Processes affecting recent and future evolution of the Xylokastro beach zone (Gulf of Corinth, Greece)

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ABSTRACT

The aim of the present study is to investigate the morphodynamic regime of the coastal area of Xylokastro (north coast of Peloponnese), in order to identify and evaluate the processes controlling its formation and evolution. Within this concept, the following factors have been considered and evaluated: near-shore morphometry and granulometry along shore-normal profiles, the direction and potential volumes of long- and cross-shore, induced by the incoming offshore waves, the decadal and future trends of coastline displacement, the available information for terrestrial sediment influx and the geological processes operating in the broader coastal region of Xylokastro (i.e. subaqueous slides) and the human interference. On the basis of these results, the formation and evolution of this coastal stretch seems to be governed primarily by the neotectonic activity and the relative change of sea level rise, and secondarily by the wave-induced near-shore sediment transport; the role of the latter could be enhanced substantially by the human intervention (i.e. construction of marina, seafront walls). Moreover, the expected eustatic increase in sea level by the year 2100, could cause a coastline retreat up to 9 m (SLR=0.38 m) or >19 m (SLR≥1 m).

KEYWORDS: wave regime, coastline changes, erosion, nearshore sediment transport

INTRODUCTION

Coastal zone formation and evolution of the beach zone, which is among the most sensitive coastal environments, is controlled by the interaction of physical factors (e.g. morphodynamics, relative sea level change, terrestrial sediment influx) and the anthropogenic intervention, either direct (e.g. waterfront engineering), or indirect (e.g. regulation of river basin). Beach erosion, is already a major global problem (e.g. CAI et al., 2009), and can be differentiated into: (i) long-term erosion, i.e. irreversible retreat of the shoreline position due to mean sea level rise and/or negative coastal sedimentary budgets (e.g. DAN et al., 2009); and (ii) short-term erosion, caused by storms, which may or may not result in permanent shoreline retreats, but could nevertheless be devastating (e.g. FRITZ et al., 2010).

Moreover, within the context of climate change, the projected mean sea level rise (e.g. RAHMSTORF, 2007) will likely exacerbate the already significant beach erosion and severely impact coastal populations, activities, infrastructure and assets (e.g. McGRANAHAN et al., 2007).

The beach zone under investigation is subjected to erosion (extensive locally), although it is exposed to low wave energy, being located at the south coast of the semi-enclosed Gulf of Corinth. It has also to be mentioned that there are not many studies worldwide on semi-enclosed low wave energy environments (e.g. RYU, 2003), since most cases concern open sea coasts and/or highly energetic coastal environments. Studies referred exclusively to the Mediterranean Sea are those of FRIHY & LOTFY (1997), PERLIN and KIT (1999), MENDOZA and JIMENEZ (2006), ZVIELY et al. (2007), SÁNCHEZ-ARCILLA et al. (2008). Additionally, the coastal zone under investigation is influenced also by intensive seismotectonic activity, as it belongs to the south flank of the tectonic graben of the Gulf of Corinth (i.e. North Peloponnese) that is subdued to a tectonic uplift of about 1mm/year during Quaternary (DOUTSOS et al., 1988; ARMIJO et al., 1996; McNEIL & COLLIER, 2004).
The aim of this study is to investigate and link both the physical processes and the impact of the human interference that govern the formation and evolution of the coastal front of Xylokastro town, with emphasis on the present and future shoreline position.

STUDY AREA
The study area is located in the central part of North Peloponnese and includes the sea front of Xylokastro town (fig. 1), extending 5 km in length. The beach zone is the seaward limit of a low-lying alluvial plain, whose central part incorporates the deltaic alluvial cone of Sithas River. The latter provides some 0.17×10^6 t of sediment (after GOURDOUBAS ET AL, 2010), annually. The overall subaqueous morphology reveals a rather narrow and steep shelf, even in front of mouth area of Sithas river. This is due normal faults almost parallel to the present coastline, which contributes to the ongoing widening of the Corinth Gulf rift (BRIOLE et al., 2000, VASSILAKIS et al., 2011). Moreover, the associated seismic activity causes sediment instability in the shelf and slope areas of the Gulf (e.g. LYKOUSIS 1991; PAPATHEODOROU and FERENTINOS 1997; HASIOTIS et al. 2002). Besides, a series of human interventions have been also affecting its sediment budget directly (i.e. breakwaters, seafront wall, ports) and/or indirectly (i.e. river flow regulation).

