

## Erosion problems in Alexandroupolis coastline, North-Eastern Greece

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**Abstract** This paper deals with the coastal erosion processes and the related problems around the city of Alexandroupolis, NE Aegean Sea, N. Greece. The area is very fast developing, as the city is an important port and a summer resort center in SE Balkans, and will become soon a transportation and energy center, as well. The coastline under study exhibits an east–west orientation and has a length of more than 50 km. The spatial distribution and the characteristics of the changes in the shoreline were studied by comparing old and new air photographs and topographic maps, as well as through repeated series of field observations and local measurements regarding the erosion process. From these studies it was concluded that the greater stretch of the western part of the coast, under consideration, is of moderate to high relief, with a considerable participation of coastal cliffs. It consists of conglomerates of varying granulometry and consistency and is under moderate to severe erosion process. The erosion phenomena in the western part of the coast may be attributed, primarily, to strong S, SW winds, blowing in the area and to trapping of sediments by Alexandroupolis' port breakwaters; the port stops or/and diverts the sediments to the open sea; and to the east to west longshore sea current, prevailing in the area. The eastern stretch of the coast is a plain area, formed by sandy–silty sediments; being a part of the river Evros' Delta, it is under deposition and accretes seawards. The majority of the coasts under consideration are classified as coasts of high wave energy potential. Hard structures, as shore protection measures, have been con-

structed in some places, but they were proved, in rather short time-period, ineffective and suffered extensive failures. Thus, it is argued that for a long-term cost-effective tackling of the various erosion problems on any stretch, priority must be given to soft engineering measures; although, certain hard measures, carefully selected and locally implemented, can contribute to forming a rational combination of protection/mitigation measures. Besides, the development pressures in the coastal zone have to be confronted, in a sustainable way, through new integrated coast management regulations.

**Keywords** Coastal erosion · Classification of coasts · North Greece · Aegean Sea currents · Evros River Delta

### Introduction

North Aegean Sea coastline is an east–west oriented coastline of more than 280 km long. The majority of this coastline belongs to Greece. We are involved here with a stretch of about 51 km long, of the eastern part of it, ending to the west at the ancient town of Mesimvria and to the east at the Evros River Delta (Fig. 5). Administratively it belongs to Evros Prefecture, Eastern Macedonia and Thrace Region, N. Greece. The biggest city and capital of the Evros Prefecture is Alexandroupolis, a city of 50,000 inhabitants, and one of the biggest ports in North Aegean Sea. It lies on the central part of the coastline under study. The New Egnatia highway, a motorway crossing Greece from west (Igoumenitsa port, in Adriatic Sea) to Turkish borders in the east and connected with the North–South European motorway through Bulgaria, is passing just north of the city. Here is where the Burgas–Alexandroupolis oil conduit, transferring Russian oil from Caspian and Black

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Sea to Aegean Sea and to the world, will end; from this city the Caspian and Middle East–Turkey–Greece–Italy–Central Europe gas conduit will pass through, as well. Given the energy and transport infrastructures and the developing tourism, the whole region is quickly upgrading economically, and the coastal zone, mainly to the west of the city, is under high stress of urbanization and economic growth. Nevertheless, significant erosion phenomena are observed along the western part of the coast, from Mesimvria to Alexandroupolis, with negative impacts on private and public structures situated at or near the coastline.

In this paper an attempt is made to locate, record and investigate sea-erosion and coastal failure phenomena, encountered in the aforementioned study area; and to examine the plausible causes of these phenomena and suggest feasible remedial measures.

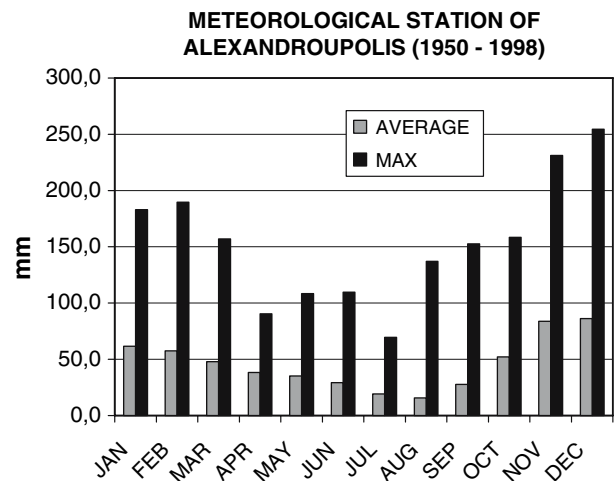
### Climatic conditions of the broader area

The climate of the area is of Mediterranean type with mild, rainy winters and cool summers. Some details of the climate are given in the following paragraph.

#### Precipitation

The rainfall data, which are presented in Table 1 and in Fig. 1, have been taken from the eight meteorological stations of the broader area and refer to the time period from 1950 to 1998. As it is shown, there exists an unequal annual distribution of the rainfall with maximum values, in all stations, recorded in December–January (rainy season) and minimum ones, respectively, in July–August (dry season). The observed differences between mean and maximum annual rainfall values justify for the occurrence of intensive flood incidents throughout the year.

According to Alexandroupolis station's data, that is, obviously, more representative to the coastal area under study, it comes out that:



**Fig. 1** Bar diagram of the mean monthly precipitation in Alexandroupolis meteorological station, period 1958–1998 (Xeidakis et al. 2006)

1. The mean annual rainfall, in the coastal zone under study is 554.2 mm; the most rainy month is December with a mean rainfall of 86.3 mm, and the driest month is August with a mean rainfall of only 15.7 mm (Table 1, Fig. 1).
2. The air temperature data for the time period from 1951 to 1996 reveal that the warmest time period is also the driest one; the warmest month is July with a mean temperature of 25.8°C and the coldest is January with 4.96°C mean value (Table 2, Fig. 2).

