estimation of the future shoreline retreat, due to the anticipated sea level rise (i.e. 0.38 or 1 m for the year 2100), has shown that there is a potential coastal zone loss from 48% up to 100%, respectively. A gross evaluation of the economical impact due to the aforementioned beach loss accounts to approximately from $ 270,000 up to $ 720.000, annually.

KEYWORDS: shoreline retreat, N. Crete, erosion, land loss, touristic beaches.

INTRODUCTION

Tourism plays a very important role in the social and economical development of Greece, as it has been ranked as one of the top 20 touristic destinations, globally. This highlights the significance of the preservation of the Greek beach zones, where the international visitors seek the traditional "sun, sea and sand" package vacations (Anastassopoulos *et al.*, 2009). Crete, in particular, has a large economical profit from tourism and is interested in maintaining this wealth-source for the prosperity of the local and national population. Coastal erosion and especially beach erosion, is obviously a threat for the local and national economy; usually, it can be caused by a combination of factors, natural and anthropogenic, resulting in two types of hazards: (a) loss of land and/or distraction/degradation of the coastal environment, with economic consequences; and (b) the undermining of coastal infrastructure.

Coastal erosion is defined as the long term loss of the shore material relatively to a fixed reference line (baseline). It is a very complex natural phenomenon, caused by a variety of natural processes that change in space and time. The main characteristics of the beach zone that control coastal erosion are: (i) the beach and coastal zone slope, (ii) the lithology, (iii) the nearshore wave regime, (iv) the frequency of storm events, and (v) the anthropogenic interventions (Pranzini and Rossi, 1995; Khalil, 1997; Berriolo *et al.*, 2001; Medina and Lopez, 1997). Moreover, according to the moderate scenario A1B of IPCC (2007), a mean sea-level rise of 0.38 m for the year 2100 has been predicted, while other scientists (e.g. Rahmstorf, 2007; Pfeffer *et al.,* 2008), have predicted a SLR of

more than 1 m. Such rates will cause a significant retreat in the majority of the coastlines and particularly in beach zones that are exposed to high wave energy.

Costanza *et al.* (1997) have tried to convert "land-loss" to "money-loss", by estimating the financial value of ecosystem services worldwide. They have concluded that considering only the coastal environments, the annual Total Global Flow Value is about $ 12.6x10^{13}, with an average estimation of $ 4x10^{3} for every coastal hectare (10^4 m^2), being also the most significant coastal ecosystems. According to these estimates, each Greek coastal hectare accounts on an annual basis of about $ 9-10,000 (in prices of 1997).

Cretan coast is under extended erosion, as its 65.8% of coastline is retreating, when the average percent of the total coastline length of Greece is about 30% (EUROSION, 2001); this large percentage of eroding coastline of Crete is related to its extended presence of beach zones. Alexandrakis *et al.* (2006) have shown that the northern coast of Crete, in all of its length, presents the highest vulnerability to erosion, in comparison to other coastal areas of Greece. Thus, for the Cretan and national welfare, very important measures have to be taken in order to mitigate the impact of beach erosion, due to the anticipated SLR caused by climate change.

The present research concerns recent and future trends of shoreline evolution, based on anticipated SLR, in the case of the Almiros Bay tourist beach (see Figure 1), which is exposed to medium to high wave energy, is characterized by the mouths of four small rivers (or ephemeral streams) and is under intensive touristic development.

