Coastal vulnerability assessment to sea-level rise bαsed on geomorphological and oceanographical parameters: the case of Argolikos Gulf, Peloponnese, Greece*

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ABSTRACT: The present investigation concerns the classification of the coast of the Argolikos Gulf according to its vulnerability to an anticipated future sea-level rise, using the Coastal Vulnerability Index (CVI) and utilizing GIS technology. This index allows the following six physical variables: geomorphology, coastal slope, relative sea-level rise rate, shoreline erosion or accretion rate, mean tidal range and mean wave height, to be related in a semi-quantitative manner. Each variable is ranked on the basis of its potential contribution to physical changes on the coast as sea-level rises. The variable of geomorphology expresses the relative erodibility of various coastal landforms and was derived from detailed field geomorphological mapping. Shoreline erosion or accretion rates were obtained from interpretation of aerial photos taken at various years concerning the last 50 years. The regional slope of the coastal zone was calculated using the Digital Elevation Model (DEM) of the area derived from topographic diagrams at the scale of 1:5,000. Mean tidal range for the study area is derived from available onshore tide gauge measurements and published information. Mean significant wave height is obtained from POSEIDON program. Following the division of the coastline in sections, with a length of 10 m, the coastal vulnerability index (CVI) is calculated for each section, as the square root of the values of the ranked variables divided by their total number involved. According to the produced CVI values (ranging between 0.53 and 7.56), the most vulnerable coastal regions (of high and very high risk) were found to be mainly along the eastern (Koilada bay, Iria, Kalithea, Tolo) and northern (Argive plain) coast, while the least vulnerable sections belong to the rocky cliffs along the western shore of the Gulf. The former are related to low-lying coastal formations consisting of highly erodible lithology, while the latter is associated with less erodible lithologies.
Key-words: *Coastal Vulnerability Index (CVI), coastal geomorphology, sea-level rise, Argolikos Gulf, Greece.*

ΠΕΡΙΛΗΨΗ: Σκοπός της παρούσας εργασίας είναι η ταξινόμηση των ακτών του Αργολικού κόλπου ως προς την τρωτότητά τους στην αναμενόμενη (μελλοντική) άνοδο της θαλάσσιας στάθμης εφαρμόζοντας τον Δείκτη Παράκτιας Τρωτότητας με τη χρήση Συστημάτων Γεωγραφικών Πληροφοριών (ΣΓΠ). Ο δείκτης αυτός επιτρέπει τη συνεκτίμηση έξι παραμέτρων με ημι-ποσοτικό τρόπο. Οι παράμετροι αυτές είναι η παράκτια γεωμορφολογία, η παράκτια μορφολογική κλίση, ο ρυθμός μεταβολής της σχετικής στάθμης θάλασσας, ο ρυθμός προέλασης ή υποχώρησης της ακτογραμμής, το μέσο εύρος παλίρροιας και το μέσο ύψος κύματος. Κάθε παράμετρος κατηγοριοποιήθηκε με βάση τη δυνητική συνεισφορά στις φυσικές μεταβολές της ακτής καθώς η θαλάσσια στάθμη ανυψώνεται. Η παράμετρος της γεωμορφολογίας έχει να κάνει με την ανθεκτικότητα στη διάβρωση των διάφορων παράκτιων γεωμορφών που αναπτύσσονται κατά μήκος της ακτογραμμής. Τα δεδομένα για τη γεωμορφολογία προέκυψαν από τη λεπτομερή υπαίθρια γεωμορφολογική χαρτογράφηση σε κλίμακα 1:5.000. Οι ρυθμοί προέλασης ή υποχώρησης της ακτογραμμής προέκυψαν από τη συγκριτική παρατήρηση αεροφωτογραφιών και δορυφορικών εικόνων διαφορετικών ετών λήψης που καλύπτουν τη χρονική περίοδο των τελευταίων 50 ετών. Η μορφολογική κλίση της παράκτιας ζώνης υπολογίστηκε χρησιμοποιώντας το Ψηφιακό Μοντέλο Εδάφους που κατασκευάστηκε για την περιοχή από τοπογραφικά διαγράμματα κλίμακας 1:5.000. Ως μέσο εύρος παλίρροιας για το σύνολο των ακτών του κόλπου χρησιμοποιήθηκαν μετρήσεις παλιρροιογράφων και δημοσιευμένα στοιχεία της ευρύτερης περιοχής. Το μέσο σημαντικό ύψος κύματος εκτιμήθηκε από δεδομένα του προγράμματος POSEIDON. Η ακτογραμμή του κόλπου διαιρέθηκε σε τμήματα μήκους 10 μέτρων και για κάθε τμήμα εκτιμήθηκε η τιμή του Δείκτη Παράκτιας Τρωτότητας ως η τετραγωνική ρίζα του γινομένου των τιμών των έξι μεταβλητών προς τον αριθμό 6 που είναι το σύνολο των παραμέτρων που ελήφθησαν υπόψη. Οι τιμές του δείκτη που εκτιμήθηκαν για την περιοχή κυμαίνονται από 0,53 έως 7,56 με τις περισσότερο τρωτές περιοχές (πολύ υψηλού και υψηλού κινδύνου) να εντοπίζονται στις δυτικές (όρμος Κοιλάδας, Ίρια, Καλλιθέα, Τολό) και τις βόρειες (Αργολικό πεδίο) ακτές του κόλπου. Αντίθετα οι δυτικές ακτές του κόλπου, κυρίως αυτές που καταλαμβάνονται από παράκτιους βραχώδεις κρημνούς, είναι λιγότερο ευάλωτες με εξαίρεση τις περιοχές Λιβάδι, Τυρός και Άστρος. Οι τρωτές περιοχές είναι εκείνες που εμφανίζουν μικρή μορφολογική κλίση που αποτελούνται από ευδιάβρωτους γεωλογικούς σχηματισμούς ενώ οι λιγότερο τρωτές αυτές που συνίστανται από ανθεκτικές στη δράση των θαλάσσιων διεργασιών λιθολογίες.
Λέξεις-κλειδιά: *δείκτης τρωτότητας ακτών, παράκτια γεωμορφολογία, ανύψωση στάθμης θάλασσας, Αργολικός Κόλπος, Ελλάδα.*

INTRODUCTION

A natural hazard that is expected to affect coastal areas in the near future is the anticipated coastline retreat due to sea-level rise. The IPCC (2007) report predicts temperature rise of 1.1–6.4 ^{o}C by the year 2100; this is a wider range than the 1.4-5.8 ^{o}C increase given in the 2001 report. However the 2007 report suggests that the best estimate for temperature rise is

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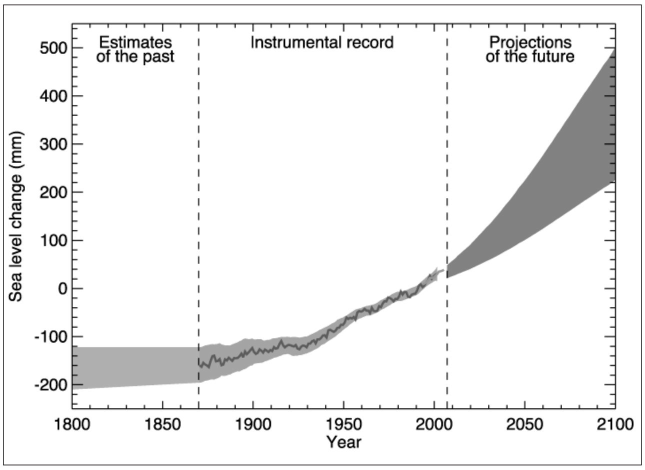


Fig. 1. Past and projected global average sea level trend, according to IPCC (2007; SRES A1B scenario).

