AN ASSESSMENT OF THE VULNERABILITY TO EROSION OF THE COASTAL ZONE DUE TO A POTENTIAL RISE OF SEA LEVEL: THE CASE OF THE HELLENIC AEGEAN COAST

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Contents

Summary

The global climatic change has significant repercussions on the natural environment, with obvious changes in the natural processes that have a severe socio-economic impact on the coastal zone, where a great number of human activities are concentrated.

The Coastal Vulnerability Index (CVI) is a relatively simple and functional method, developed to estimate the vulnerability to erosion (coastline retreat) of any coastal zone in relation to a future sea-level rise. This approach combines the "sensitivity" of the coastal zone to changes, like the set back of the coastline, with the ability of the coastal system to reach a new equilibrium in the new environmental conditions. The main idea of the CVI is to rank the vulnerability of the coastal zone aiming to identify coastal regions that are comparatively more vulnerable to sea-level changes. The variables that are used for the calculation of the CVI fall in two categories: (i) the geological variables, concerning coastal geomorphology, historical coastline changes and regional coastal slope and (ii) the variables representing the marine processes, i.e. relative sea level rise, mean significant wave height and tidal range.

The present investigation examines the vulnerability of the Hellenic Aegean coastline to an expected sea level rise of up to ~40 cm by the year 2100, according to the latest (2007) IPCC (Intergovernmental Panel for the Climatic Change) scenario. Erosion problems have already appeared in the coastal zone of the Aegean Sea affecting approximately 28% of its length according to the report of the EUROSION (2001) program. The vulnerability index has been found to vary significantly along the coast of the Aegean Sea, depending on the local influence of each variable. Moreover, it seems that the geomorphological diversity of the Hellenic Aegean coastline and the difference in height of the incoming waves along the northern and southern Aegean coast play the major role in the development of the CVI values. If the sea-level rise trend of the last 5000 years (approximately 1mm/year) continues, the estimated CVI values indicate moderate to high vulnerability of the Hellenic Aegean Coast. The vulnerability becomes high for 60% of the Aegean coast and very high for the remaining 40%, if the predicted rise of >3.5 mm/year for the next 100 years according to the latest IPCC (2007) report, is adopted.

1. Introduction

One of the consequences of the global climatic change is the loss of coastal land, an area where the main human activities have been traditionally concentrated, due to a potential sea-level rise; on a global scale, the latter has been predicted to range from 38 cm up to 68 cm for the year 2100, according to the latest report by the IPCC (2007). This prospect has led the IPCC, since 1988, to define the term “vulnerability” as "the level in which the coastal system is influenced by the various factors that consist the climatic changes", aiming at the improvement of coastal zone management by developing strategies that will provide solutions to this problem. However, initial estimates of these repercussions were based mainly on the elevation of the coastal areas, not taking into account other factors, such as the coastal erosion, that will bring the coastal zone to a new equilibrium.

Coastal erosion is usually the result of a combination of factors, both natural and human-induced, that operate on different scales. The most important natural factors are: winds and storms, nearshore currents, relative sea level rise (the combination of vertical land movement and sea level change) and the slope of the coastal zone. Human-induced factors of coastal erosion include: coastal engineering, land claim, river basin regulation works (especially the construction of dams), dredging and vegetation clearing. The principal consequences of coastal erosion are: (1) loss of land with economic value; (2) destruction of natural coastal defences (usually dune systems), which, in turn, results in flooding of the hinterland and (3) undermining of artificial coastal defences that may also lead to increased flood risks.

Sea-level rise over the next century is expected to contribute significantly to physical changes along shorelines, enhancing coastal erosion, particularly of low-gradient coastal zones lacking significant fluvial inputs. Even though it is widely believed that sea-level changes over the last century have contributed significantly to shoreline change and to the inundation of coastal land, it has been proved difficult to quantify this relationship. This is due to the wide range of processes that affect coastal areas, the frequency at which coastal changes occur and the closely coupled links between the sea-level rise and the other processes driving coastal change, such as: (i) sand availability in the coastal sediment transport system; (ii) large storms that could cause changes of the shoreline position that persist for weeks to a decade, or more, and (iii) complex interactions between nearshore sand bodies and the geological and hydrodynamic conditions of the coastal zone.

Various methods have been proposed over the years for the prediction of shoreline changes, such as the Bruun rule, extrapolation of shoreline displacement rates from historic charts, and simple inundation of a static topography. These methods are based on assumptions that are either difficult to validate or too simplistic to account for the complex processes driving coastal change; thus, the ability of these methods to quantify the link between sea-level rise and shoreline change has been questioned by various authors.

