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

G. Alexandrakis, A. Karditsa, S. Poulos, G. Ghionis
Faculty of Geology & Geoenvironment, Department of Geography &
Climatology, University of Athens, Institute of Applied and Computational
Mathematics, Foundation for Research and Technology, Hellas.

N.A. Kampanis
Institute of Applied and Computational Mathematics, Foundation for
Research and Technology, Hellas

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Summary
The global climatic change has significant repercussions on the natural
environment, with obvious changes in the natural processes and severe socio-
economic impacts on the coastal zone, where important human activities are
concentrated.

The Coastal Vulnerability Index (CVI) method 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 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 the coastal geomorphology, the historical coastline changes and
the regional coastal slope and (ii) the variables representing the natural
processes, in the form of sea level rise, mean significant wave height and tidal
range.

The present investigation examines the vulnerability of the Aegean (Hellenic)
coastline to an expected sea level rise of up to 59 cm by the year 2100,
according to the latest (2007) IPCC scenario. Erosion problems have already
appeared in the coastal zone of the Aegean Sea affecting approximately 28%
of it as those were presented in the Eurosion program. The vulnerability index has found to vary significantly along the coast of the Aegean Sea, depending on the influence of each variable. Thus, the geomorphological diversity of the Hellenic Aegean coastline (i.e. the extended coastal plains of the northern coast), the increased wave height along the southern Aegean Coast are strongly influenced the CVI values. Furthermore, the CVI estimated values show that the Hellenic Coast of the Aegean presents a moderate to high vulnerability in the case of the observed sea level rise of 1mm/a over the past 5000 years, becoming high (60%) and very high (40%) if we adopt the prognostic range >3.5 mm/a for the next 100 years according to IPCC latest (2007) predictions.

1. Introduction

One of the consequences of the global climatic change is the loss of coastal land, an area where the main human activities are concentrated, due to a potential sea-level rise; on a global scale, the latter has been predicted to be in between 38 and 68 cm for the year 2100, according to the latest report by the IPCC (2007). This prospect has led the IPCC, in 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 rise and the slope of the coastal zone. Human-induced factors of coastal erosion include: coastal engineering, land claim, river basis regulation works (especially the construction of dams), dredging and vegetation clearing. Three are the principal impacts (or risks) related to coastal erosion: (1) loss of land with economic value; (2) destruction of a natural coastal defenses (usually a dune system) as a result of a single storm event, which in turn results in flooding of the hinterland and (3) undermining of artificial coastal defenses, potentially also leading to flood risk.

Sea-level rise over the next century is expected to contribute significantly to physical changes along shorelines enhancing coastal erosion particularly on low-gradient coastal zones lacking significant fluvial inputs. While it is widely believed that changes in sea-level over the last century have played some role in shoreline change and land loss along the coast, it has been difficult to quantify this relationship. The difficulty is due to the 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 sand availability in the coastal sediment transport system, large storms that could cause changes in shoreline position that persist for weeks to a decade or more and complex interactions between nearshore sand bodies and the geology of the coastal zone.
Various methods have been proposed over the years for shoreline-change prediction, such as the Bruun Rule, extrapolation of historic shoreline change rates, 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 to be reliable for many real-world applications; 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 the 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, and estimate of the shoreline's natural vulnerability to the effects of sea-level rise. The method has been applied in the U.S.A., in 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. This method yields numerical data that cannot be equated directly with particular physical effects. It does, however, highlight areas where the various effects of sea-level rise may be greatest.

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 and accretion rates variable \(b\) expresses the trend of the coastal area 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, whilst the tidal range variable \(f\) expresses the contribution of the tides to coastal erosion.

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

\[
CVI = \sqrt{\frac{a \cdot b \cdot c \cdot d \cdot e \cdot f}{6}} \quad (1)
\]
The calculated CVI values are ranked into five categories, in consistency to variable ranking, to highlight the different levels of vulnerability.

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 $160 \times 10^3$ km$^2$. To the northeast, it is connected to the Sea of Marmara and to the Black Sea through the Strait of Dardanelles (62 km long, 0.45-7.4 km wide and of an average depth of 55 m) and 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, beaches (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, November to March, climate is cool and rainy, while May to September 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 (July-Aug).

Astronomical tides are in the order of a few tens of centimeters. Wave climate is primarily wind driven with offshore heights average heights $<1.5$ m, which may exceed the 5 m due to meteorological forcing.

The Aegean Coastal zone is of great importance as accommodates the majority of the socio-economic activities of Greece as about the 1/3 of the population of Greece within a coastal strip of a few kilometers from the coastline, the majority of the industrial activity (>85%) including tourism, while the coastal plains and deltaic plains forms fertilized grounds for agriculture. Hence, coastal zone evolution and integrated coastal zone management schemes incorporating the potential impact of a future accelerating sea level rise is 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), which are combined and interrelated spatially. Besides, for the needs of the present investigation, the Aegean (Hellenic) 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 consist 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).](image)

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).](image)

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 and 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. The 45% of the coasts of Central Macedonia have very low (<3%) low (3-6%) slopes, the 53% have high slopes (9%-12%) and very high slopes (>12%), while only 2% of the coastline has medium slopes Thessaly has very high slopes in 17% of the coastline, while 17% and 18% are high and medium sloping coasts, respectively. The 39% are coasts of low slope and 9% are very low sloping coasts, representing primarily 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 of 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 beaches. 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 extended beach zones.