1.8-4 °C. This will cause an increase in global eustatic mean sea-level of 18-58 cm while an additional 10 to 20 cm is possible if the recent rapid melting of polar ice sheets continues (Fig. 1). The previous IPCC report (2001) gave a much wider range for sea-level rise (8-88 cm). Thus sea-level rise will have the largest sustained impact on coastal evolution at the societally important decadal time scale.

One of the most important applied problems in coastal geomorphology today is the physical response of the coastline to sea-level rise (Gaki-Papanastassiou *et al*., 1997; Karymbalis & Gaki-Papanastassiou, 2008). The rate and extend of coastal erosion is expected to intensify as a result of increased sea-level rise but erosion trends are not easily predicted because of the interplay between various factors including the sediment budget and nearshore hydrodynamics along with climatic variables (Gornitz, 1991). The prediction of future coastal evolution is not straightforward. Thus, there is no a standard methodology and sometimes even the appropriate data required to make such a prediction, which are the subject of scientific debate between researchers of the coastal zone. Various approaches have been proposed in order to predict the evolution of the coastal zone under the influence of the anticipated sea-level rise each of one has its shortcomings or could not be applicable in certain occasions. The most important among these methodologies include the extrapolation of historical data (concerning mainly the shifting of the shoreline), the application of static inundation models or simple geometric models like the Bruun Rule (1962), application of sediment dynamics models and probabilistic simulation based on parameterized physical forcing variables (Thieler & Hammar-Klose, 1999). Although a viable totally quantitative prediction of the coastal response to the sea-level rise is not available, the relative vulnerability of different coastal environments to sea-level rise may be quantified taking into account information on coastal geomorphology, rate of sea level rise, shoreline shifting and other related factors.

The aim of this study is the classification of the coastal zone of the Argolikos Gulf with respect to its vulnerability to the anticipated future sea-level rise. For this purpose the Coastal Vulnerability Index (CVI) proposed by Thieler & Hammar-Klose (1999) was applied, on the basis of field data, existing topographic and geo-environmental information and utilizing GIS technology. This approach constitutes a relatively simple and objective way to quantify vulnerability of the Argolikos Gulf coastline. Furthermore, this method has already been applied for the coasts of Porto Heli and Ermioni (Seni, 2007), at the scale of the Aegean coast (Alexandrakis *et al*., 2008) as well as for the W/NW coast of Attica (Chatzieleftheriou *et al*., 2010). Such identification will be useful for coastal management and could find immediate application to many strategies regarding coastal development in both short and long term time scales.

STUDY AREA

The Argolikos Gulf and the Argive plain, located in the Peloponnese (Southern Greece), is a fault-bounded tectonic depression of Plio-Pleistocene age. It has an elongated shape of NW-SE direction with 75 km long and 30 km wide, ending at the SE towards the Aegean Sea, reaching a maximum depth of 800 m (Fig. 2). An approximately 8-10 km wide shelf occupies the northern gulf, ending in a shelf break between 95 m and 100 m, from where the bottom descends steeply up to a depth of 150 m where it meets a more gentle seafloor (Van Andel *et al*., 1990, 1993). Its northern terrestrial part is occupied by the Argive plain. This neotectonic basin separates the mainland of Peloponnese from the Argolis peninsula, which during the Pliocene to early Pleistocene continued to the NW forming a channel linking the southern Aegean Sea with Korinthiakos Gulf and isolating the Argolis peninsula from the mainland of Peloponnese to the west. The western shelf is extremely narrow (a few tens or hundreds of meters). Along the eastern margin the shelf is better developed (0.41 km). To the north, the shelf is wide (3-5 km) because of the progradation of the discharging rivers (Papanikolaou *et al.*, 1988).

The Argive plain is bordered mainly by a mountainous massif of Mesozoic limestones, flysch and ophiolites and Late Mesozoic-Eocene flysch, the edges of which are flanked by Plio-Pleistocene lacustrine marls and terigenous conglomerates. NW-SE striking faults mark the eastern margin of the plain, while faults of similar orientation, along with NE-SW and E-W striking faults, occur within the adjacent mountain massif. Drainage networks have been influenced by tectonism, with several main channels following fault lines (Dufaure, 1975; Gaki-Papanastassiou, 1991). The Argive plain has been built by rivers draining the surrounding ranges with Xerias and Inachos, descending from the Arcadian mountains, being the major streams. The investigated shoreline (including the islands) has a total length of 247.21 km (automatically measured after the digitization of the coastline from 1:5,000 topographic diagrams) and lies between cape Sambatikis and cape Hinitsa. It is an area char-