#### Winds

As far as the intensity and frequency of blowing winds is concerned, the coastal area of Alexandroupolis can be characterised as a quite windy one; this is attributed, among other factors, to the opening of the Black Sea to the NE (Katsoulis 1970). According to Alexandroupolis sta-

**Table 1** Rainfall data of eight meteorological stations from the broader region of Evros prefecture for the period 1950–1998

| Station         | Alt. (m) | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov   | Dec   | Mean  | Min   | Max    |
|-----------------|----------|------|------|------|------|------|------|------|------|------|------|-------|-------|-------|-------|--------|
| Alexandroupolis | 3        | 61.5 | 57.4 | 47.9 | 38.3 | 35.2 | 29.2 | 19.2 | 15.7 | 27.7 | 52.1 | 83.8  | 86.3  | 554.2 | 325   | 867.1  |
| Dikea           | 85       | 54.5 | 39.4 | 43.6 | 41.1 | 49.1 | 40.9 | 29.1 | 22.5 | 39.6 | 51   | 68.7  | 60.5  | 535.5 | 310.7 | 1,160  |
| Didimoticho     | 50       | 50.9 | 53.4 | 49.8 | 39.2 | 35   | 37.5 | 20.1 | 14.9 | 30.7 | 49.6 | 73.3  | 60.9  | 515.3 | 214.9 | 989    |
| Metaxades       | 120      | 79.5 | 63.4 | 63.3 | 56.3 | 44   | 46.1 | 22.5 | 15   | 28   | 56.4 | 76.3  | 81.6  | 632.3 | 260.5 | 1,022  |
| Mikro Derio     | 250      | 84.9 | 94.9 | 81.3 | 60.9 | 62.8 | 58.9 | 30.6 | 20.9 | 49.1 | 70.2 | 84.6  | 93.9  | 792.9 | 454   | 1317.3 |
| Orestiada       | 43.51    | 54.9 | 49   | 50.3 | 48.7 | 39.7 | 42.1 | 31.4 | 22.9 | 31.9 | 44.5 | 66.4  | 61.3  | 543.1 | 320.2 | 949    |
| Soufli          | 15       | 64.6 | 71.3 | 60.4 | 51.7 | 42.5 | 41.5 | 26   | 16.9 | 33   | 60.9 | 102.2 | 107.2 | 678.3 | 383.2 | 1,178  |
| Feres           | 26       | 62.9 | 53.2 | 64.9 | 39   | 29.2 | 31.5 | 11.4 | 8.6  | 52.9 | 41.8 | 83.5  | 81.5  | 559.6 | 257.9 | 839.3  |

**Table 2** Monthly temperature data of Alexandroupolis Meteorological Station (1951–1996)

|      | Jan  | Feb  | Mar  | Apr   | May  | Jun   | Jul  | Aug   | Sep   | Oct  | Nov  | Dec  |
|------|------|------|------|-------|------|-------|------|-------|-------|------|------|------|
| Mean | 4.96 | 6.01 | 8.3  | 13.16 | 18.3 | 23.05 | 25.8 | 25.48 | 21.12 | 15.7 | 10.8 | 7.08 |
| Min  | 0.5  | 1.3  | 4.5  | 11.2  | 16.5 | 21.4  | 23.9 | 21.6  | 18.5  | 12.7 | 6.6  | 2.7  |
| Max  | 8    | 10.8 | 10.9 | 16.1  | 21.4 | 24.9  | 28   | 27.9  | 24.6  | 19.4 | 14.7 | 11.2 |

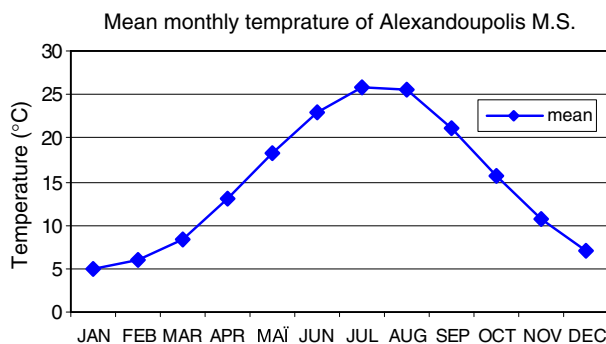
tion’s data, the prevailing winds during the winter period are of NE and N directions; during summer (July, August and September), in North Aegean Sea prevail N and NE winds, as well, called locally “Etesian winds” and sea breezes of S to SE directions. These summer winds (Etesians), known also to Ancient Greeks, are sometimes quite strong with intensity up to 8–10 BF.

The percentage annual frequency allocation of the winds in the area is: NE winds with low to moderate intensity and occasional extremes up to 8–10 BF 26.04%; moderate to low and rarely of high speed N winds 15.06%; moderate to high speed S-SW winds 11.28%; and dead calm 21.08% (Greek Navy, Pilot, vol IV, 1987; Mediterranean Pilot, vol IV, 1987; Anon 1984).

**Sea currents**

The Hellenic Navy Hydrographic Service has performed measurements of sea currents within the greater area of Alexandroupolis bay, during two time periods:

- One set of measurements carried out in summer (July) 1981, during the low discharge of Evros river, 15 km west of the river’s mouth. During that measurements two retrogressive currents were recorded: one with directions from NW to SE and another from SE to NW (reverse).
- A second set of measurements carried out in March 1982, during the river’s high discharge and under the influence of strong S winds. This survey recorded a sea current of west direction, parallel to the coastline.