STUDY AREA

Almiros Bay is located at the western part of the northern coast of Crete, with a coastline length of approximately 9.5 km. It includes a sandy beach zone associated with a low relief dune field, in front of an alluvial (Holocene in age) plain, consisted by alluvial, marl and riverine deposits; the latter is an agricultural field with vineyards, olive trees and graze land. In the Almiros bay four rivers debouch, Almiros (160 km^2), Delfinas (39 km^2), Mouselas (51 km^2) and Petres (140 km^2), together with four smaller torrents (Fig. 1). Furthermore, the hinterland area to the west of river Mouselas is included in the Natura_2000 network (site-code: GR4340010*), which is categorized in *"Special Protection Areas (SPA), for Sites Eligible for identification as sites of community importance (SCI) and for Special Areas of Conservation (SAC)".* Within this framework and according to results of the Life project, (*LIFE04NAT/GR/000105*) this area has been recognized to be most vulnerable to: (i) construction of seasonal residencies, (ii) construction of new touristic facilities, (iii) extension of arable ground, (iv) extensive irrigation, (v) hunting, (vi) grazing and (vii) waste from oil-industry.
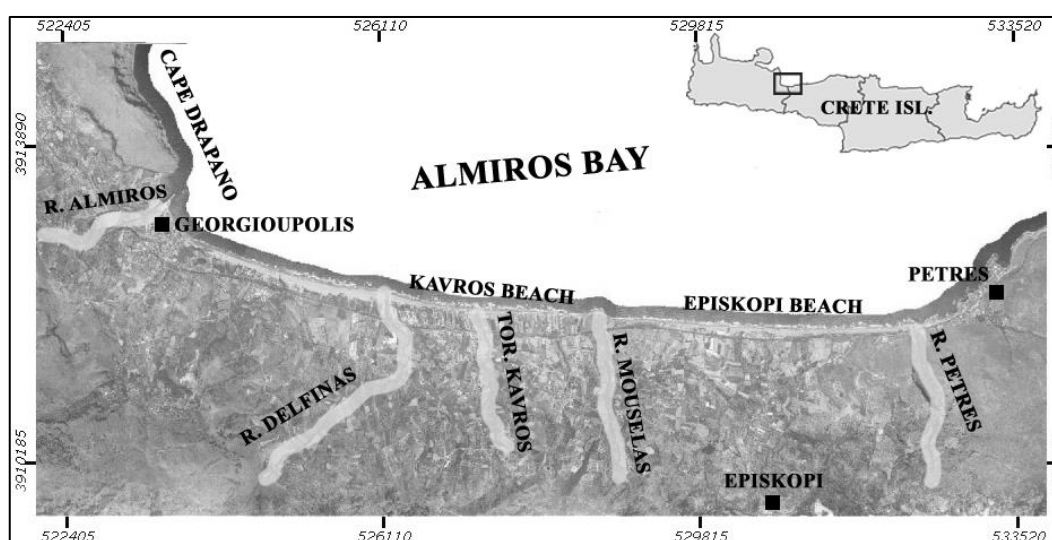

Figure 1. Map of the Almiros beach zone
(background picture obtained from Ktimatologio S.A, 2007)

The Almiros Bay includes the beach zones of Georgioupolis (western sector), Kavros (central sector) and Episkopi (eastern sector) (Figure 1), with Georgioupolis and Kavros beach zones to be more

tourist developed with large hotels, beach facilities, parking lots etc, compared to the Episkopi beach zone.

The Almiros Bay is exposed to northerly winds (NW, N and NE), with NW winds being the most frequent, with an annual frequency of occurrence of 25.5%. However, the small fetch distances of the NW wind-induced waves (7.7 km), due to the presence of cape Drapano, are related to offshore waves with significant heights of <1 m and periods of <3.5 s. On the contrary, N winds, with an annual frequency of occurrence of 14.4%, and a fetch of 176.5 km, generate waves with significant heights and periods that can reach the 4.3 m and 9 s, respectively. NE waves, even though they are generated over the biggest fetch distance (208 km), due to their small frequency of occurrence (only 3.0%), have significant wave heights and periods of up to 2 m and 7.2 s (Soukissian *et al.*, 2007).