A different approach for the assessment of shoreline changes due to a potential sea level rise is the Coastal Vulnerability Index, which uses the physical characteristics of the coastal system to classify the potential effects of sea-level rise on open coasts. This approach combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, yielding a quantitative, although relative, estimate of the shoreline's natural vulnerability to sea-level rise. The method has already been applied in the U.S.A., Canada and elsewhere and is presently used by the U.S. National Park Service as a planning tool for coastal park units. This index, without being a predictive tool of the future position of the coastline, provides a rank-based vulnerability assessment, permitting a comparative classification of the various coastal stretches, which allows scientists and decision makers to identify portions of the coast that are at a higher risk.

2. Coastal Vulnerability Index (CVI)

The CVI includes six variables, which are related in a quantifiable manner that expresses the relative vulnerability of the coast to physical changes due to a future sea-level rise. CVI variables can be classified in two categories: (i) the geological variables (coastal geomorphology, historical coastline changes, regional coastal slope); and (ii) the variables that represent natural processes (sea level rise, mean significant wave height, tidal range). The coastal geomorphology variable (a) expresses the relative erodibility of different landform types. The shoreline erosion/accretion rate variable (b) expresses the trend of the coastal change. The regional coastal slope variable (c) quantifies the relative vulnerability to inundation and the potential rapidity of shoreline retreat, as low-sloping coastal regions should retreat faster than steeper regions. The relative sea-level change variable (d) includes both eustatic sea-level rise and regional sea-level rise due to isostatic and tectonic adjustments of the land surface. The mean significant wave height variable (e) is used as a proxy for wave energy, which drives the coastal sediment budget (e.g. coastal erosion, sediment transport). Finally, the tidal range variable (f) expresses the contribution of tides to coastal erosion vulnerability.

The six variables are ranked in five categories of vulnerability (see Table 1). The CVI is calculated as the square root of the product of the ranked variables divided by the total number of variables (eq. 1).

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

The calculated CVI values are ranked into five categories, in consistency to variable ranking, to highlight the different levels of vulnerability.

VARIABLES	**CATEGORIES**				
	1	**2**	**3**	**4**	**5**
Geomorphology	Rocky, cliffed coasts	Medium cliffs, indented coasts	Low cliffs, alluvial plains	Cobble Beaches, Lagoon	Barrier beaches, beaches, deltas
Shoreline Erosion / Accretion rate (%)	>2.0	from 1.0 to 2.0	from -1.0 to 1.0	from -2.0 to -1.0	<-2.0
Coastal Slope (%)	12	12 - 9	9 - 6	6 - 3	<3
Relative Sea-Level (mm/a) *	<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, negative values indicate erosion

Table 1. Ranges for vulnerability ranking of variables.

3. The Aegean Sea: Physicogeographic setting.

The Aegean Sea constitutes the NE part of the Mediterranean basin (Fig. 1), covering an area of approximately 160 10^3 km^2. To the northeast, it is connected to the Sea of Marmara through the Straits of Dardanelles (62 km long, 0.45-7.4 km wide and of an average depth of 55 m), which is then connected to the Black Sea through the Bosporus Strait.

The length of the Aegean (Hellenic) coastline, which includes the islands of the Aegean Sea and the north coast of Crete, is 960.5 km. The Hellenic coastline includes various landforms, which are predominantly rocky coasts, alluvial (including deltaic) plains, beach zones (mainly pocket beaches) and a small percentage of artificial beaches.

The climate in the Aegean Sea is of the “Mediterranean” type with four distinct seasons. Furthermore, from November to March, the climate is cool and rainy, while from May to September it is hot and rather dry. The annual variation of the wind field is dominated by the persistence of northerly winds, which present a double maximum: the first during the winter period (Dec-Feb) and the second (also known as the "Etesians") during the summer period (especially July and August).

Astronomical tides are of the order of a few tens of centimetres. The wave climate is primarily wind-driven with average offshore wave heights <1.5 m, which may exceed 5 m during storms.

The Aegean coastal zone is of great socio-economic importance, as it accommodates about 1/3 of the population of Greece within a coastal strip of a few kilometres from the coastline, the majority of the industrial activity (>85%), including tourism, while the coastal plains (including deltas) form most of the fertile agricultural land of Greece. Hence, coastal zone evolution and integrated coastal zone management schemes incorporating the potential impact of a future and accelerating sea level rise are of great importance for Greece, as to the other Mediterranean countries.