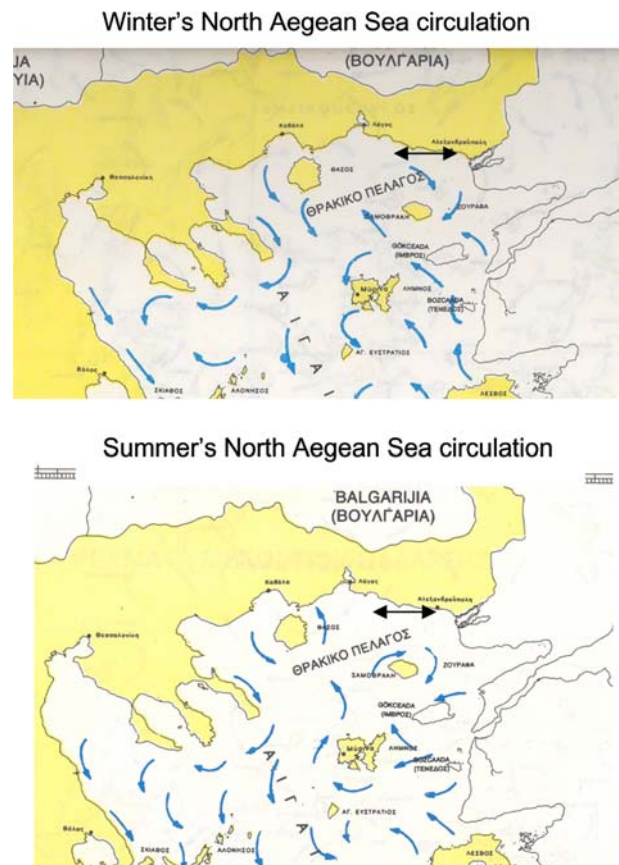


**Fig. 2** Annual temperature variation in Alexandroupolis area, N. Greece

In general, the prevailing sea current direction in North Aegean Sea, offshore, is from E to the W, especially during the winter time. However, this current is affected much by the S and SW winds and the high discharge of Evros River to the Aegean Sea and it may be reversed, especially nearshore. It has been observed also that, under the influence of N winds or calm periods, the prevailing longshore sea current in the area exhibits a W to E direction (Fig. 3) (Greek Navy, Pilot, vol. IV 1987, Mediterranean Pilot, vol IV 1987)

**Sea waves**

The whole coast of North Aegean Sea, including Alexandroupolis coastal part, has a southward orientation

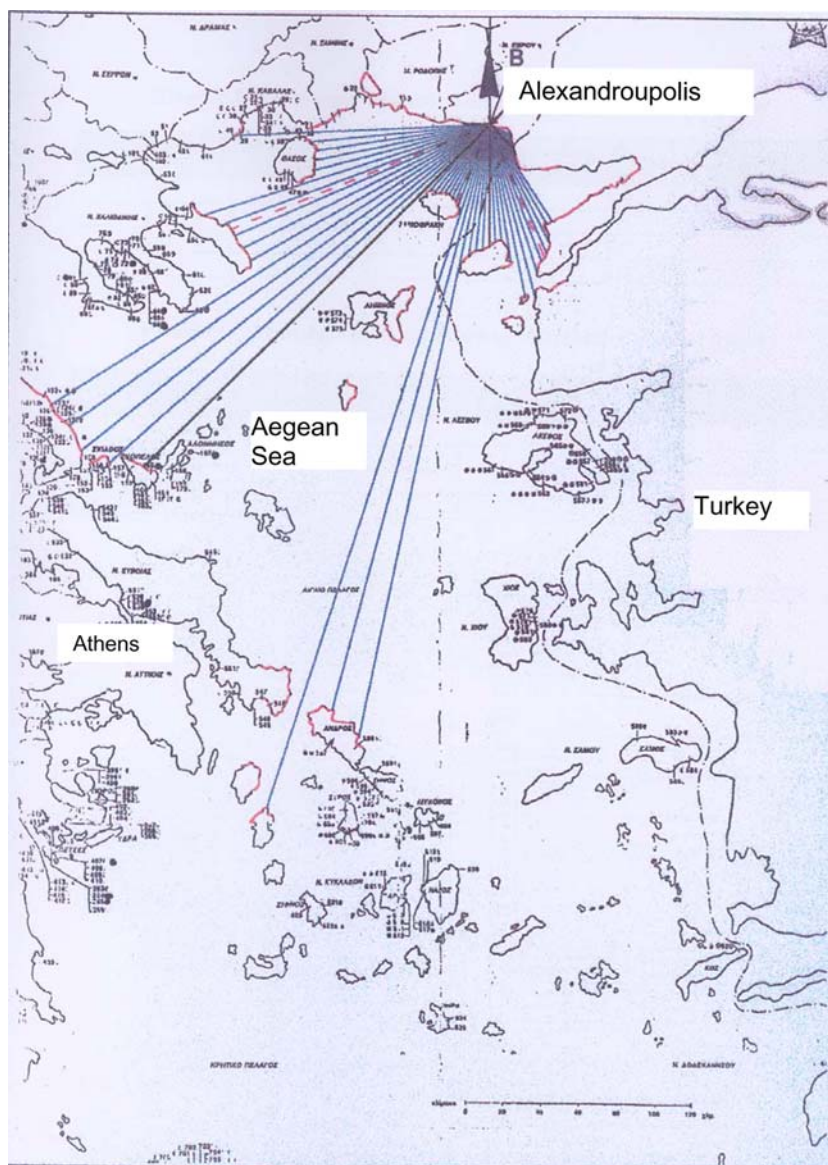


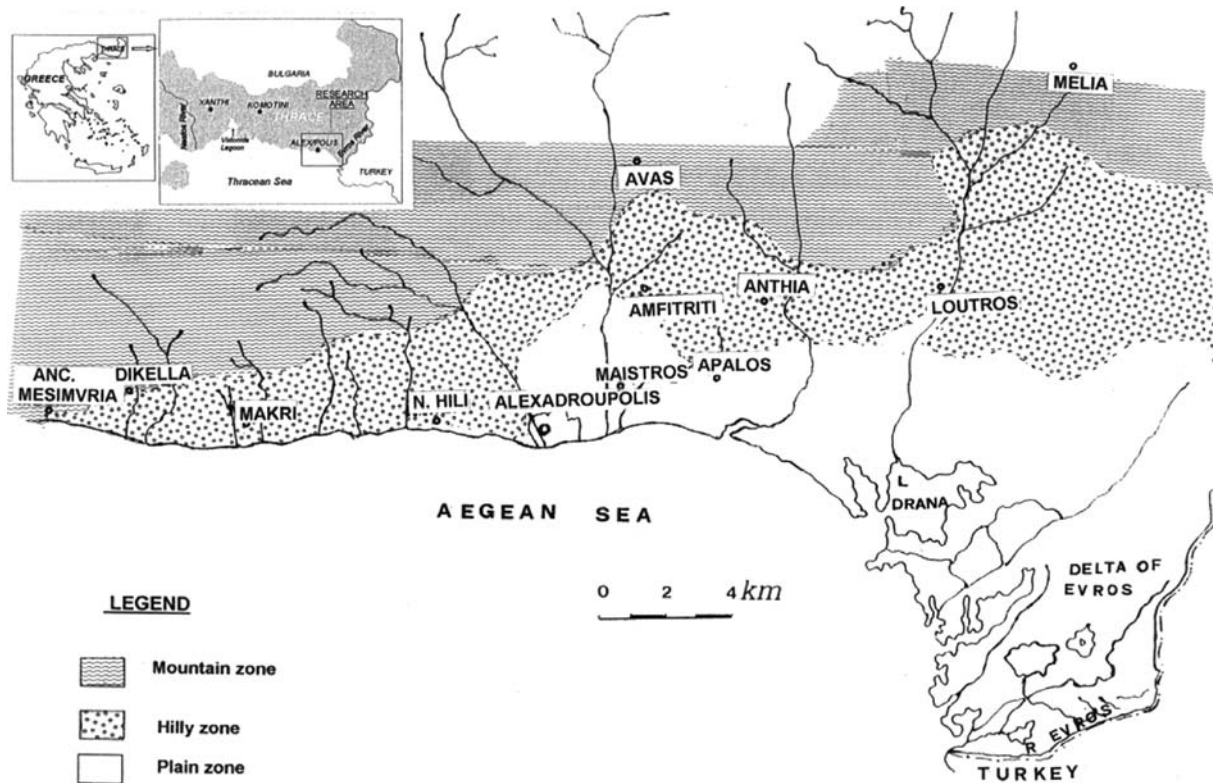
**Fig. 3** North Aegean Sea circulation in winter and in summer (Greek Pilot 1987)