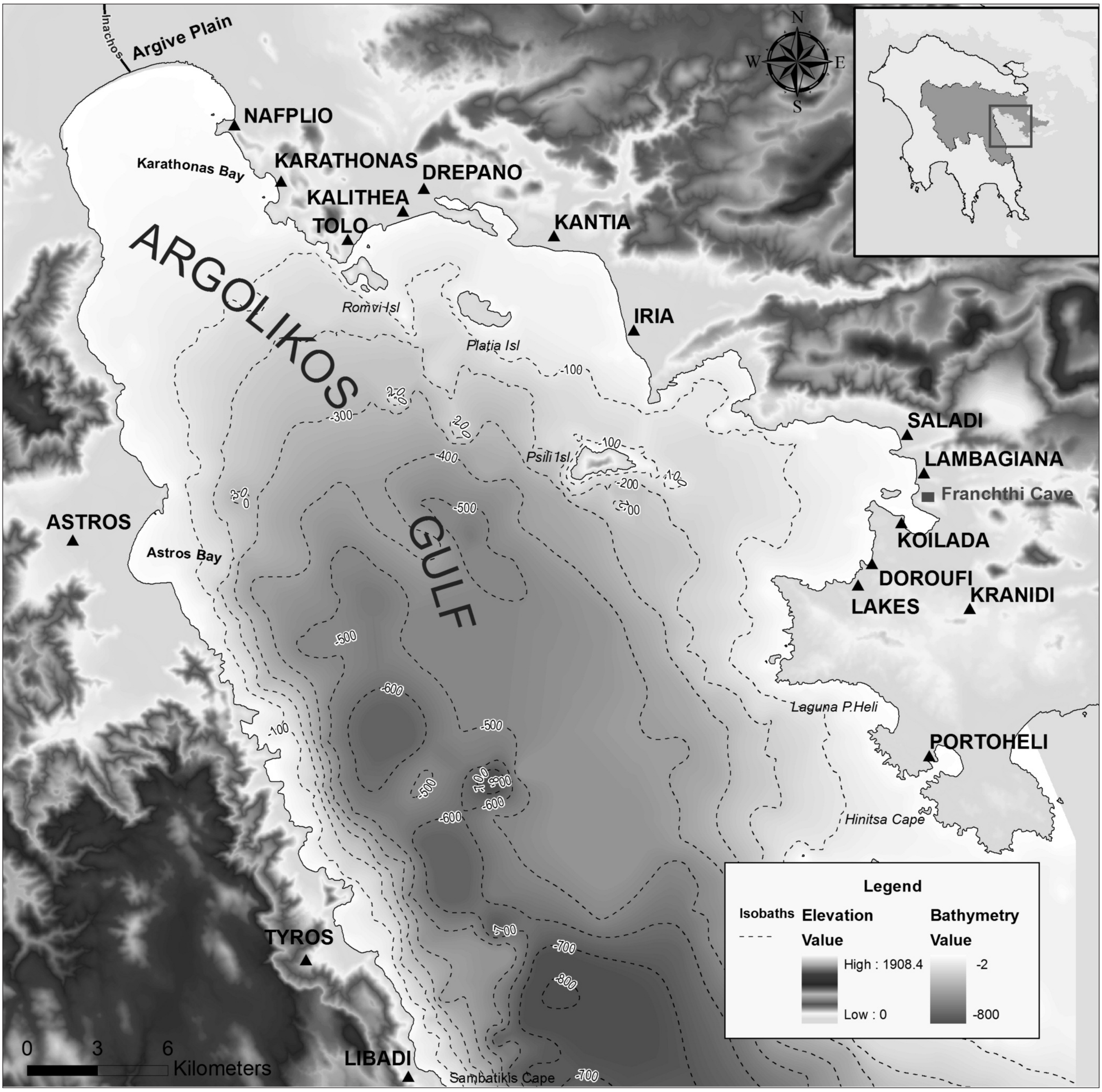


Fig. 2. Location map and subaqueous morphology of the Argolikos Gulf, Peloponnesus.

acterized by various coastal geomorphological features (Fig. 2). The present morphology of the coast is not only the result of tectonic factors but also the nature of rocks, the fluviotorrential deposition and the erosive intensity of sea waves (Karymbalis & Seni, 2005). The coastal geomorphology of the Argolikos Gulf is the result of the interaction between marine processes and sediment supply of the ephemeral torrents during the last 5,000 years after the stabilization of the sea-level rise (Poulos *et al.*, 2009). The western shore is almost linear with a NNW-SSE direction, composed mostly of limestones with steep slopes locally broken by some pocket beaches corresponding to the mouths of torrents running through deep valleys. The eastern side is characterized by an indented coastline with steep cliffs and extensive sandy beaches, corresponding to the inlets of large bays, while there are some small islands. The most low-lying part of the gulf is the northern one, where the Argive plain is located (Gaki-Papanastassiou *et al.*, 2005).

Argolikos Gulf has been selected as a case study area for the application of the Coastal Vulnerability Index mainly due to the variability of its coastal landforms and the prevailing land uses.

DATA COLLECTION AND METHODOLOGY

The Coastal Vulnerability Index (CVI) presented here was proposed by HAMMAR-KLOSE & THIELER (2001) that modified the initial index produced by GORNITZ *et al.* (1994). A similar formula named as sensitivity index was applied by SHAW *et al*. (1998). The CVI is calculated as the square root of the product of six variables, ranked from 1 to 5 according to Table 1, and divided by their total number (equation 1):

$$CVI = \sqrt{\frac{a \cdot b \cdot c \cdot d \cdot e \cdot f}{6}} \quad (1)$$

where, a: geomorphology, b: coastal slope, c: rate of relative sea-level rise, d: rate of shoreline erosion / accretion, e: mean tide range, and f: mean significant wave height.

Data concerning the geomorphology variable were derived from detailed (at the scale of 1:5,000) field geomorphological mapping along the study coastline carried out during the summer of 2008. Since the type of the coast and coastal landforms (erosional or depositional) are in close relation to the coastal lithology, during the field mapping qualitative observations about the relative erodibility of the geological formations developed along the coastline were also collected. Additionally, geological formations along the shoreline were identified using geological maps of the Institute of Geology and Mineral Exploration of Greece (IGME) at the scale of 1:50,000.

The regional slope of the coastal zone was calculated using the Digital Elevation Model (DEM) of the area created from topographic diagrams at the scale of 1:5,000 with 4 m contour interval (1 m for the low lying coastal plains) obtained from the Hellenic Military Geographical Service. In order to estimate the gradient of the subaerial coastal zone the slope of each grid cell with 10X10 m size was calculated by defining elevation extremes.

Although relative sea-level change is the combination of both the global eustatic sea-level rise as well as local isostatic and/or tectonic land movements, for this study this variable includes only the eustatism component since no historical records of the recent time relative sea-level change were available for the Argolikos Gulf.

Shoreline erosion or accretion rates were derived using remote sensing data. Two satellite images LANDSAT 7 ETM covering the area for the years of 1987 and 2000, respectively. For some locations along the coastline, aerial photographs of 1945 (at the scale of 1:45,000) obtained from the Hellenic Military Geographical Service, were used. The reference image for the geometric correction of the aerial photographs was the 2000 LANDSAT satellite image. The mosaic data were manipulated in a GIS and three different coverages were created by digitizing the shorelines of the two different periods. These were overlapped in order to detect shoreline changes during the period 1945-2000.

Tidal range was deduced from published information (e.g. TSIMPLIS, 1994; TSIMPLIS & BLACKMAN, 1997).

Mean significant wave height is used as an indicator of the incoming wave energy. The mean annual values of significant wave height have been abstracted from the Wave and Wind Atlas of the Hellenic Seas (SOUKISIAN *et al.*, 2007), which is based on offshore measurements for the period 1999-2007 (POSEIDON program). In addition, the anticipated increased level of wave energy associated with storm surge, in the case of southerly waves has been estimated using available data from the Piraeus sea level (tidal) gauge.

Each variable for each coastal segment has been ranked from 1 (very low) to 5 (very high) vulnerability, according to the values provided by THIELER & HAMMAR-KLOSE (1999) and presented in Table 1. Subsequently the CVI value for each coastal segnment was calculated using equation 1. In order to have a preliminary assessment of the impacts of the

TABLE 1
Ranges for vulnerability ranking of the six variables used in equation 1 (after THIELER & HAMMAR-KLOSE, 1999).

VARIABLES	Categories				
	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts	Medium cliffs, indented coasts	Low cliffs, alluvial plains	Cobble beaches, Lagoons	Barrier beaches, beaches, deltas
Shoreline Erosion (-) / Accretion (+) Rate (m/yr) *	> (+2.0)	(+1.0) – (+2.0)	(-1.0) – (+1.0)	(-2.0) – (-1.0)	< (-2.0)
Coastal Slope (%)	> 12	12 - 9	9 - 6	6 - 3	< 3
Relative Sea-Level Change (mm/yr)	< 1.8	1.8 - 2.5	2.5 - 3.0	3.0 - 3.4	> 3.4
Mean Wave Height (m)	< 0.55	0.55 - 0.8	0.85 - 1.05	1.05 - 1.25	> 1.25
Mean Tide Range (m)	> 6.0	4.0 - 6.0	2.0 - 4.0	1.0 - 2.0	< 1.0
CVI	Very Low	Low	Moderate	High	Very High

(*) Positive values (+) indicate accretion while negative values (-) indicate erosion.

TABLE 2
Coastline length and corresponding percentages of the thirteen land use categories along the coastline of the Argolikos Gulf (data obtained from CORINNE, 2000).