4. Coastal Vulnerability of the Hellenic Aegean Coast.

4.1. Controlling Variables

The six variables controlling the CVI are determined and assessed on the basis of existing information (e.g. EUROSION, CORINNE programs), which are combined and interrelated spatially. Besides, for the needs of the present investigation, the Hellenic Aegean Coast has been divided into 9 sub-regions, according to administrative peripheries.

4.1.1. Geomorphology

The geomorphological ranking is based upon the classification of the EUROSION project (2001), according to which the following four coastal types have been recognized along the Hellenic coast (see Figure 1); these are:

1. Rocky coasts and/or cliffs made of hard rocks (low level of erosion), sometimes with a rock platform.
2. Cliffs consisting of conglomerates and/or soft-rock (e.g. chalk), which are subject to low level of erosion, with pocket beaches (<200 m long), not localized on the segment.
3. Beach zones including small beaches (200 to 1000 m long) separated usually by rocky capes (<200 m long), extensive beaches (>1 km long), often with strands of coarse sediment (gravel or pebbles), extensive beaches (>1 km long) with strands of fine to coarse sand. In addition, coastlines of soft non-cohesive sediments e.g. barriers, spits, tombolos are occasionally included together with artificial and nourished beaches.
4. Muddy coasts, represented by strands of muddy sediments, associated with deltaic deposits.

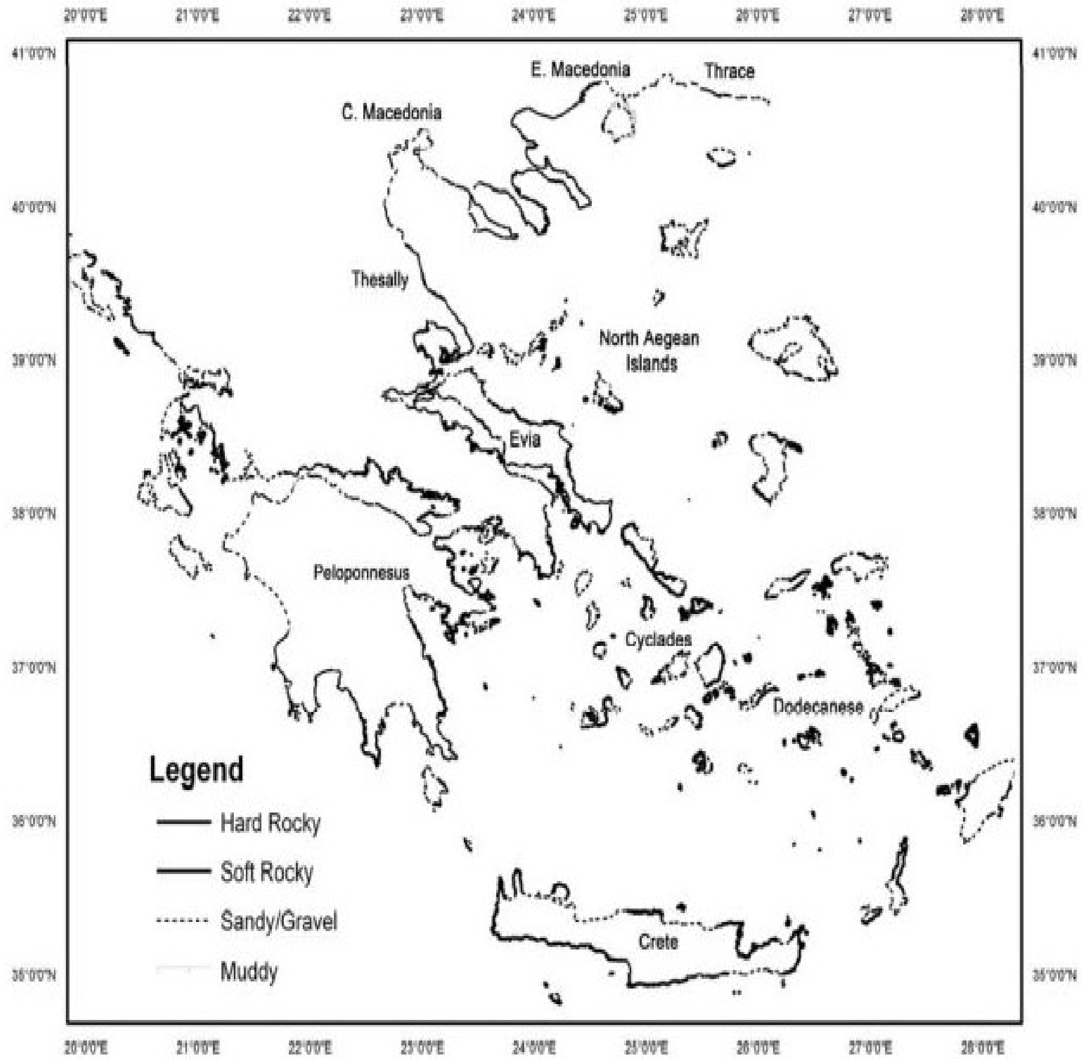

Figure 1. Major coastal types along the Hellenic coast (modified from EUROSION, 2001).