In Table 1, the main characteristics of the incoming offshore waves are presented, together with their characteristics in the nearshore zone (after Alexandrakis *et al.*, 2011). According to wave run-up ability and the closure depth values, the beach zone of the Almiros Bay seems to be extending landwards, to elevations of ~2.5 m and seawards to water depths of about 10 m. The beach zone undergoes small astronomical tidal ranges (<20 cm) (Tsimplis, 1994), although sea surface can rise sporadically, mostly due to storm surge, that can exceed 0.5 m; as deduced by sea level measurements in the ports of Souda (western Crete) and Heraklion (central Crete) (HHS, 2004).

Table 1. Wave regime of the beach zone (Fetch$_{max}$=176.5 km); most frequent (MF) and maximum (MAX) are presented for: wind speed (Ua); wave period (T_p); significant height (H_s); closure depth (h_c); breaking height (H_b); breaking depth (h_b) and run-up (R)

	Wind	Ua (m s^{-1})	freq (%)	T_p (m)	H_s (m)	h_c (m)	H_b (m)	d_b (m)	R (m)
	N	8.32		6.76	1.79	4.07	2.11	2.29	2.47
MF	NE	3.32		5.27	0.77	1.76	0.98	0.99	0.57
	NW	6.64		2.23	0.30	0.68	0.32	0.38	0.38
	N	19.85	0.20	9.01	4.26	9.70	4.75	5.47	3.8
MAX	NE	8.46	0.10	7.18	1.97	4.49	2.34	2.53	0.94
	NW	19.85	0.10	3.21	0.89	2.03	0.90	1.14	0.59

DATA COLLECTION AND METHODOLOGY

For the morphological mapping of the study areas, topographic maps (1:5000, published by the Hellenic Army Geographical Service (H.A.G.S.)), geological maps of the study areas (scale 1:50.000, published in 1989, by the Institute of Geological and Mineral Exploration (IGME)) and an aerial photograph of 2007 (source: KTIMATOLGIO S.A.) were used. The morphological measurements included 8 descriptive shore-normal profiles along the beach zone, which extended from the sand dunes to the depth of ~5 m. Beach elevations and slopes were measured with the use of a laser distance meter and a GPS device, whilst depth soundings (at distances of every 5 m) were taken with the use of a portable echo-sounder (accuracy ±3 cm), up to a water depth of about 5 m.

In order to investigate recent coastline evolution, the latter was divided into 6 sections according to its orientation and geomorphological characteristics (Figure 4). Subsequently, coastline spatial changes were identified with the comparison of air-photographs of the years 1982 and 1996 and a Satellite Image from 2007. The air-photographs and satellite image were corrected geometrically, and the maximum total error (from coastline definition and digitizing) was estimated to be ±2m.
The future coastline retreat (R$_\infty$), due to the anticipated SLR and incorporating the effect of storm surge, has been estimated utilizing the Dean's (1991) (1) and Kriebel & Dean's (1993) (2) semi-empirical equations:

$$R_\infty = (S + 0.068 H_b) \cdot (\frac{W_b}{B + h_b})$$ (1)

$$R_{\infty} = S \cfrac{W_b - \cfrac{H_b}{m_o}}{h_b + B - \cfrac{S}{2}}$$

(2)

where: S is the relative mean SLR (in m); W_b is surf zone length, i.e the horizontal distance from wave breaking zone to shoreline; m_o is the slope of beach profile at the coastline; H_b is wave breaking height; h_b is wave breaking depth; and B is the subaerial berm height.

RESULTS-DISCUSSION

The subaerial part of the Almiros beach zone can be generally divided into three sectors, with respect to the presence of the torrents' mouths. The western part (sector 1) includes the area between Almiros and Delfinas torrents. In this sector, the beach zone presents its largest width (~80 m). The central part (sector 2) includes the area between Delfinas and Mousselas torrents; with a beach zone width less than 50 m. The eastern part (sector 3) includes the area between Mousselas and Petres torrents, having a beach width of approximately 60 m. As shown in figure 2, the majority of the beach zone granulometry, according to Folk (1980), is characterized as sand and gravelly sand, except for the central part of the study area (profiles III-VI), where the beach sediment is coarser and is characterized as gravel and sandy gravel.