extending on an E–W axis. Thus, the coastal zone is affected by the winds coming from south directions (SE, S, SW and W) and, those related to them, sea waves and currents. The critical wind duration depends on the effective fetch—longer durations are critical for longer fetches. The effective fetches for Alexandroupolis' Harbor, in various directions are as follows (see Fig. 4):

- From SE the sea fetch (freeboard), is relatively short, as it is limited by the presence of the west coasts of Eastern Thrace's and Kallipolis (Galibolu) peninsula. The mean sea-fetch in this direction is 25 km.
- In the S direction the sea-fetch is limited by the presence of Imvros (Gokceada) and Samothraki islands, but there exists a sub-sector, of about 4° wide, where the sea-fetch extends up to the NE coasts of Kythnos
- and Andros islands (Vories Sporades) with a maximum fetch of about 380 km. Within the remaining sector the mean fetch is around 75 km.
- In the SW sector, the corresponding fetches are of primary importance for Thrace coasts and can be divided in three sub-sectors: the eastern one which is limited by the Samothraki and Limnos islands; the central one which reaches up to North Sporades islands and the Magnesia (Volos) peninsula coasts (central Greece); and the western sub-sector extending up to Athos peninsula's coasts. Within these three sub-sectors the maximum freeboard of sea is about 280 km and the mean one is about 140 km (Figs. 3, 4).
- In the W sector, the sea fetch is bound by the coasts of Thrace and Thassos island. The corresponding maxi-

**Fig. 4** Fetch length of Alexandroupolis' Harbor in various directions (Alexandroupolis Municipality 2000)





**Fig. 5** Relief map of the broader area of the eastern part of the N Aegean Coast

num free length of the sea is about 160 km and the mean one about 40 km (Figs. 3, 4). (Data obtained from Alexandroupolis Municipality 2000.)

From the aforementioned fetches, it becomes clear that the greatest interest is presented by the waves which are developed by winds of SW and S directions. These winds blow, occasionally, with speeds up to 10 BF and can create, in the open sea, waves with a height  $\geq 6.5$  m and a period of  $\approx 10$  s.

As it is known, the maximum height of sea waves is directly proportional to sea fetch and to sea floor depth. In the study area the sea’s depth, in a zone up to 300 m off-shore, is less than 3 m. Therefore, the maximum wave’s height nearshore cannot be higher than 2.5 m.

**Classification of the coast’s stretches according to their wave energy potential**

According to the Armstrong–Price coasts classification system (Price 1954a, b; 1955; May 1982) and the proposed seafloor inclination criteria: coasts with seafloor inclination (bottom slope)  $< 0.0286\%$  are classified as *coasts with low potential energy waves*; coasts with seafloor inclination  $0.0286\text{--}0.0476\%$  are classified as *coasts with moderate potential energy waves*; and coasts with seafloor inclination  $> 0.0476\%$  are classified as *coasts with high potential energy waves*.

In accordance with this classification the coast under study could be characterized as follows:

In the west part, from Makri up to Alexandroupolis, the nearshore bottom slope was calculated from isodepth maps of Hellenic Navy, up to isodepth of 20 m (contour of  $-20$  m), in various locations, and found: a. west of Alexandroupolis, in Makri section,  $1.66\%$ , and in Nea Hili section,  $0.55\%$ ; east of Alexandroupolis in Apalos section,  $0.296\%$  (see Fig. 5 for sites). Therefore, the western stretch of the coast (Makri–Alexandroupolis) is classified, mostly, as *coast with high potential energy waves*; whereas the eastern stretch, from Alexandroupolis up to Apalos coast is classified as *coast of high potential energy waves*. The coast from Apalos up to Evros river mouth, with bottom slope  $> 0.296\%$ , is classified as *coast with moderate to high potential energy waves*.

**Geology and geomorphology of the coastal zone**

**Geology**

The geological structure of the bedrock, in the broader area under study, is quite complex. Tectonically the area belongs to the *Circum of Rhodope Zone (Peri-Rhodopic zone)* with meta-volcanosedimentary green schists, tuffs, dacitic

lavas (Maronia Series), in the west part; meta-sedimentary marbles, sericite schists, phillites and travertine on the top (Makri Series), in the middle part; and with Quaternary deposits in the remaining part. The Quaternary deposits consist of terraces of loose to semi-consolidated pebbles, cobbles, gravels, sands; and alluvial sediments and coastal sands near the coastal zone. Further N–NE of Alexandroupolis prevail tertiary deposits e.g. conglomerates, sands, clays and marls of Miocene and Pleistocene age; and volcano-sedimentary facies (Rhyolites, andesites, ignimbrites, tuffs, etc.) of Oligocene age. (Vergis 1982; Papanikolaou 1984; Maganas 1988)

Tectonically the area is crossed by four groups of faults with different age and direction each (Karfakis 1991). One of them, possibly the more recent one with E, NE–W, SW direction, shaped the modern coasts of East Macedonia and Thrace.