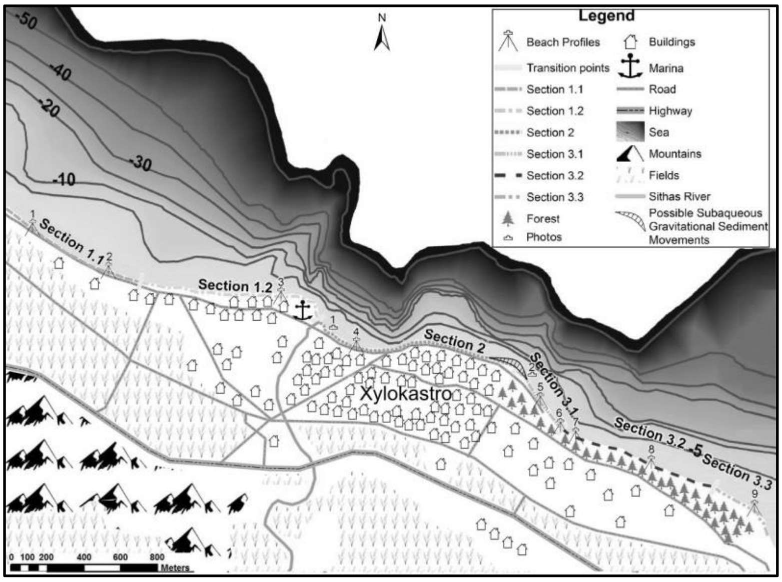

Figure. 1: The beach zone of Xylokastro coast (Gulf of Corinth).

From the oceanographic point of view, the study area, as part of the Gulf of Corinth, is characterized as micro-tidal, concerning the astronomical tide, since its contribution to the change of sea lever is very small (i.e. <20cm, TSIMPLIS (1994)). On the contrary, due to the closed morphology of the gulf, under the effect of the wind (especially the westerly),

the sea level change might rise >1m, according to the Poseidonia tidal gauge (HNHS, 2005). Wave energy is expected to be low due to limited fetch distances (<42 km).
For the needs of the present investigation, the study area is divided into three main sections (see fig. 1): The western section (1), where the beach zone is rather narrow and sparsely populated; the central section (2), which is strongly affected by the human constructions (i.e. regulation of Sithas River mouth, construction of a tourist marina and a seawall to protect the buildings reaching the coastline); and, the eastern section (3) that "hosts" the Pefkias pine-forest, vegetated on a low relief dune field.

MATERIALS AND METHODS

The morphodynamic measurements, applied to ten shore-normal representative beach profiles (for locations see fig. 1), with the use of a handheld laser distance meter and a portable simple beam echosounder (Hondex PS-7); they extend from the backshore to the water depth of ~5m. Along the 9 profiles, 29 samples (both subaqueous and subaerial) were collected and analysed granulometrically according to FOLK's (1974) procedure. The present position of the shoreline was traced by using differential GPS and real time kinematics procedures (HiperPro, Topcon) of less than 1cm accuracy.
The near-shore wave regime characteristics (i.e., breaking wave height (H_b), depth of breaking (h_b) and breaking angle (a_b)) were calculated with the use of the CEDAS 2.01f, utilizing the available offshore wave characteristics (significant wave height and period) provided by GHIONIS & FERENTINOS (2002). The calculation of potential longshore sediment transport (Q_L) was conducted according to KOMAR's (1998) equation:

$$Q_L = 1.1 \cdot \rho \cdot g^{3/2} \cdot {H_b}^{5/2} \cdot \sin a_b \cdot \cos a_b \qquad (1)$$

where: (ρ) the sea water density (1025 kg/m^3), (g) the gravity acceleration, (H_b) the wave height the moment of breaking and (a_b) the angle of the wave peak line and the isobath at the breaking zone.
Cross-shore sediment transport is provided from the Bailard and Inman's (1981) equation:

$$Q_l = \rho \cdot C_D \cdot u_o^3 \left\{ \frac{\varepsilon_B}{\tan\phi} \left(\psi_1 + \frac{3}{2}\delta_u - \frac{\tan\beta}{\tan\phi} u_3^* \right) + \frac{u_o}{w_s} \varepsilon_s \left[\psi_2 + 4 \cdot \delta_u \cdot u_3^* - \frac{u_o}{w_s} \varepsilon_s \cdot u_5^* \tan\beta \right] \right\} \qquad (2)$$