LAND USE TYPES	Length (km)	Percentage (%)
Principally agricultural land, with areas of natural vegetation	38.84	15.71
Salt marshes	9.06	3.67
Complex cultivation patterns	42.83	17.33
Sclerophyllous vegetation	75.63	30.60
Fruit trees and berry plantations	6.91	2.79
Sport and leisure facilities	1.84	0.74
Discontinuous urban fabric	13.69	5.54
Natural grassland	26.42	10.69
Olive groves	3.96	1.60
Coniferous forest	17.22	6.97
Transitional woodland-scrub	8.61	3.48
Construction sites	1.46	0.59
Beaches, dunes, sands	0.70	0.28
Total	247.17	100.00

anticipated sea-level rise on the socio-economic activities along the investigated shoreline, land-uses along the coastal zone below the 20 m elevation were defined utilizing the relevant map of the CORINE 2000 land cover Program and were checked in detail, during the field mapping (Table 2). Thirteen land use categories were recognized, which include sandy beach zones (including also dunes), complex cultivation patterns, coniferous forest, construction (or man-made) sites, discontinuous urban fabric, fruit trees and berry orchards, land primarily occupied by agriculture, natural grassland, olive groves, salt marshes, sclerophyllous vegetation, sport and leisure facilities, and transitional woodland-scrub. Land uses were compared with the high vulnerable areas with the higher CVI values.

Data management has incorporated the development of a spatial database, utilizing GIS technology, for the Argolikos

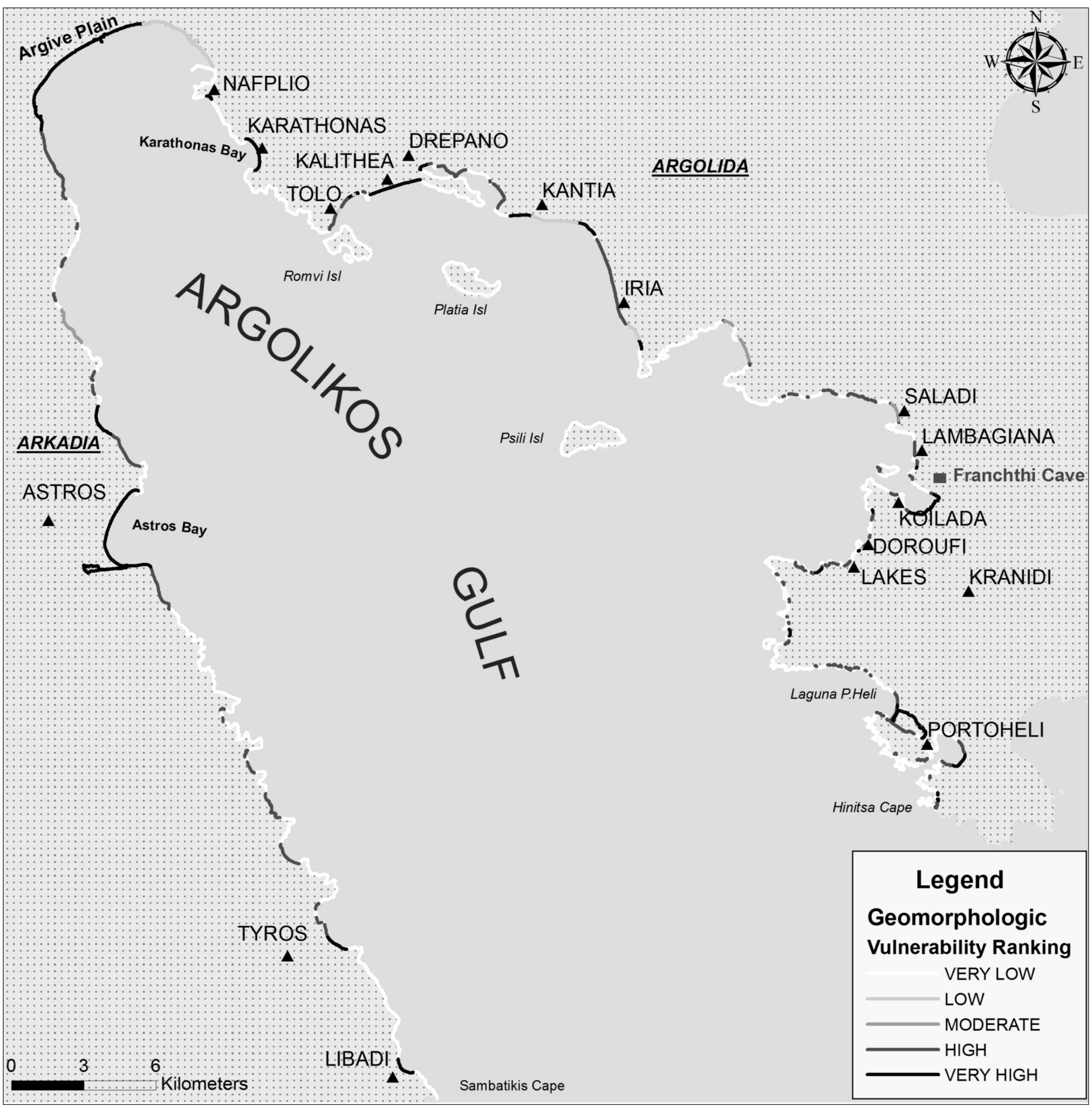


Fig.3. Map of vulnerability classification of the Argolikos Gulf coastline, according to the variable of geomorphology.

Photo 1. Low-lying marshy area between Iria and Kantia (for locations see Fig. 2).

Photo 2. Sand dunes in the area of Tolo (for location see Fig. 2).

Photo 3. Eroding beach in the area of Tolo (for location see Fig. 2).

Gulf derived from detailed analogue topographic and geologic maps of various scales, satellite images, land use maps and field observations. These maps were georeferenced to the Greek map projection system, EGSA87. A fundamental contribution element of GIS is data integration, which includes a common geographical reference system (EGSA87 for this study), common spatial and temporal coverage and similar scale and quality of data. Thus, for each CVI variable a polyline layer was created, while each variable forms a feature class (coverage), which can be displayed graphically. Individual feature classes can be superposed, and areas with a common set of attributes can be identified. Data for each of the six variables were added to the shoreline attribute table and for each section of the coastline a CVI value was calculated using the above mentioned formula. For the estimation of the coastal slope, a buffer zone of 15 m has been created and the mean slope value for this strip has been calculated.

RESULTS AND DISCUSSION

The CVI variables

The geomorphology, as a non-numerical variable, expresses the relative response of different types of coastal landforms to sea level rise. It is ranked qualitatively according to the relative resistance of the coastal landforms and rocks to marine erosion. The main coastal landforms at the study area (from very high to very low vulnerability) were coastal marshes, sandy to gravelly beaches, developed especially where the main channels of the drainage networks meet the sea, sand dunes and rocky cliffs (Fig. 3; Photos 1 & 2). Marine cliffs represent the dominant landform along the Argolikos Gulf occupying a total length of 160.1 km, which corresponds to 64.7% of the total coastline, followed by cobble beaches (38.8 km which is 15.7 % of the coastline) and beaches (25.6 km – 10.3 %). Swamps occupy 4.1 % of the shore (10.1 km) while sand dunes form 1.3 % (9.5 km) (Fig. 4a). Lithological formations range in terms of their erodibility from non cohesive sediments to hard rocks, such as limestones and dolomites. About 35.2 % of the coast is underlain by unconsolidated sediments, the remaining being limestones and dolomites (43.7 %) and clastic formations (21.0 %).