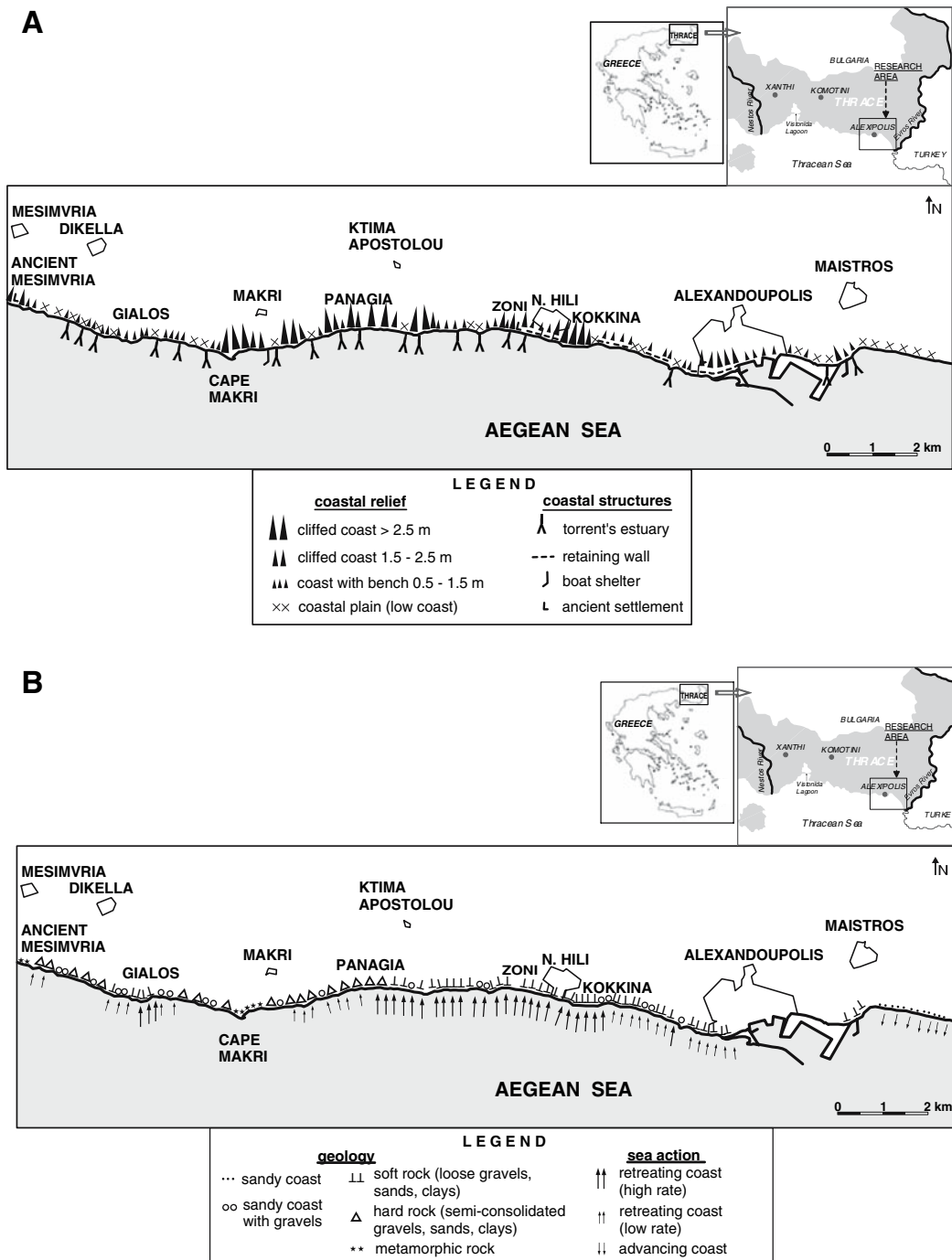
### Geomorphology

From a geomorphological point of view, the coastal zone can be distinguished between two unities: the western unity and the eastern one. The western unity starts from the Mesimvria coast and extends up to Alexandroupolis city, and the eastern one covers the coastal zone from Alexandroupolis up to the Evros river mouth. The relief of the western unity is characterised as hilly to mountainous with gentle ground slopes, whereas the eastern unity represents a plain area relief; the outer southeastern part of the plain area (eastern unity) is covered by the Evros River Delta. To the north and northeast of the hilly and plain areas, the highlands of Rhodope Range are situated which are part of the drainage basin of Evros River and its tributaries (Fig. 5).

*Evros River* is one of the biggest rivers in SE Balkans, having a drainage basin of 52,788 km<sup>2</sup>, extending into three border countries: Bulgaria, Turkey and Greece. Its mean annual discharge is around 271 m<sup>3</sup>/s, and the sediment load transferred to the sea is nearly 105,300 ton/year (Pehlivanoglou 1995); adding to this the stereo-load carried by the two local torrents (Loutros and Maistros), the total sediment load reaching the coastal area and North-eastern Aegean Sea is estimated about 150,000 ton/year. It should be noticed that the stereo-load coming out from the Elispondos Straits (Chanakkale) is not included in this sediment load estimation.

As far as the erosion and deposition phenomena along the two previously defined western and eastern unities, the situation appears as follows:

- Coastal erosion, landsliding phenomena and retreat of the coastline are observed along the whole western stretch of the coastline (west of Alexandroupolis), varying in intensity from place to place.
  - Deposition and advancement of the coastline is experienced along the eastern unity (east of Alexandroupolis). This is due to great supply of sediments by river Evros. However, there are some places in delta area where erosion is observed locally. For example, it has been estimated that the coastline (bar island) in front of Drana lagoon, west of the river mouth, retreats at a mean rate of 0.5 m/year, in the past 10 years.
- In the following paragraph, a particular description of the specific geomorphological features of the successive sub-sections constituting the coastal zone under consideration is presented, in a west to east direction (see Figs. 5, 6a, b).
- Starting from the western end of the unity, in the sub-section of Mesimvria, the coast is relatively high with cliffs up to 5 m high, consisting of metamorphic rocks and/or hard breccia-conglomerates; the beach is narrow, 5–6 m, and is covered by cobbles, pebbles (mostly) and coarse-grained sands (Photo 1).
  - Next is situated the Dikella sub-section (south of the Dikella village) where the coast has been formed and shaped by alluvial sediments provided by the local torrents and presents gentle slopes and low relief. The beach and the first 5 m of the sea bed, consist, predominately, of coarse-grained sand mixed with gravels and pebbles. The coastline itself (the cliff) consists of loose conglomerates, on the top, and hard breccia-conglomerates below. The loose conglomerates are made, principally, of clayey-silty sands, colored light gray to yellowish or reddish and present low cohesion, especially in the surface layers. They are exhibiting a clear heterogeneity as far as their granulometry and the nature of the cementing material and they are easily erodible. At the “Gialos” site the local coastal road, founded on the loose conglomerates, suffers extensive damages (pavement failures) due to wave erosion (Photo 2).
  - In the next sub-section, located west to Makri cape, the coast is of 2–5 m in height, and consists of layers of loose to moderately hard conglomerates, presenting high degree of heterogeneity and suffering various rates of erosion and block falls (Photo 3).
  - The cape Makri’s coast presents relatively high slopes, 10–20 m high, that are formed by the Makri’s unit schists and overlaid with travertine formation. The travertine slopes, nearly vertical (70°–90°), appear highly fractured, weathered, eroded and cavernous in places. Besides, due to extensive jointing and the favorable orientation of discontinuities, the sea wave erosion and destabilizing energy facilitates the frequent occurrence of rock falls and other slope failures in both



**Fig. 6** **a** Classification of the coast of eastern N. Aegean Sea according to its coastal relief, coastal structure, etc. **b** Classification of the coast of eastern N. Aegean Sea according to its geology, erosion rates, etc.

formations, but more often within the travertine rock-mass (Photos 4).

- The 10 km long coast sub-section, east to Makri cape, presents low relief and almost vertical slopes varying from 5–20 m in height. It is formed by conglomerates and breccias, in layers of various thicknesses and consistency, and having a clear stratification in places.

They exhibit a varying degree of spatial heterogeneity, as far as the nature, the color (gray, yellow, red) and the granulometry (from clay fraction up to big angular stones) of their materials. In places, there appeared also horizons with calcareous crusts. Due to the geomorphological characteristics of the particular coast, and the physical and mechanical properties of the forming



**Photo 1** Ancient Mesimvria's coast protected with a retaining wall, after failure



**Photo 4** Sea cliff in metamorphic rocks south of Makri Village with travertine formation on the top



**Photo 2** Erosion of the road pavement at Dikella



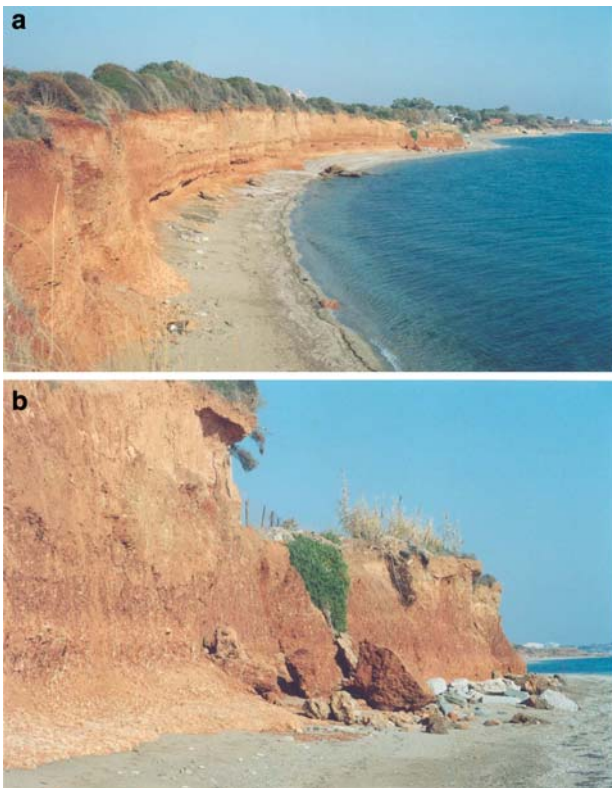
**Photo 3** Rock falls in hard conglomerate layers, west of Makri village

materials, the coastal slopes are greatly susceptible to sea erosion mechanisms. The retreat rate varies in magnitude according to the existing, in places, combination of



**Photo 5 a, b** Coast erosion west of Hili Village affecting human structures

interacting factors. In fact, the slope susceptibility to erosion is manifested by the frequent slope failures along the coastal cliffs of this section. Besides, a continuous retreat of the coastline is clearly taking place in this coast. The beach in front of this coast has a width of 3 to 10 m and is covered by coarse sand and gravels (Photos 5a, b, 6a, b).



**Photo 6** **a** Sea cliff in semi-consolidated argillaceous conglomerates west of Hilli Village. The cliff’s undercut and some block falls can be distinguished. **b** The same as **a**, a closer view



**Photo 7** Foundations of Ancient Greek City of Zoni on argillaceous semi-consolidated conglomerates



**Photo 8** Coast erosion at Hilli Village. The destruction of the fence and the stairs and various layers of conglomerates are distinguished

- The sequential sub-section of the coast is extending up to Nea Hili, a suburb of Alexandroupolis; it presents a low relief, to almost plain area, controlled by the existence of local torrents. Adjacent to this section and for a length of about 1 km, the coast is made of a river terrace with fluvial conglomerates and height ranging from 0.5 to 1.5 m; instability phenomena and retreat of the coastline are observed here, as well.
- Next to the above section, the Ancient settlement of Zoni sub-section presents coastal slopes constructed by conglomerates, 2.5 to 4 m in height and almost vertical (slope angles 80°–90°) (Photo 7). During the Ancient Classical Greek Times, there was an important Greek settlement here, called Zoni; the foundation ruins of this settlement are presently observed at the coastal cliffs. These findings constitute additional evidence that the coastline at that time was further seaward (to the south of its present position). The remaining conglomerates, at the base of the foundation of the ancient buildings, are fine-grained with calcareous cementing material and they host cavities and signs of coastline retreat. The beach, in front of the coastline, consists of coarse sand with gravels and exhibits a width ranging between 10