where, ε_B=0.2; ε_S=0.025; C_D: dragging coefficient; w_s: sediment fall velocity; φ: the angle of repose; β: the beach slope; u_b: near bed water velocity; ρ: water density; and, ρ_s: density of sediment.
The velocity components u_m, u_3^* and u_5^* (in cm/s), the normalized mean onshore current δ_u and the ψ_1 and ψ_2 skewness parameters were estimated from the significant wave height H_s (in cm), using the regression equations provided by BAILARD (1982); thus, δ_u=0.458+0.00157 H_s; u_m = 31.9 +0.403 H_s; u^*_3= 0.548+0.000733; u^*_5= 1.5-0.00346 H_s; Ψ_1=0.303-0.00144 H_s; and Ψ_2= 0.603-0.0051 H_s.
For the direction of the cross-shore sediment transport the HATTORI & KAWAMATA (1980) equation was used:

$$\frac{g \cdot H_o \cdot \tan\beta \cdot T}{L_o \cdot w_s} \begin{cases} < 0.5 & onshore \\ > 0.5 & offshore \end{cases} \qquad (3)$$

The settling velocity for different ranges of grain size (D) is given by Van RIJN's (1992) equations.
The long-term recent coastline changes were identified through the comparison of topographic maps (1:5,000, published during the 1970's by the Hellenic Geographic Military Service), with ortho-photo maps (interpreted air-photographs of 1996), high spatial resolution satellite images (IKONOS-2 acquired during 2000) and the traced coastline by the RTK-DGPS on March 2011. The comparison of the coastlines took place after digitizing them with the use of a Geographic Information System platform (ArcGIS), projecting them in the same projection system which was the HGRS'87.

Finally, future coastline evolution (retreat) due to the anticipated sea level rise (Rc) was calculated by Dean's (1991) semi-empirical equation, which combines sea level and associated storm effect:

$$R_c = (S + 0.068 H_b) \cdot (\frac{W_s}{B + h_b}) \quad (4)$$

where: S is the relative mean sea level rise; W_s (surf zone length) is the horizontal distance from the wave breaking point to the coastline; B is the highest terrestrial berm height; H_b is the wave breaking height; and, h_b is the breaking depth (all in meters).

RESULTS AND DISCUSSION

Beach zone morphology

The western part of the study area is characterised by a rather narrow (<10 m wide) subaerial beach zone, with the exception of the beach on the west side of the harbor due to sediment accumulation resulted from the eastward long-shore sediment transport. In addition, a part of the beach in section 1.2 has been eroded totally; this seems to be associated with the near-shore bathymetry, i.e. the reduced distance between the 5 m isobaths and the coastline that increases the erosive ability of the incoming waves. The subaerial part consists mostly of sand, with relatively coarser material at its beach face. The subaqueous part deepens smoothly to 5 m of water depth (Fig. 2: profiles 1-3), with increasing slopes eastwards, while it is composed of sandy material.

The central part (section 2), extending to the east of the Sithas mouth, is essentially deprived of the subaerial part of the beach zone, being the seafront of Xylokastro town, that has been consolidated (protected) by a seawall. The subaqueous part is rather steep (e.g. profile 4 in figure 2) consisting of mixed material (sand and gravels). The eastern part of the beach zone, under investigation, is the seaward natural extension of the low relief dune field covered by pine trees. It consists of mixed material to a water depth of 2-3 m, whilst its deeper part is covered by Poseidonia meadows, indicating also the stability of the seabed (see profiles 7 and 8 in figure 2). Profile 9 at the east end of the study area is characterized by the lack of fine-grained material and a steep subaqueous profile.

Near-shore hydrodynamics and sediment movement

Wave regime

As shown in table 1, the most frequently observed waves in the studied area develop heights of ~25cm and are induced by NW winds of 2 Beaufort wind force. The maximum wave heights are induced by NW and E winds and are around 2 m in height, although they are observed very rarely. The associated breaking characteristics, produced by the CEDAS software, are given also in table 1.