The inshore zone is characterized by the presence of underwater welded (crescentic) sandy bars (Figure 3), which are extending to water depths of 2-2.5 m, in a horizontal distance of ~100 m from the coastline. This shape of underwater bars usually occurs at unprotected coasts to incoming waves, with an inshore zone of very small slopes (Carter, 1988), such as that of the Almiros bay, while absolute crescentic in-shape bars are formed under high wave energy. Furthermore, this type of sandy inshore formations relates to sediment recycling between the breaking zone and the crest of the lowest subaerial berm.

The surficial sediment of Sector 1 (profiles I & II) is mainly sandy (S), except on the crest of the berm, where it becomes coarser, being gravelly sand (gS). The surficial sediments of the subaqueous beach zone are characterized as slightly gravelly Sand ((g)S), up to the depth of ~4 m. The slope of the beach zone is generally smooth (~2%), while at the beach face the slope is approximately 5%. At water depths of ~1.5 m and ~2.5 m (corresponding distances from the coastline 60-80 m and ~200 m), troughs followed by a bar of ~0.5 m high are observed. Due to the fact that these bars are present in all 8 profiles, it is considered that their formation is related to the presence of the above described alongshore welded bars. Furthermore, the trough-bar system, which is closer to the coastline, is formed by the most frequent incoming waves, while the trough-bar system at the water depth of 2.5 m, is formed by the highest (and less frequent) waves (for details see Table 1).

In sector 2 (profiles III & IV), the subaerial part of the beach zone has a width of ~40 m, with a smooth slope of about ~2% towards the sea. Sediments are generally coarser grained, i.e. sandy gravel (sG) in relation to the other two sectors. The beach face has an increased slope of 6-7% consisted by gravelly sand and sandy gravel. The subaqueous surficial sediments are characterized as sand (S) and slightly gravelly sand ((g)S). The subaqueous beach zone slope at the first 80 m varies from ~1% (profile III) to ~3% (profile IV). Deeper within and for the next 20 m, the slope increases to 3.5% (corresponding distances from the coastline ~100 m) and then flattens until the depth of ~3 m, where the permanent bar exists. At the end of sector 2, the width of the subaerial beach zone reaches its smallest width (<20 m).