- and 20 m, timely varying, depending on the tidal phase (Photos 8).
- To the east, it follows the coast of Nea Hili where the slopes are made of clayey conglomerates and exhibit heights from 1 to 5 m. The coastal zone hosts houses and other structures which, depending on their closeness to the coastline, might exhibit marginal safety and high maintenance costs. At various points along this coastline retaining walls have been constructed to protect the houses. These walls suffer successive failures thus being, to a great extent, ineffective or even useless.
- The next sub-section refers to the coast of cape Kokkina Chomata where the slopes are quite high, of the order of 15–20 m, made of reddish colored conglomerates exposing almost vertical cliffs. In front of the coast, a relatively narrow beach, 5–10 m wide, exists. Numerous block falls and other slope failures and erosional retreat are experienced along this part of the coastline (Photo 9).
- The last section of the western coastal unity extends from Kokkina Chomata cape up to the west side of Alexandroupolis harbor. This coast represents a terres-



**Photo 9** Kokkina Chomata, Nea Chili. Soil-rock falls and slides

trial terrace, 1–3 m in height, made of conglomerates, sands and clays with yellow–gray color and calcareous cementing material. Here too, the coast suffers intensive erosion, a lot of failures on structures and protective walls and considerable sanding and retreat. The latter fact is manifested in the majority of the structures being close to the coastline. Most of these structures necessitate costly repairs and maintenance (Photos 10, 11a, b, 12, 13).

- The eastern unity refers to the alluvial plain of Evros river and consists of silt–sandy deposits. It extends from Alexandroupolis harbor up to Evros river mouth (Photos 14, 15). The coast of this part is an almost plain area. Here, the prevailing geomorphological process is sediment deposition and coast progression to the sea, apart from a few places like the coastal zone situated in front of the Drana lagoon, within the Evros river deltaic area (Greek part), where some erosion has been experienced.

According to their geomorphological characteristics, the coasts of the western unity can be differentiated into four types (Fig. 6a):



**Photo 10** Nea Chili. Failure of hard protection measures



**Photo 11** **a** Aerial photo of Alexandroupolis City coast at recreation club “ARGO”, after the construction of a retaining wall, in 1990s for the coast protection. **b** Destruction of part of the retaining wall of the coast, at recreation club “ARGO”, from sea (storm) waves in 2004

- a. Low relief coast, coastal plain
- b. Coasts with low bench 0.5–1.5 m
- c. Cliffed coasts with bench 1.6 to 2.5 m, and
- d. Cliffed coasts with bench 2.6 to 25 m in height.



**Photo 12** Destruction of an open recreation plateau, outside of the Sea-Scout Center at the west side of the Alexandroupolis City Port, in 2004



**Photo 13** The coast of Alexandroupolis City in front of the lighthouse in 1950s, with no protection structures (the natural slope)



**Photo 14** Aerial view of the port of Alexandroupolis City with its new extension eastwards in 2004–05. The SW directed sea waves and eastern deposition coast, up to Evros River Delta, is shown as well



**Photo 15** The sand–silty depositional coast, east of Alexandroupolis City Port (Apalos Village), extending to the east up to Evros River Delta

### Factors and mechanisms engaged in coastal erosion

As it is deduced from the aforementioned field investigations and observations, carried out during 2004–2005, the coasts of the western unity are subjected to an intensive sea erosion process that is manifested by the various slope failures (mainly rock falls) and the retreat in the greatest part of the coastline of this unity.

As it is known, the coastal erosion phenomena express the result of a combination of interacting factors representing the inherent characteristics of the two engaged systems: the land system and the sea system. As far as the land system is concerned, the main factors engaged are: tectonic regime of the broader area, geomorphology, lithology and geotechnical properties of the coastal material. The main factors representing the sea system are: sea waves, tides, longshore currents and morphology of sea bottom nearshore. The local climate influences both of these systems, and might be considered as a third intervening system.

The cliff instability involves: episodic stress-release fracturing and cantilevered block falls, frontal toppling, sheet sloughing, and small plane or wedge failures.

The principal mechanisms promoting the cliff/slope failure are:

- Tensional stress generated during the release of horizontal confining stress;
- Reduction of the soil strength and increase of the pore water pressure with increasing saturation levels;
- Undercut of the slope (cliff) toe by waves' erosion. Waves usually affect the lower 2 m of the cliff toe.
- Opening of the pre-existing rock/soil joints and weakening of the rock/soil structure by the wave impacts;
- Variation of the saturation levels of the ground with time and space, generally being higher during the rainy season and moderate to high in the dry season. This process reduces the ground cohesion and strength.

### Volume of material in each failure incident

Individual failures comprise typically less than a cubic meter of material; but in some cases can reach up to tenths of cubic meters of loosened and slit material. Usually, only the outer 1–2 m of material is removed in a failure episode. Large failures that extend over most or all the face of the cliff are uncommon, but a few big wedge or plane failures and/or topples sometimes occur.

### Factors engaged in the erosion phenomena of the western unity of the coast

The question arises: why the erosion rate in this stretch of the coast is higher than the adjacent coasts, although there

is an east to west sea current from river Evros carrying a large quantity of sediments? The answer is neither easy nor simple. Some of the plausible reasons are:

- The long existing and lately extended breakwaters of the port of Alexandroupolis trap most of the sediments coming from east, from the Evros river mouth, and diverts the longshore current with the rest of the carried sediments to the open sea; thus the branch of the sea current reaching the western shore is deprived of sediment load and thus is getting more aggressive.
- The western part of the coast is open to the sea. The fetches in the SW and S directions are very long, and the speed of the blowing winds from these directions is very high, up to 10 BF, developing high waves that impact the cliff at an acute angle and impose very high stresses to the coast; this promotes erosion, and creates a longshore current with an eastwards component.
- It has been observed that, with some strong N and NE winds, a longshore current from west to east is developed in the western part of the coast; this current contributes to the coast's erosion, as it comes from deeper waters and is deprived of much sediment load.
- The local torrents do not supply large quantities of sediments to the sea for they are small and their watershed extends on hard rocks.
- The rise in sea level worldwide has also a serious effect on the erosion phenomena of the coasts in North Aegean Sea. This increase has been assessed for the North Aegean Sea about  $0.15 \pm 0.05$  m (Tsimplis and Rixan 2003)

### Protection measures

It should be initially stated that the sequence of selecting, spatially allocating and implementing the case-appropriate coastal zone protective measures, constitutes a very difficult and complicated decision making process, given the existing legislative, socio-economic and scientific constraints. These difficulties, complexities and constraints are always encountered (though case-varying) and must be dealt with in a rational way through a sound environmental impact assessment as well as through a proper cost over benefit analysis. The aforementioned scientific difficulties are due to the inherent uncertainties engaged with highly complex and dynamic natural systems, as the coastal ones.