Among the considered variables, relief expressed by the coastal slope is the main indicator of inundation risk while the other variables of the database are associated with erodibility risk. The determination of regional coastal slope identifies the relative vulnerability of inundation and the potential rapidity of shoreline retreat. Low sloping coastal regions should retreat faster than steeper ones. Regions with coastal slopes lower than 3 % were characterized as of very high vulnerability, while coastal cliffs with slopes higher than 12 % were of very low vulnerability (Table 1). The 48.4 % of the coastal zone mainly at the northern (Argive plain) and the eastern part of the gulf is low lying and is characterized as highly vulnerable to inundation (Fig. 4b). Low lying beaches are developed mainly along the apron of coastal alluvial fans of the ephemeral streams that empty into the gulf. A large percentage (80%) of the western coast is of low vulnerability area due to the presence of steep rocky cliffs. Astros Bay, Tyros and Livadi are the only low lying (classified as highly vulnerable) coastal plains of the western shore (Fig. 5).

Relative sea-level change is considered to have the same value along the Argolikos coastline. Due to the lack of recent sea-level measurements, this variable took the value of 1.8 mm/yr (low vulnerability – class 2 in Table 1), which is the mean eustatic global sea-level rise rate for the time period between 1850 and 1950 (IPCC, 2007).

According to Table 1, coastline change rates in Argolikos Gulf incorporate from accretion greater than +2 m/yr (very low vulnerability) to retreat greater than -2 m/yr (very high vulnerability). Approximately 137.2 km, which corresponds to 55.5 % of the Gulf's coastline, is relatively stable (shoreline displacement within ±1 m/yr), while 18.4% of the coastline is eroding; the latter includes a 2.2 % that is characterized by a mean retreat rate >2 m/yr (Fig. 4c). Field coastal geomorphological mapping has verified that erosion is the main process along the broader area of Tolo, Kantia, Iria (Photos 3, 4, 5) and Koilada bay, while accretion takes place at the mouths of the ephemeral streams due to increased sediment supply (especially during the rainy period of the year).

A microtidal coastline is essentially always near high tide and, therefore, being always at the greatest risk of inundation and/or erosion during storms (Thieler & Hammar-Klose, 1999). The Argolikos Gulf as part of the Aegean Sea is a microtidal region with tidal (astronomical) range <15 cm, according to Tsimplis (1994). As such, the tidal variable is ranked according to Gornitz *et al*. (1994) with the value 5 (highly vulnerable).

Wave heights are proportional to the square root of wave energy, which is a measure of the capacity for erosion. The wave climate is dominated by offshore significant wave heights <0.4 m (Soukisian *et al*., 2007), according to the output of the wave model (POSEIDON program), which has been calibrated with the use of offshore field measurements from the Aegean Sea for a nine years period (1999-2007). Hence, most of the Argolikos coastline length has been characterized of very low vulnerability (rank 1) with the exception of the low lying and semi-enclosed stretches of its coastline (i.e. Nafplion Bay, Koilada Bay), where wave energy is higher; these areas have been ranked as low vulnerable (rank 2) (Fig. 7). The aforementioned increased wave energy is induced by meteorological forcing associated with southerly blowing winds that may cause a storm surge in the order of 0.5-1 m, as it is suggested by temporary sea level variation in the adjacent Saronikos Gulf (Hellenic Navy Hydrographic Service, 2005; Piraeus harbour).

The CVI values

The calculated CVI values along the coastline of Argolikos gulf range between 0.54 and 7.56. The median value of the index for the study area is 3.47 while the standard deviation is 1.83. The geographical distribution of Argolikos Gulf coast vulnerability to the potential sea-level rise is presented schematically in Figure 8. The classification method was natural breaks with five classes.

Values below 1.69 are assigned to the very low vulnerability category. A large part of the gulf coastline having a length of 115.1 km (46.6 %) is classified as having very low vulnerability (Fig. 4d). This category represents steep relatively stable coasts composed of hard rocks (limestones and dolomites). CVI values above 5.35 are classified as having very high vulnerability. Nearly 9.8 km, corresponding to 3.4% of the total coastline, belongs to this category. Low lying areas like those of Libadi, Doroufi, Tyros, Astros, Argive plain, Karathonas, Tolo, Drepano, Kantia, Iria and the southern shore of Koilada bay are characterized by very high vulnerability, mainly due to low regional slope, the sensitiv-

Photo 4. Eroding beach in the area of Kantia (for location see Fig. 2).