Sector 3 (profiles V-VIII) has a subaerial width of about 40 m, consisted by sand (S) and slightly gravelly sand ((g)S). The subaerial slope of the beach is ~3%, while the slope of the beach face is ~7%; the latter consists of relatively coarser material, i.e. sandy gravel (sG) – gravel (G). Subaqueous slopes are in the order of 1-3% and the surficial sediments are characterized as slightly gravelly sandy ((g)S) to sandy (S). There is a trough-bar formation in a 10-15 m distance from the shoreline, with an elevation of 0.5 m, while a second trough-bar appears in various distances from the coastline, being slightly smaller than the first one.
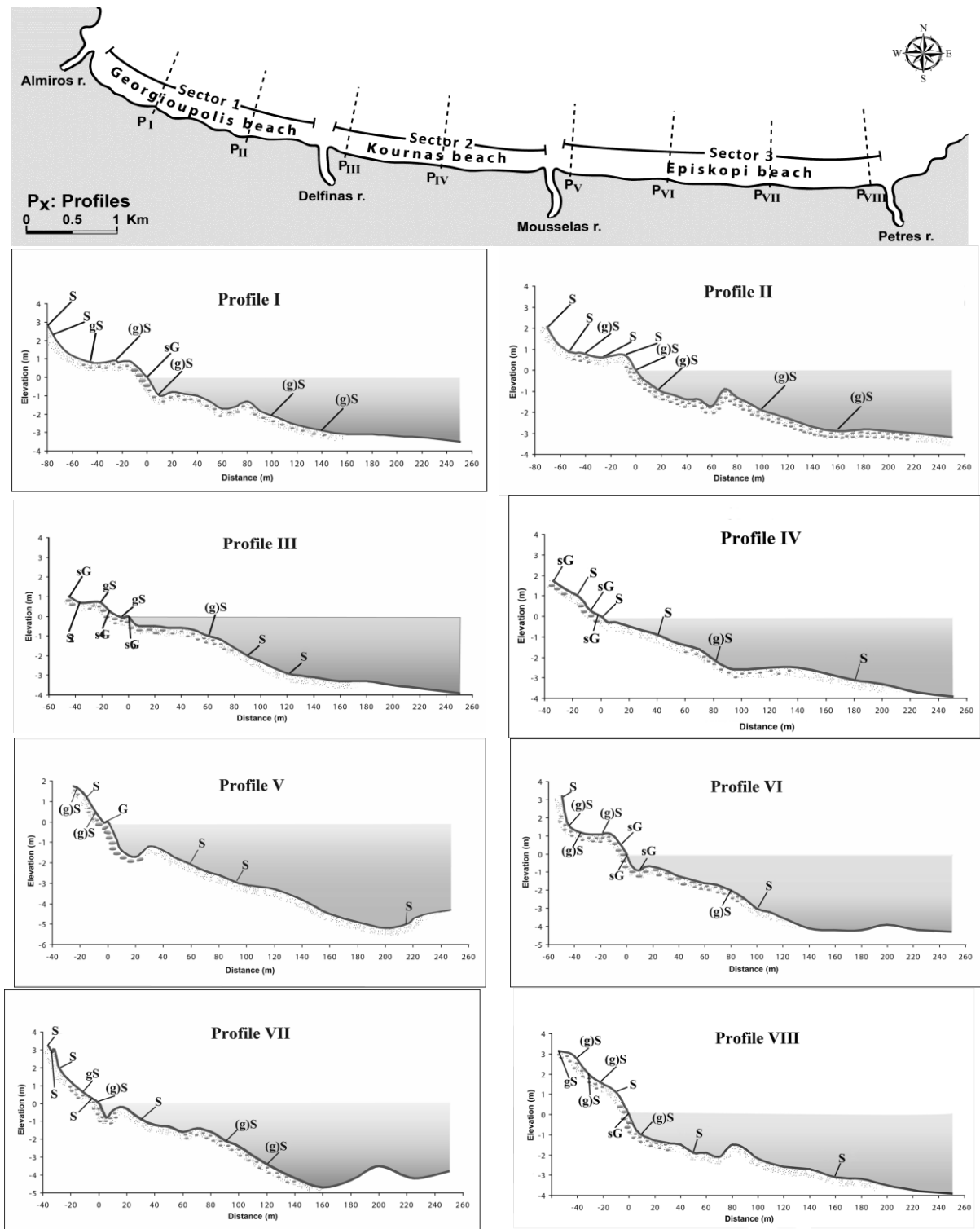
Figure 2: Current morphology and granulometry along the eight normal profiles
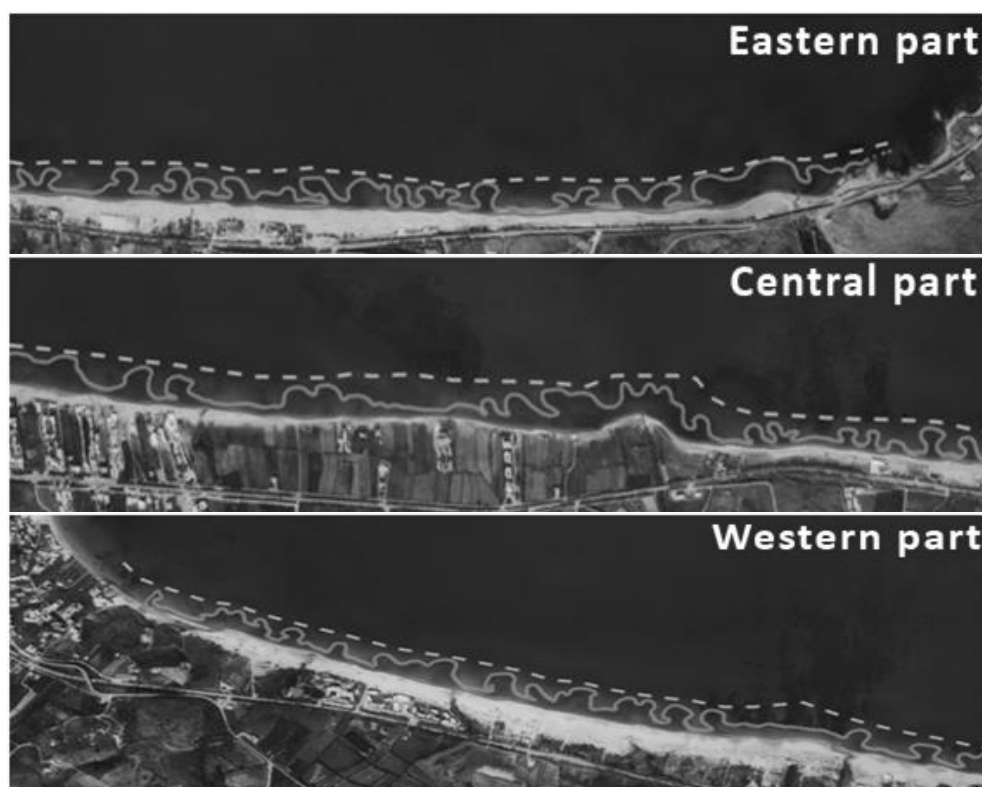of Almiros shoreline face