It is, nowadays, a common practice to divide all the existing and used worldwide engineering measures–techniques used for the protection of environmentally sensitive sites, into two broad groups: (a) *hard* engineering measures and (b) *soft* engineering measures. In coastal erosion management, hard structures like: *revetments, groins, seawalls,*

*breakwater and jetties* belong to hard measures (Headland et al. 1999; Bell 1999; May 2002; EuroSION 2004, part I).

Hard engineering structures, used for coastal defence, create negative environmental impacts because they modify coastal sediment transport patterns through three major processes:

1. By trapping of sediments transported alongshore and creating a sediment deficit downdrift
2. By reflecting incoming waves which, thus, hamper energy dissipation and augment turbulence resulting in increased cross-shore erosion.
3. By diffracting incoming waves, thus resulting in alteration of the wave crest direction which results in diluting the wave energy in some places leading to accretion and concentrating it in some other places with subsequent erosion and coastal retreat.

On the other hand, hard structures, if they are designed, located and constructed properly, can tackle an urgent and fast growing, locally sited erosion problem effectively. However, they have a limited lifetime of positive action.

In the group of soft engineering, measures and structures like: *artificial reef creation, floating breakwaters, beach nourishment, beach scraping, marsh creation and vegetation planting* belong to soft measures. The major advantage of the soft techniques is the fact that they are environmentally friendly and present great resilience as it is considered that they are “working with nature”. However, they are found to be effective solutions only in a medium- to long-term perspective, i.e. when coastal erosion does not constitute a risk in a short-term perspective (5 to 10 years). Thus, the long-term positive effect of soft solutions may be optimised by hard structures which make it possible to tackle a local erosion problem efficiently but only in a rather short time basis.

From the aforementioned discussion it is evident that a proper combination of hard and soft coastal protection measures would constitute the optimum solution.

Our negative experience from the coastal zone under investigation concerns, mainly, hard structures (as vertical concrete retaining walls, breakwaters, etc.) which have been of a very time-limited and local success (protective measures), as it is demonstrated through photos 5a,b, 8, 10, 11a, b, 12 and 13. Up to present time, no soft techniques have been implemented as protection measures for the erosion-suffering coasts of the western unity; thus there is not a vivid experience regarding their probable positive impacts in effectively mitigating the erosion process.

Given all the aforementioned comments and facts, summarising our direct and indirect experience and engaged to it “lessons learned” from local and worldwide coastal erosion cases, we express, briefly, our opinion in the following:

First of all, the “no action” option should be thoroughly examined. Since, it is known that any human induced intervention in the coastal zone change the existing equilibrium of the concerned natural system and facilitates erosion at places and accretion at others.

If the existing range of problems and social necessities make the “action” option inevitable, then the priority, in managing the erosion problems of any coastal unity, in a long-term basis, must be given to soft engineering techniques. Besides, carefully selected, designed and constructed hard solutions should be applied in limited, already developed or urbanized sites of the coastal zone. In these locations, the high value of the engaged land and beach infrastructure make these hard structural solutions urgent and cost-effective. It is believed that optimal results (in a money and time basis) can be achieved by carefully combining different types of coastal erosion defence including hard and soft solutions; the advantage of their respective benefits although mitigating their respective drawbacks should consist the basis for structuring the optimal combination of measures to be implemented. Due regards should be given to socio-economic and environmental criteria and pre-set objectives.

Finally, it seems that the appropriate solution regarding structures/houses being at risk, due to their vicinity to coastal fast eroding cliffs, lies in their relocation. Nevertheless, this problem has to be rationally confronted and sustainably solved through the new coastal zone management regulations which are, currently, under compilation in Greece.

## Conclusions

From the previous discussion the following conclusions can be drawn:

- The greater part of the western stretches of the coast under study are cliffed with a moderate to high relief (2–20 m high) and consists of conglomerates of varying granulometry and consistency. The eastern part is a plain area and is formed by sandy and silty sediments.
- The majority of the coastline western of Alexandroupolis City presents erosion and retreat problems, whereas the eastern coastline exhibits, principally, deposition and progression seawards.
- The erosion phenomena may be attributed to trapping of sediments by the Alexandroupolis’ port breakwaters, for the east to west sea currents, and to the high sea waves, as well as to the west to east longshore currents developed, locally, by the strong S–SW winds blown in the area.
- The sea level rise enhance to these phenomena, too.
- The longshore currents in the area are quite complicated. The main current appears to flow from east to west, but

with S–SW and sometimes with strong N–NE winds they are reversing to opposite direction, flowing from west to east.

- The majority of the coasts in the study area are classified as coasts with high wave energy potential, owing to openness of the North Aegean Sea, the high slope of the sea bottom nearshore and the intensity of the local winds.
- The erosion phenomena in the western stretch of the coast have created serious problems in buildings/structures of the City of Alexandroupolis situated near the coastline.
- There exists a negative experience from the implementation of hard structures as protection measures, very time-limited and local success. However, up to the present time, no soft techniques have been applied as protection measures for the erosion-suffering coasts; thus there is not a vivid experience regarding their probable positive impacts.
- Given the relevant direct and indirect experience, it is believed that optimal results (in a money and time basis) can be achieved by carefully combining different types of hard and soft solutions. However, the “no action” option should be, firstly and carefully, examined and if “action” has to be taken then, soft engineering measures deserve a priority consideration, due to their ability in working better with nature.
- The relocation seems an inevitable solution for the buildings being at risk, due to their vicinity to fast eroding coastal cliffs.
- Coastal erosion and its short- and long-term impacts in the studied area are closely related to the fast increasing development process; thus, they have to be rationally confronted and sustainably solved through the new coastal zone management regulations which are, currently, under compilation in Greece.

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