Near-shore sediment transport

In this study, long-shore and cross-shore sediment transport have been calculated for the potential transport of sediment; thus, these estimates are used as indicative, whilst the emphasis has been placed on their inter-relationship, in terms of quantity and direction, and to their affiliation to long term changes of shoreline position. With respect to the potential long-shore sediment transport (PLST), as it can be seen in Table 2, the NW wind-induced waves have, by far, the most significant contribution in the PLST, moving southeastwards an average sediment volume of approximately 6.5 10^4 m^3/yr. This amount is more than 4.5 times greater than the second in order north PLST, i.e. 1.5 10^4 m^3/yr. The dominance of the long-shore sediment transport, induced by the NW incoming waves, is attributed to their higher frequency of occurrence (46.7%), in relation to the other three wind/wave directions. Overall, in the western part (zones 1 and 2) and in the central region of the eastern part (section 3.2) the PLST is directed eastwards, with annual mean values in the order of 125-150 $10^4 m^3$, whilst in sections 3.1 and 3.3 the PLST is directed to the west, but with much smaller quantities (39 10^4 m^3). The Potential Cross-shore Sediment Transport (PCST) has been calculated at the 9 shore normal profiles, where sediment texture and slopes are known. On the basis of these calculations (Table 3), PCST has an onshore direction in the western section and at the eastern part of the eastern section, with values between 47 and 65 10^3 m^3.