Figure 3. Inshore zone and underwater bars morphology along the three sectors
of the Almiros Beach zone

Recent shoreline evolution

The comparison of shoreline position in 1982, 1996 & 2007 shows that the Almiros beach zone is characterized by a mixed picture, considering the achieved accuracy of ±2 m, with areas rather stable and areas with variable rates of shoreline retreat (Figure 4 – Table 2). More specifically, in section (a) the measured retreat is about 15±2 m that corresponds to an annual rate of retreat, equal to 0.6 m yr^{-1}. The shoreline displacement in sections (b) and (c) are within the limit of accuracy (±2 m) and, therefore, they may be considered as rather stable. This can be explained from the fact that the western part of the Almiros Bay is semi-protected by the prevailing NW winds and the induced by them waves and nearshore currents. Section (d) presents the highest shoreline retreat, in the order of 15-20 m that corresponds to an annual rate of 0.6-0.8 m y[-1]. In section (e), as in sections (d) and (c), there is no significant shoreline change. In the eastern section (f), shoreline retreat accounts for 7-8 m, with annual rate of 0.3 m yr^{-1}.

Table 2. Decadal & annual rates of coastline retreat for each section of the Almiros Bay

Section	Total Retreat[1] (m)	Area of beach loss[2] (km²)	Annual rate of retreat for the period 1982-2007 (m yr^{-1})
a	15	0.045	0.6
b	-	-	-
c	-	-	-
d	15 – 20	0.05 – 0.06	0.6 – 0.8
e	-	-	-
f	7 – 8	0.08	0.28 – 0.32

([1]): accuracy of coastline retreat equals to ±2 m
([2]): accuracy of the estimated lost area equals to ±0.05 km².

Expected shoreline retreat due to future sea level rise

Estimations of the Almiros bay shoreline retreat due to the anticipated SLR, including the effect of storm waves were computed for two scenarios of SLR, referred to the year 2100: the A1B scenario

of IPCC (2007) that predicts SLR=0.38 cm; and the scenario of SLR=1 m, according to Pfeffer *et al.* (2008). On the basis of these estimations, shoreline retreat of the Almiros Bay ranges from 26.5 m up to 33.3 m. Exception to this is the eastern part of the beach zone (profile VIII), in which the maximum estimated retreat can reach up to 63 m. These values, considering the morphological characteristics of the beach zone, can lead to a mean land loss of 37.5% in Sec. 1, 66.7% in Sec. 2 and 50% in Sec. 3 (Table 3).