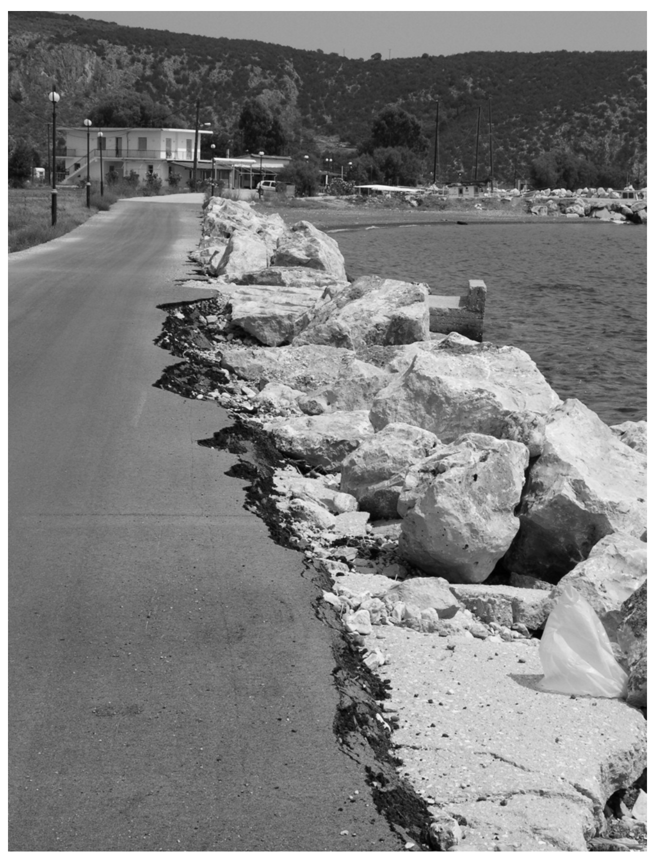


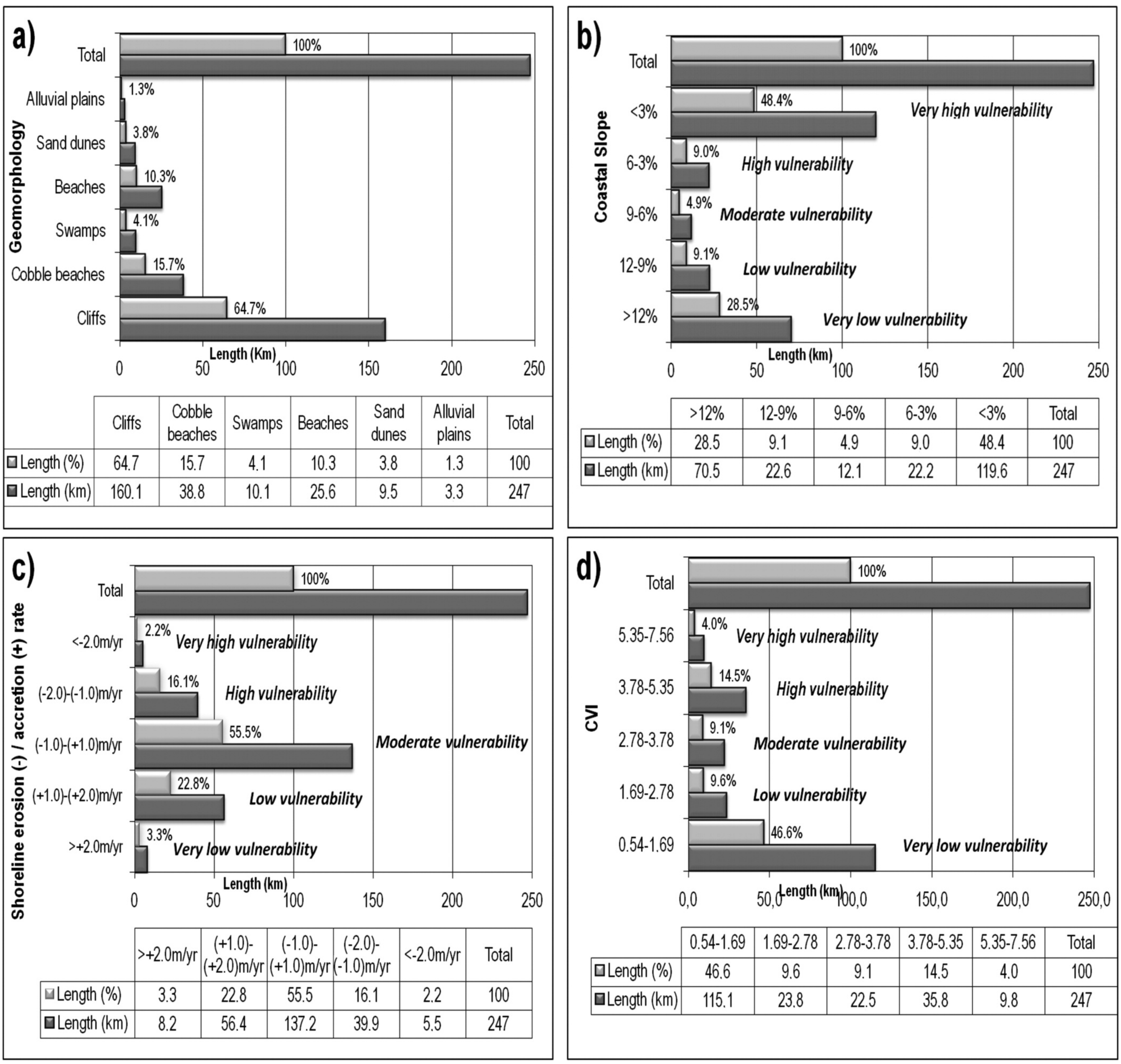
Photo 5. Coastline erosion near Iria (for location see Fig. 2).

ity of the coastal landforms and the highly erodible lithology. Finally, 14.5 % of the shoreline is classified as having highly vulnerability, 9.1% as moderately vulnerable and 9.6 % as of low vulnerability.

In terms of the socio-economical implications related to the anticipated sea-level rise, most of the coastal urban areas (cities and settlements as well as tourism activities and facilities) of the Gulf are concentrated in the above mentioned high and very high vulnerable coastal segments. Thus, a length of 2.05 km along the coastline (7.71 % of the high and very high vulnerable coast) is characterized by the presence of human activities (Tables 2 & 3). Additionally, a significant length of the high and very high vulnerability coastal zone is associated with agricultural land of economic significance. Thus, some 10.84 km, corresponding to 86.17 % of the total very high vulnerable coastline, hosts agriculture activities (complex cultivation patterns and fruit trees); similarly, these agricultural types extend for 24.33 km, representing the 52.62 %, of the high vulnerable coast (Table 3).

CONCLUSIONS

In this study the relative vulnerability of the Argolikos Gulf coast to changes due to future rise in sea-level is estimated



	Cliffs	Cobble beaches	Swamps	Beaches	Sand dunes	Alluvial plains	Total
Length (%)	64.7	15.7	4.1	10.3	3.8	1.3	100
Length (km)	160.1	38.8	10.1	25.6	9.5	3.3	247

	>12%	12-9%	9-6%	6-3%	<3%	Total
Length (%)	28.5	9.1	4.9	9.0	48.4	100
Length (km)	70.5	22.6	12.1	22.2	119.6	247

	>+2.0m/yr	(+1.0)-(+2.0)m/yr	(-1.0)-(+1.0)m/yr	(-2.0)-(-1.0)m/yr	<-2.0m/yr	Total
Length (%)	3.3	22.8	55.5	16.1	2.2	100
Length (km)	8.2	56.4	137.2	39.9	5.5	247

	0.54-1.69	1.69-2.78	2.78-3.78	3.78-5.35	5.35-7.56	Total
Length (%)	46.6	9.6	9.1	14.5	4.0	100
Length (km)	115.1	23.8	22.5	35.8	9.8	247

Fig. 4. Histograms of the classification of the most fluctuating CVI variables (a: geomorphology; b: coastal slope and c: accretion/retreat rate) and the final index values (d), concerning the coastline of the Argolikos Gulf (length and related percentages) into the five vulnerability classes (1: very low, 2: low, 3: moderate, 4: high and 5: very high) according to the Table 1.

with the calculation of the Coastal Vulnerability Index (CVI). CVI values along the shoreline vary between 0.53 and 7.56. The vulnerability of the coast to sea-level rise is spatially non uniform because of variations in some of the incorporated variables. Thus, the variables introducing the greatest variability to the CVI values are those of geomorphology, shoreline accretion and/or erosion and regional coastal slope. Among the other three factors significant wave high shows a small variation, while tidal range and relative sea-level change have the same values for the entire Gulf.

According to the criteria of coastal vulnerability, as defined in this study, the sections of coast with the highest CVI ratings include low gradient coasts underlain by unconsolidated sediments, such as the aprons of coastal alluvial fans and cones and pocket beaches. These areas will be most susceptible to both permanent inundation and erosion. Highly vulnerable regions (CVI >3.8) are the coastal zone of the Argive plain to the north, beaches along the Iria, Tolo, Kalithea and Porto Heli and the southern shore of Koilada Bay to the east. Very low and moderate vulnerability presents most of the steep rocky western coast with the exception of beaches along the Astros, Livadi and Tyros Bays; the latter are characterized as very high vulnerable. A significant length of the high and very high vulnerability coastal zone (35.16 km) is