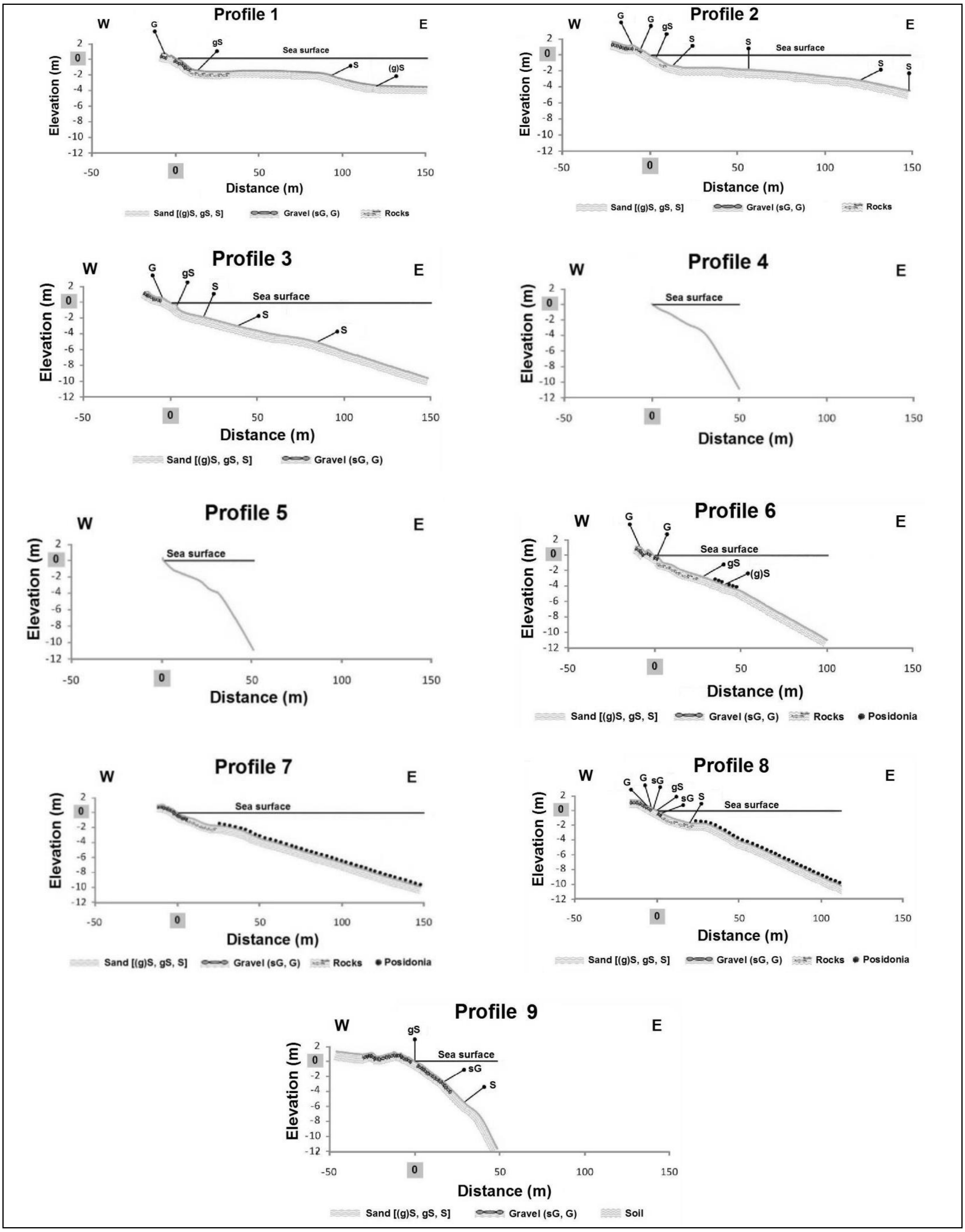

Figure 2: Profiles normal to shoreline, seabed texture and sediment samples of the Xylokastro beach zone (for locations see Fig. 1).

In the central part, the PCST is seawards, with values ranging from 32-39 10^3 m^3 (profiles 4 and 5) to approximately 6 10^4 m^3 (profiles 6 and 7).

Table 1. The offshore significant wave height (H_s), period (T_p), the estimated breaking height (H_b) and depth (d_b), along with the corresponding wind speeds (U_a) and their frequency of occurrence (f) in the case of the most frequent and maximum wind-induced wave conditions (after Ghionis and Ferentinos, 2002).

Wind	*f (%)*	U_a *(m/sec)*	T_p *(s)*	H_s *(m)*	H_b *(m)*	d_b *(m)*
Most frequent conditions						
N	2.16 (3b)	5.93	2.85	0,38	0,45	0.57
NE	0.90 (3b)	5.93	3.04	0.42	0.45	0.58
NW	18.90 (2b)	3.16	2.62	0.25	0.32	0.42
E	0.20 (1b)	1.35	1.12	0.05	0.11	0.14
Maximum conditions						
N	0.03 (5b)	14.76	3.86	0.95	1.02	1.30
NE	0.02 (6b)	20.11	4.57	1.44	1.51	1.94
NW	0.01 (7b)	25.74	5.32	2.04	2.13	2.73
E	0.01 (5b)	14.76	6.14	1.92	2.14	2.74

Table 2. Potential long-shore sediment transport (in 10^3 m^3/yr) induced by the four prevailing wind directions for each section of the Xylokastro beach zone (for section locations see Fig. 1).

	Zone 1 (Section 1.1 & 1.2)	Zone 2	Zone 3			
			Section 3.1	Section 3.2	Section 3.3	Average
NE	-5.19	-3.88	-25.71	-3.68	-22.63	-12
NW	121.34	111.90	2.32	88.62	0.44	65
E	-0.04	-0.05	-0.05	-0.06	-0.03	-0.04
N	32.57	34.66	-15.31	40.05	-16.76	15
Sum	148,68	142,63	-38,75	124,93	-38,98	

Note: Positively signed values indicate an eastward direction of sediment transport

Table 3. Potential cross-shore sediment transport (in 10^3 m^3/yr) estimated at each of the 9 shore-normal profiles (for location see fig. 1) and for the four prevailing wind directions

	Section								
	1.1		**1.2**	**2 (west)**	**3.1(west)**	**3.1 (east)**		**3.2**	**3.3**
Profile:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
N	-2.27	-2.84	-1.97	1.62	1.14	2.19	2.22	2.25	-2.86
NW	-28.08	-34.35	-24.61	21.13	16.34	27.13	27.47	-27.75	-34.58
E	-24.02	-28.39	-21.15	16.29	15.26	-23.07	-23.40	-23.51	-28.76
Total	-54.37	-65.58	-47.73	39.03	32.73	6.25	6.29	-49.01	-66.20

Note: Negative values correspond to onshore sediment movement.

The comparison of long-shore and cross-shore potential annual rates of sediment transport revealed that the dominant role in beach zone evolution plays the PLST, being 2-3 times greater than the corresponding PCST. On the other hand, it is also evident that the onshore PCST is associated with the presence of wider (more developed) parts of the beach zone under investigation. Additionally, the absence of subaerial beach zone in the central part of the Xylokastro beach zone may also be attributed (even partially) to the prevailing offshore PCST, without the role of the various anthropogenic interferences to be ignored.