4.1.2. Shoreline Displacement (Erosion or Accretion)

The stability of the coastline position of coastal areas with elevation less than 5 m above mean sea level has been assessed during the EUROSION project (2001) and is presented schematically in Figure 2.

The percentage of the coastal zone that is under retreat is about 6.1% for Thrace and East Macedonia, 10.3% for Central Macedonia, 2.3% for Thessaly, 14.7% for the North Aegean Islands, 10.8% for Attica, 25.9% for the Cyclades and the Dodecanese islands, 3.8% for Peloponnesus and 6.1% for the northern coast of Crete.

The higher percentages are associated with the increased presence of beach zones and low-lying coastal (including deltaic) plains.

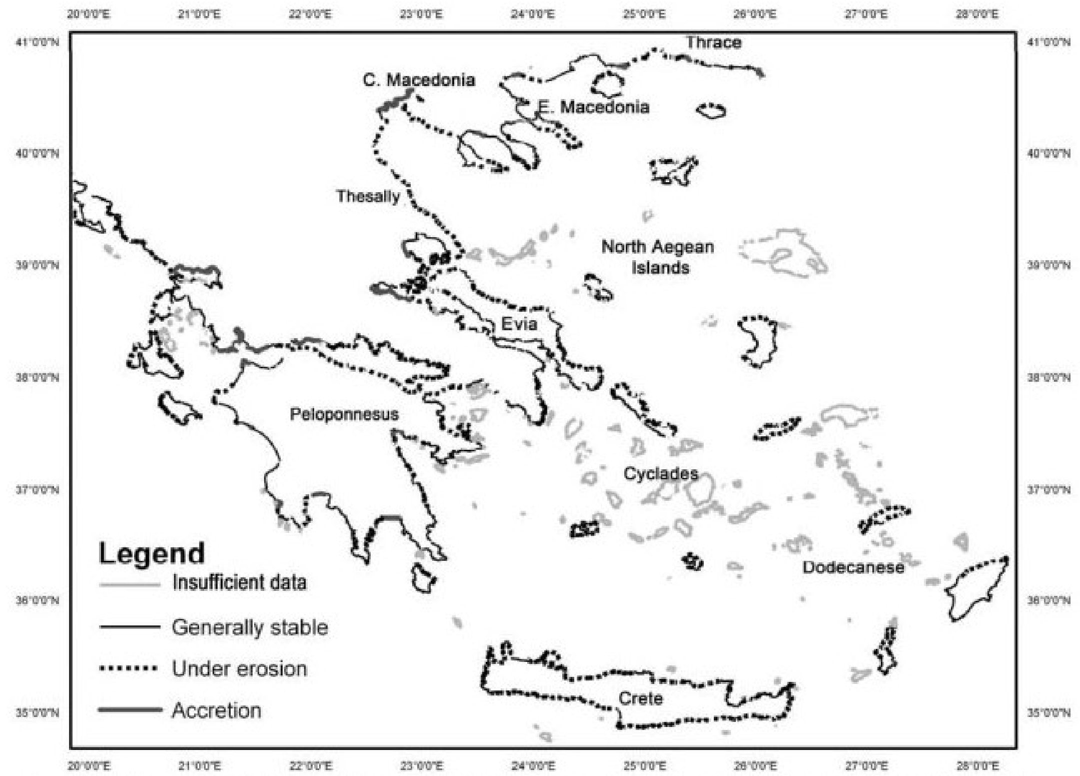

Figure 2. Current evolutionary trends of the Hellenic coastline (modified, from EUROSION, 2001).

4.1.3. Coastal Slope

The distance between the shoreline and the 5 m elevation contour line (Figure 3) was used to estimate the slope of the coastal zone for each coastal type in every sub-region. In the regions of Thrace and Eastern Macedonia, the major river deltas form coastlines with low or very low slope (<6%), which are ranked as highly vulnerable areas; they represent 72% of the total coastline length of these regions. Another 13% of the coasts have medium slopes (6-9%), 10% have high slopes (9-12%) and the rest 4% are high-cliffed coasts having very high slopes. Forty-five percent of the coasts of Central Macedonia have very low (<3%) and low (3-6%) slopes, 53% have high (9-12%) and very high (>12%) slopes, while only 2% of the coastline has medium slopes. Thessaly has very high slopes in 17% of its coastal zone, while 17% and 18% are high and medium sloping coasts, respectively; thirty-nine percent are coasts of low slope (3-6%) and 9% are very low-sloping coasts (e.g. the R. Pinios delta). Peloponnesus has mainly coastal areas with very high slopes (44% of the coastline), 25% are medium slope coasts, with the remaining 31% being coasts with low and very low slopes.