Table 3. Estimate of shoreline retreat (R_∞, in m) for the 8 profiles and corresponding area loss (A, in km^2) of the Almiros Bay, in response to future sea level rise (SLR) of 0.38 m and 1 m (for profile and sector locations, see Figure 2)

Sectors (Area)	Profiles	SLR=0.38 m				SLR=1 m			
		R_∞ (m) Dean, 1991)	R_∞ (m) (Kriebel & Dean,1993)	Estimated area loss (km^2)	%	R_∞ (m) (Dean, 1991)	R_∞ (m) (Kriebel & Dean,1993)	Estimated area loss (km^2)	%
1 (0.25 km^2)	I	31.7	28.3	0.09	37,5	87.2	77.9	0.245	100
	II	31.3	30.7			86.1	84.5		
2 (0.11 km^2)	III	31.1	27.6	0.075	66,7	85.5	75.8	0.2	100
	IV	33.3	31.4			91.6	86.2		
3 (0.21 km^2)	V	30.5	28.4	0.11	50	83.9	78.02	0.28	100
	VI	28.3	30.1			77.8	82.7		
	VII	30.8	26.5			84.7	72.9		
	VIII	28.6	63.0			78.7	173.2		
Total				**0.27**	**48**			**0.72**	**100**

According to Table 3, the anticipated retreat due to a SLR of 0.38 m will cause the loss of 0.27 km^2, which corresponds to 48% of the present subaerial beach zone area, while the 1 m SLR will result to losing a great percentage of the Almiros beach zone. Those estimations are extremely important for the local community, since its economy depends on the exploitation of the coastal zone, including its beach zone; thus, socio-economic activity is primarily based on touristic facilities (e.g. hotels, bungalows, taverns, bars etc.) and, secondarily, on agriculture. Moreover, according to Costanza *et al.*'s (1997) study, a 0.27 km^2 land loss of coastal area corresponds to a potential economical loss of income of $ 270,000 annually, whereas the loss of the total coastal area will raise the cost to $ 720,000 annually; these estimates do not take into consideration the environmental degradation of the area due to beach loss.

CONCLUSIONS

The beach zone of the Almiros bay has a shoreline length of about 9 km and a width that ranges from a few meters up to 80 m. Its subaerial part consists, generally, of sand (S) and locally of gravelly sand (gS) and sandy gravel (sG). Its morphology is characterized by subaerial slopes of ~2%, with its beach face being steeper (up to ~7%). The subaqueous part is smoother with slopes of ~2%. Two major trough-bar formations are observed, at water depths of 60-80 m and 200 m, which are related to the most frequent (H_s=1.79 m T_p=6.76 s) and maximum (H_s=4.26 m T_p=9.01 s) wave conditions, respectively. These formations of the inshore zone are associated with the presence of the almost crescentic welded bars, whose formation is related to nearshore hydrodynamics induced by the wave activity.