Shoreline position changes (recent and future)

The maximum rates of the horizontal shoreline displacement along with their average values for the various sections of the investigated coastal zone are presented in table 4. It has to be mentioned that differences in coastline position in the order of a few meters may not depict the reality, being within the accuracy of the applied method.

For the period 1970-1996, the average change in coastline position varies from -23m (retreat) to +10 m (progradation), revealing a mixed state of evolution. On the contrary, for the 1996-2011 time period the entire coastline is subjected to retreat, with average values of up to 14 m. Considering also the total time period (1970-2011), the western part retreats by no more than 8 m, whilst the central part has retreated from 20 to 35 m, whilst the eastern part seems to remain rather stable. Photographs in figures 3 has taken from positions of extended coastline retreat.

The aforementioned observations are in good agreement with both the magnitude and the direction of PLST and PCST; thus, in the western part, a relatively strong PLST undergoes, compensated partially by the onshore PCST.

Table 4. Horizontal distance (in m) of shoreline displacement along the Xylokastro coastal front for different time periods.

		Section					
	Displacement	**1.1**	**1.2**	**2**	**3.1**	**3.2**	**3.3**
1970-1996	Max. Retreat	-18	-6	-37	-40	-	-1
	Max. Advance	+14	+34	+16	+16	+17	+17
	Average change	-4	+10	-20	-23	+10	+5
1996-2011	Max. Retreat	-13	-17	-	-19	-18	-18
	Max Advance	+5	+5	-	-	-	-
	Average change	-3	-14	-	-12	-10	-5
1970-2011	Max. Retreat	-21	-14	-37	-53	-11	-9
	Max. Advance	+7	+38	+16	+8	+10	+14
	Average change	-8	-6	-20	-35	±1	±1

(a) (b) (c)

Figure 3: Photograph from the central part of the study area (a), where the coastline has retreated up to 37m (from 1970 to 1996), the western part of section 3.1 (b) taken in 1992 and in 2011 (c), showing a further retreat of 15-20 m (as indicated by the “loss” of a semi-demolished tennis court).

The central part is dominated either by a strong PLST and/or offshore PCST. Finally, the rather stable eastern part is favored by the onshore PCST and the relatively lower values of the PLST. In addition, the most extended coastline retreat (some 53 m) observed in the section 3.1 is associated also with a coastal subaqueous gravitational sediment movement that took place in the 1970s (Dr G. Ghionis pers. com.). Such gravitational mass movements are usual in the tectonically active Gulf of Corinth (as presented in section 2).

The future coastline retreat, owing to the anticipated sea level rise, is given numerically in Table 5; in these estimates no vertical tectonic displacement has been considered, whilst the central part of the study area has been excluded, as it is artificially stabilized by a concrete seawall. According to the IPCC (2007) moderate scenario of sea level rise (0.38 m) in the next 100 years, the western part retreats up to 10.9 m, when the eastern part up to 4.1 m. If sea level rises by more than a 1 m (e.g. RAHMSTORF, 2007; PFEFFER et al., 2008), then the retreat in the western part will exceed the 23.8 m and the 8.9 m in the eastern part. These values of coastline retreat, for the moderate scenario, are related to a land loss from 25% (section 3) up to 100% (section 1) of the Xylokastro beach zone; these values will become even higher (54-100%) for the worst scenario of sea level rise ≥1 m (Table 5).

Table 5. Estimates of future coastline retreat (Rc) and lost area (LA) at each profile and for each section for a potential sea level rise by the year 2100 of 0.38 m and 1 m.

SLR (m)	Section	Area (km^2)	$\overline{R_c}$ (m)	LA (km^2)	LA (%)
0.38	1.1	11.64	10.9	11.6	100
	1.2	9.13		3.6	39
	3.1, 3.2, 3.3	32.80	4.1	8.2	25
				Sum: 23.41	Aver.: 55
1.0	1.1	11.64	23.8	11.6	100
	1.2	9.13		7,8	85
	3.1, 3.2, 3.3	32.80	8.9	17.8	54
				Sum: 37.2	Aver.: 80

Obviously, the situation described above will have negative economic and possible social impact on the Xylokastro population, as it is almost certain that the infrastructure in the backshore zone will be affected by the accelerated sea level rise, even according to the moderate scenario. On the other hand, the Pefkias pine forest (section 3) that has undergone the mildest anthropogenic interference, carries possibly the greater ability to adapt better to the anticipated sea level rise.