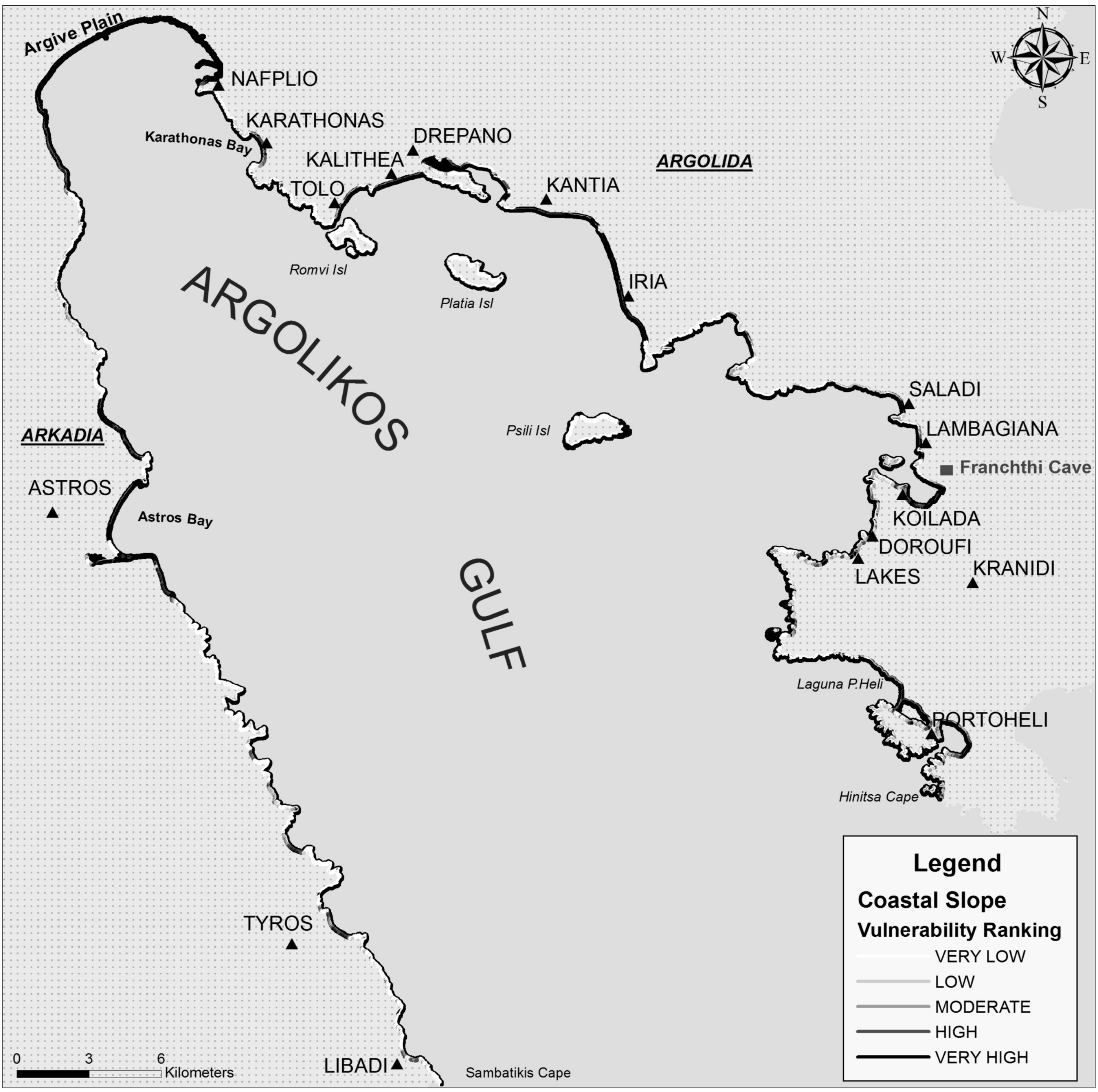


Fig. 5. Map of vulnerability classification of the Argolikos Gulf coastline, according to the variable of regional coastal slope.

occupied by economically significant agricultural land while 7.71% of the vulnerable coast hosts urban areas.

Moreover, the development of a spatial GIS database to accommodate and interrelate the variables involved in the calculation of the CVI values (including relief morphology such as elevation data and coastal slopes, coastal landforms, geomorphology, relative sea-level changes, shoreline erosion or accretion, tidal range and wave heights) could be renewed and expanded further in order to incorporate new available data (e.g. storm surge), including new variables (e.g. sediment budget), in the future for better results of the CVI. Besides, the coupling of geomorphological observations and oceanographical parameters utilizing GIS techniques allows eventual integration with socio-economic data sets concerning the study area, which is a very useful planning tool for policy makers and coastal zone managers in defining parts of the coastline, which are most likely to be threatened by sea-level rise.

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Fig. 6. Map of vulnerability classification of the Argolikos Gulf coastline, according to the variable of shoreline accretion or erosion.

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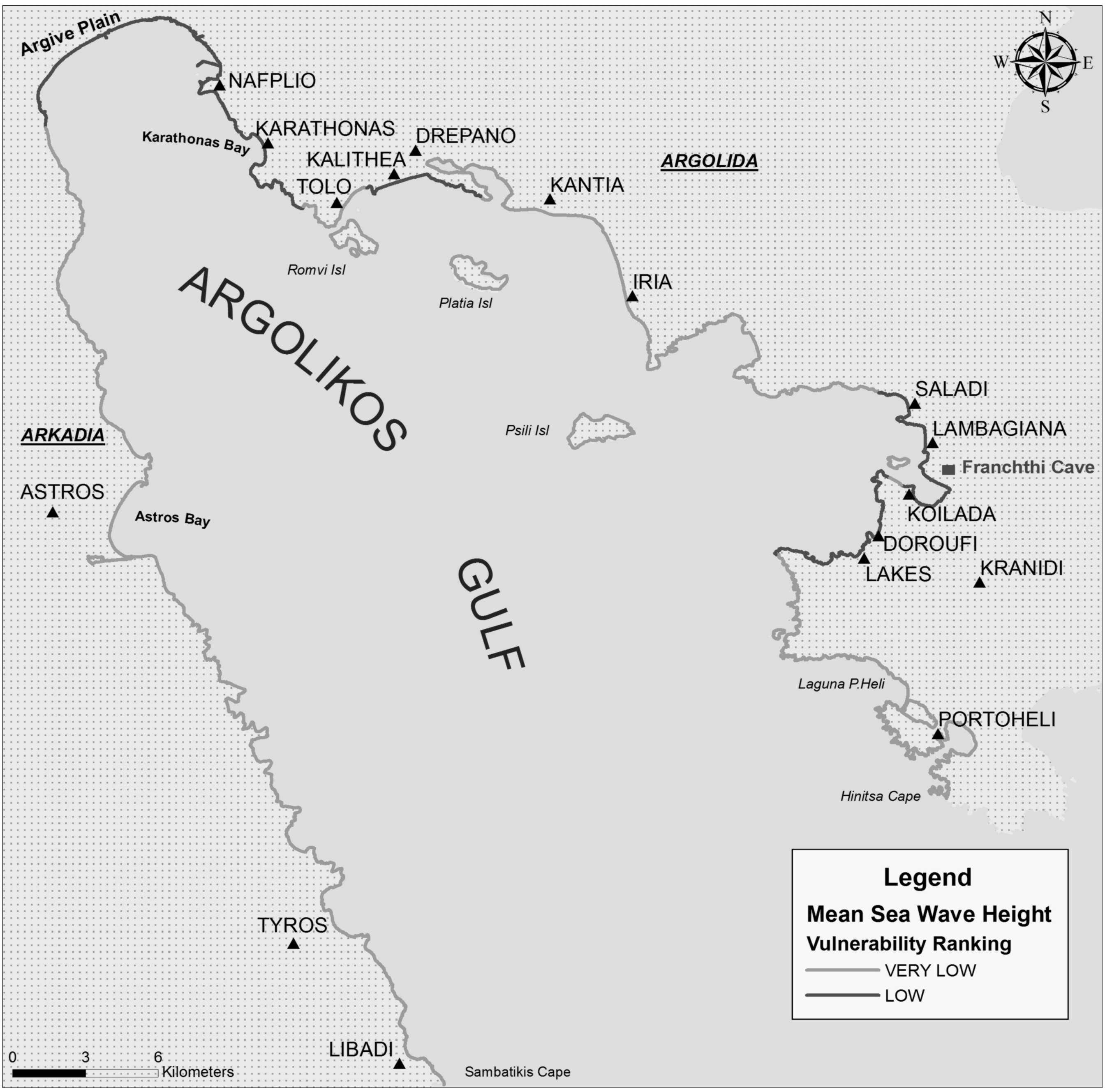