The island of Evia has mainly (45%) low cliff coasts with medium slopes (6%-9%) and a large percentage (31%) of hard rocky cliffs with very high slopes, while only the 15% are cobble and sandy beaches with low and very low slopes. In the case of the North Aegean Islands, 64% of their coastline consists mainly of pocket beaches with low slopes, while the other 36% of the coastline are hard rocky cliffs with high and very high slopes. Similarly, 51% of the coastline of the Cyclades and the Dodecanese Islands are low-cliffed coasts with slopes 6-9%, while the 46% represent pocket beaches with low slopes. In Crete, the percentage of the coastline that has high and very high slopes is almost equal to that of low and very low slopes; the former are related to cliffed coastal areas and the latter with extensive beach zones.

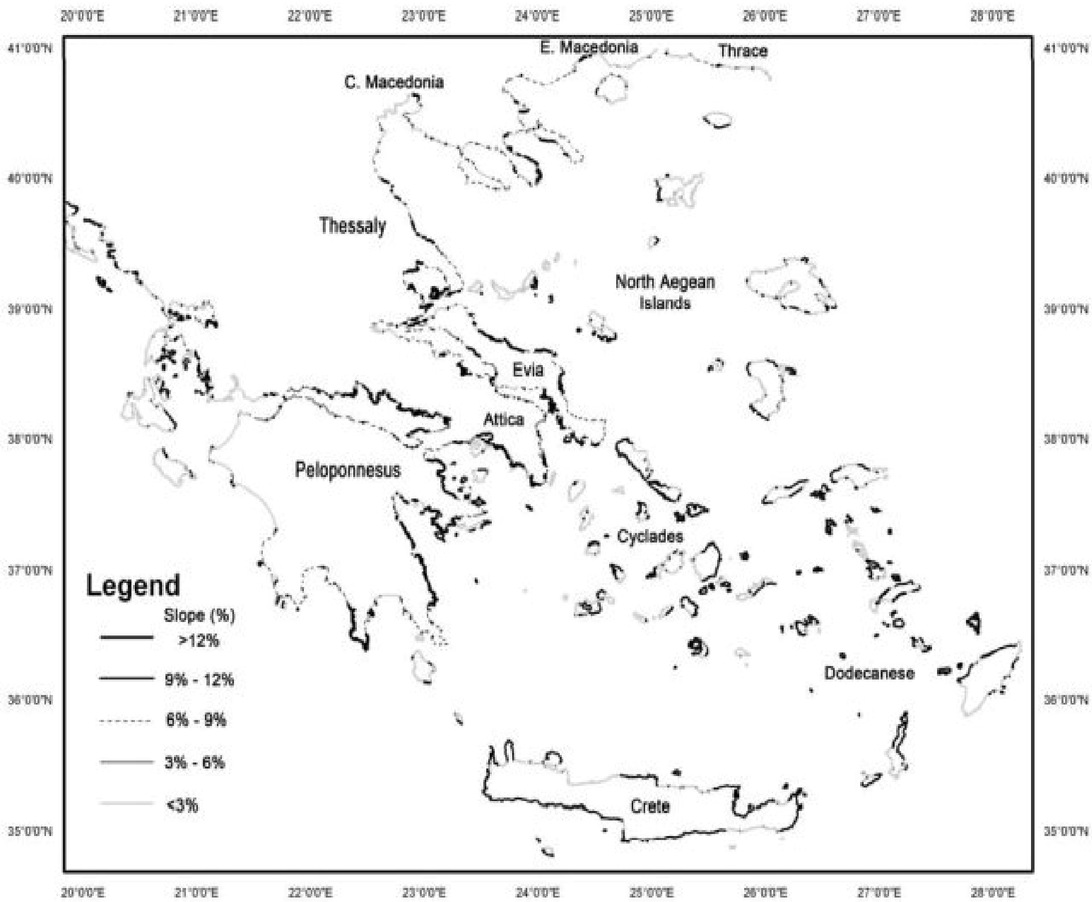

Figure 3. Coastal slope variation along the Hellenic coastline (modified, from EUROSION, 2001).

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