Assessment of the comparative contribution of physical processes and human intervention in the beach zone evolution

The outcome of the present analyses, the geological setting of the broader area and the human interference in the coastal stretch under investigation, the following factors (natural and anthropogenic) have been identified in controlling the formation and evolution of the Xylokastro beach zone. The natural factors include: the (i) *inner continental shelf morphology (I.C.S.M.)* whose limited width and increased steepness favor the gravitational mass movements towards the deep basin of the Gulf; (ii) the *subaqueous gravitational sediment movements (S.G.S.M.)* in response to the existing intensive seismotectonic regime; (iii) the *relative sea level change (R.S.L.C.)* that accounts more than 3 mm/year, over the past decades due to climate change; (iv) the *riverine sediment flux (R.S.I.)* that refers to the sediment influx of Sithas River; (v) the *near-shore sediment transport (N.S.T.) that includes a long-shore and a cross-shore component (as discussed earlier).* Between the anthropogenic factors, the most important seems to be: (i) the *waterfront engineering works (W.E.W.)* that include mainly the marina, the seawall and the coastal road that affect near-shore sediment transport; (ii) the *river basin and main channel regulation (R.B.M.C.R.)* that affects the sediment discharge (usually negatively). Moreover, in figure 4, the natural and anthropogenic factors identified above, are presented with respect to their spatial and time-period scale of occurrence. The spatial scale includes the clusters of mega (regional), macro (1-10km), meso (m-km) and micro (mm-cm), while the time scale clusters are micro (sec-min), meso (week-yr), macro (1-10yr) and mega (continuously).

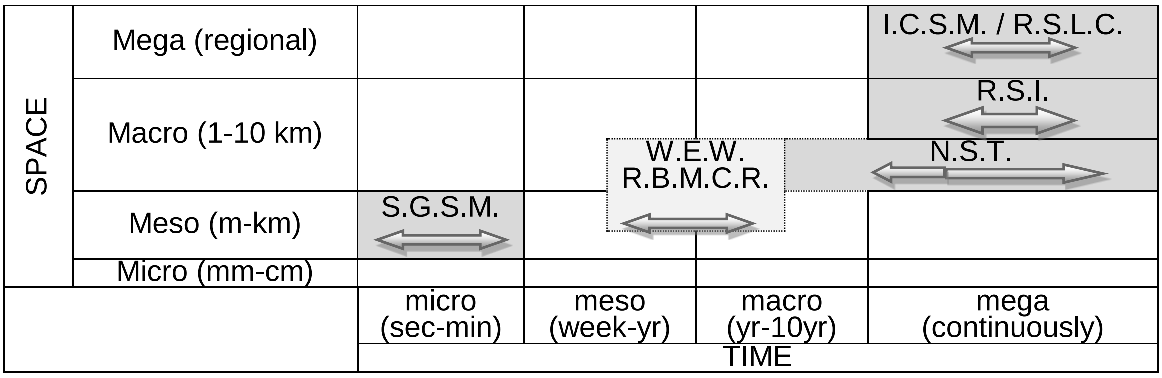

Figure 4: Processes affecting the formation and evolution of the Xylokastro beach zone in different spatial and time scale. Natural factors are highlighted in dark and anthropogenic in soft grey (for abraviations see text).

CONCLUSIONS

The formation of the Xylokastro beach zone is controlled primarily by the morphotectonics and secondarily by near-shore hydrodynamics and sediment dynamics. Human intervention that contributes also to the beach zone evolution is related mainly to changes in coastal sediment budget.

The recent and current tendency of shoreline position is the retreat, accounting about 14 m, on average. The eastern part of the study area (the Pefkias forest) seems to have undergone minimal retreat, as it has been affected to much less extend by the anthropogenic activity in relation to the western and central parts of the Xylokastro coastal front area.

The evolution of the Xylokastro coastal area, incorporating the expected rise of the sea level, will be the combined effect of the magnitude of sea level rise and the possible seismotectonic activity, if we assume no further human intervention. Nearshore sediment movement is expected to contribute to the future morphological conditions (induced by changes in sea level/geology) by adjusting the available sediment budget to the new conditions.

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