During the past 25 years, the eastern and central part of the Almiros bay has presented a retreat of up to 15 m, while its western part seems to be rather stable, as it is protected by the prevailing NW winds and associated wind-generated waves and the induced by them nearshore currents.
Estimates for future shoreline retreat, due to anticipated SLR, provide values of 30 m for SLR=0.38 m and approximately 80 m for SLR=1 m; the former corresponds to a loss of the 48% of the present beach (subaerial) area, while the latter to a loss of a great percentage of the existing beach. The aforementioned beach zone losses correspond to an annual economic damage of $ 270,000 and $ 720,000, respectively.
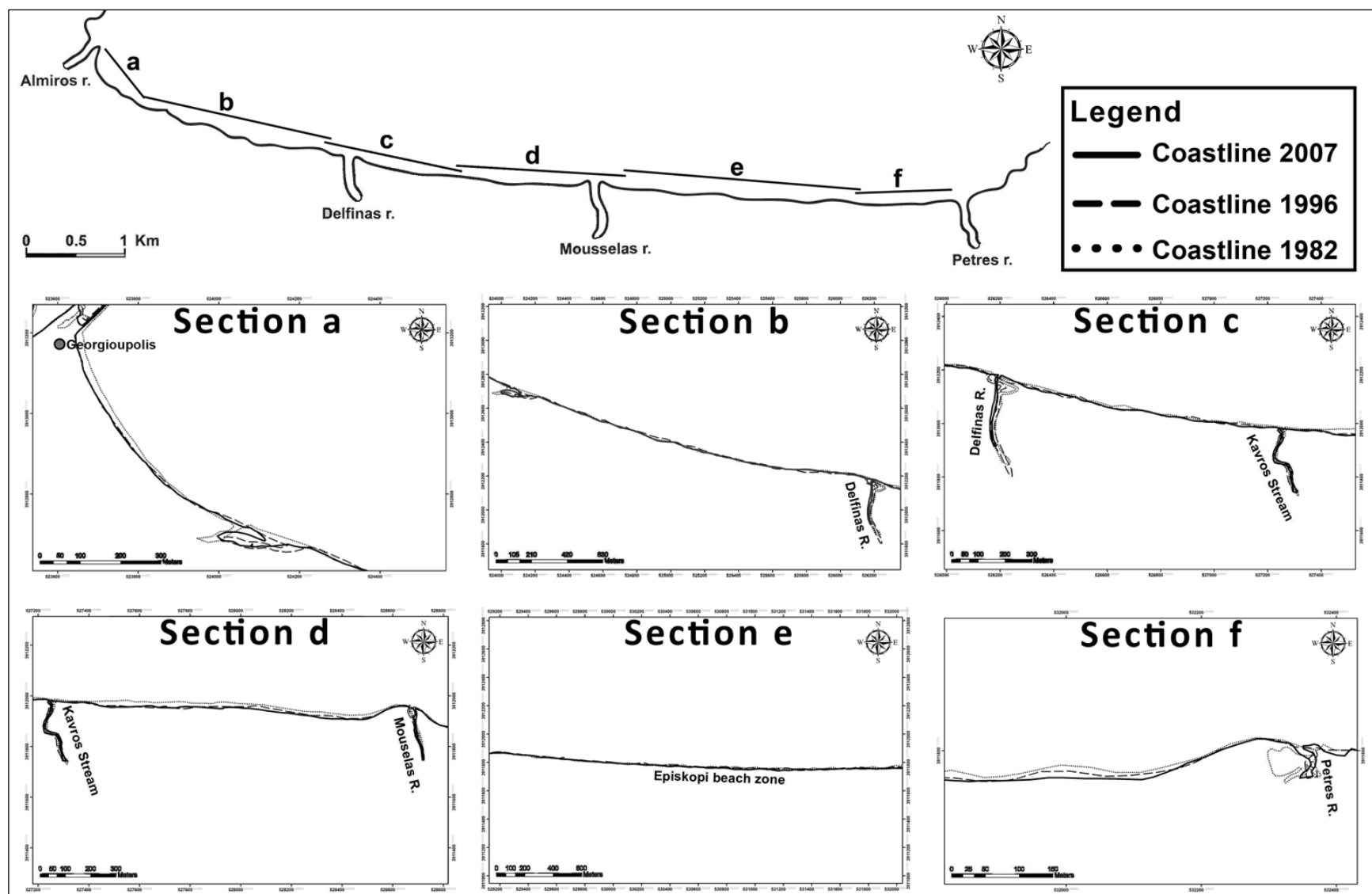
Figure 4. Recent coastline evolution along the six sections (a, b, c, d, e and f) of the Almiros Bay

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