Fig. 7. Map of vulnerability classification of the Argolikos Gulf coastline, according to the variable of mean significant wave height.

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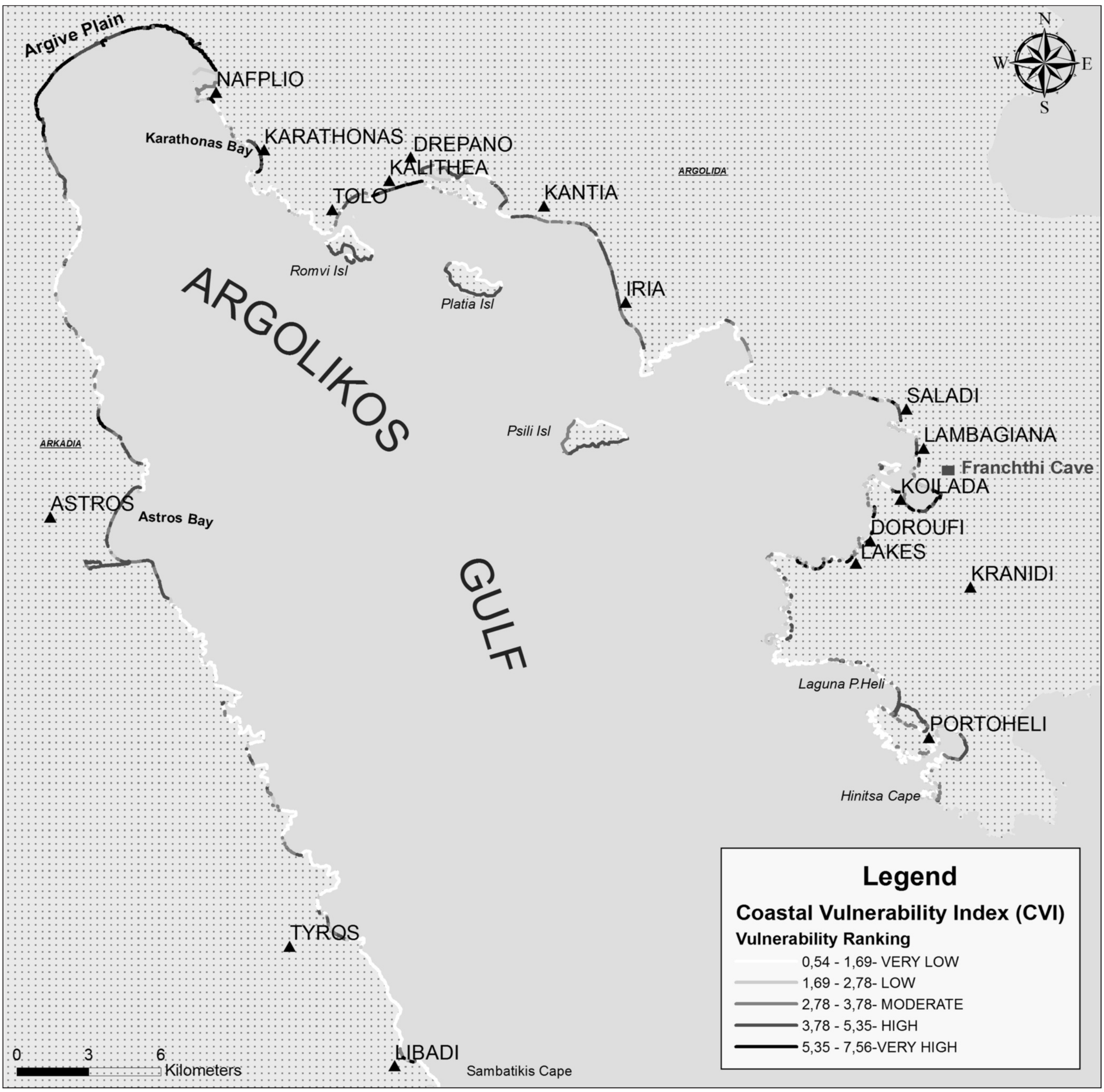

Fig. 8. Coastal Vulnerability Index (CVI) map of the Argolikos Gulf. The coastline is divided into five ranges (from very low to very high).

TABLE 3
Coastline length and corresponding percentages of the thirteen land use types, in relation to the five CVI categories.

	Vulnerability									
	Very low		Low		Moderate		High		Very high	
Land use types	(km)	(%)	(km)	(%)	(km)	(%)	(km)	(%)	(km)	(%)
Aagricultural land, with significant areas of natural vegetation	19.90	16.00	5.18	13.79	5.40	21.83	7.66	16.57	0.70	4.91
Salt marshes	0.23	0.18	0.69	1.84	1.85	7.48	5.75	12.44	0.54	3.80
Complex cultivation patterns	8.75	7.03	3.94	10.49	8.50	34.36	12.34	26.70	9.30	65.21
Sclerophyllous vegetation	52.83	42.47	8.28	22.04	1.99	8.04	10.33	22.35	2.20	15.43
Fruit trees and berry plantations	0.04	0.03	0.82	2.18	1.24	5.01	3.96	8.57	0.84	5.92
Sport and leisure facilities	0.91	0.73	0.56	1.49	0.13	0.53	0.20	0.43	0.04	0.28
Discontinuous urban fabric	2.51	2.02	6.78	18.05	2.66	10.75	1.11	2.40	0.63	4.45
Natural grassland	20.76	16.69	1.81	4.82	0.33	1.33	3.52	7.62	0.00	0.00
Olive groves	1.37	1.10	1.35	3.59	0.88	3.56	0.36	0.78	0.00	0.00
Coniferous forest	10.90	8.76	5.47	14.56	0.41	1.66	0.44	0.95	0.00	0.00
Transitional woodland-scrub	4.73	3.80	2.17	5.78	1.23	4.97	0.48	1.04	0.00	0.00
Construction sites	1.06	0.85	0.21	0.56	0.12	0.49	0.07	0.15	0.00	0.00
Sandy beaches (includind also dunes)	0.40	0.32	0.3	0.80	0.00	0.00	0.00	0.00	0.00	0.00
Total	124.39	100	37.56	100	24.74	100	46.22	100	14.26	100

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