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

4.1.4. Relative Sea Level Change

The curves of sea level rise for the past 10,000 years presented in Figure 4 have a very good agreement for the last 2000 years, whilst prior to 4000 BP the curve referred to the Thermaikos Gulf (NW Aegean Sea) together with Van Andel’s (1990) global eustatic curve indicate a lower sea level (about 2 m); on the contrary, Lambeck’s (1996) glacio-hydro-isostatic model estimates the position of sea surface to be approximately 1 m higher than the others. Thus, in the case of the Central Aegean, according to the curves of Figure 4, the sea level 5000 years ago was 4.5-5 m below its present level and it continued to rise at a steady rate of approximately 0.9 mm/a up to present. Furthermore, it can be seen that between 2000 and 2500 years BP, sea level was 1.5 to 2.5 m below its present stage; a similar pattern of sea-level rise in the Aegean Sea has been also reported by the scholar Negris in the beginning of the 19th century interpreting relevant archaeological data.

Figure 4. Sea-level curves, based upon a compilation of published
Similarly, a positive tendency of sea-level rise during the last centuries has been deduced from the records of 16 out of 23 tidal gauge stations in the eastern and central Mediterranean Sea and for time-spans between 1880 and 1980 AD; in 14 stations the rates of sea-level change varied between +0.3 mm/a and +2.5 mm/a. A more recent study, based on data for the whole of the Mediterranean Sea, has given a relative sea level rise >2 mm/a.

On the basis of the above in the case of the Aegean, a steady rate of sea level rise of up to 1 mm/a is attributed to most of the Aegean region for the last 5000 years, whilst a potential rise for the next 100 years (IPCC report, 2007) assumes a rate of more than 3 mm/a.

4.1.5. Offshore Wave Climate

The offshore wave regime of the Aegean Sea has been measured by the POSEIDON environmental monitoring system of the Hellenic Centre for Marine Research (2007) and is presented schematically in Figure 2.

![Figure 5. Mean Annual significant wave height of the Aegean Sea (HCMR, 2007)](image)

The average annual significant wave height is 0.4 m for Thrace and East Macedonia, 0.5m for Central Macedonia, 0.6m for Thessaly and 0.9 m for the North Aegean Islands. In the case of the coastlines of the Cyclades and the Dodecanese islands the average annual significant wave height is higher (from 0.9 to 1.1 m) to become smaller (0.5 m) to the west, along the eastern coasts of Attica and Peloponnesus. Finally, the average annual significant wave height for the northern coastline of the island of Crete is 0.6 m in the central section becoming 0.8 m towards its eastern and the western sections of the coastline.

4.1.6. Tidal Data and Sea-level Rise

Sea level variation over the past decades is due to the combined effects of astronomical and meteorological tides. The astronomical tide, in the case of Hellenic waters, is generally less than 10 cm, having as principal constituents the $M_2$ and $S_2$ (1-9 cm) with phase angle of propagation between $30^\circ$ - $370^\circ$ (Fig. 6). However, the overall fluctuation of sea level exceeds 0.5 m due to meteorological forcing (differences in barometric pressure, wind and wave setup). The mean sea level fluctuations (the sum of meteorological and astronomical tide) for selected locations of the Aegean Sea are presented on Table 2. These values are based on sea-level measurements conducted in major Greek ports by the Hellenic Navy Hydrographic Service.
Figure 6. The co-tidal (---) and co-range (-) contours for M$_2$. Amplitudes are in cm and phases in degrees. The numbers (1-12) indicate the locations of the tidal stations (ports) used in the analysis.

**Table 2.** M$_2$ and S$_2$ amplitudes (cm) and phases (degrees) for selected locations of the Aegean Sea and mean tidal range.

The relative sea level variation for the northern region varies from 0.68 m in the eastern part (Thrace) to 0.87 m in the western part, in the Thermaikos Gulf. Mean tidal (water) level for the coastlines of the Cyclades and the Dodecanese islands and the eastern coasts of Attica and Peloponnesus are in the order of 0.5-0.6 m, whilst the northern coastline of the island of Crete experiences sea level variation <0.5 m.

4.2. Calculation of the CVI

The four coastal types identified along the Hellenic Aegean Coast (see Fig. 1) and the regional coastal slopes ranging from very low (<3 %) to very high (>12 %) have been ranked according to Table 1 (after Pendleton et al., 2004). The erosion/accretion rate variable for which sufficient, consistent and accurate data was not available for all coastal segments has been ranked as follows: Stable coasts were assigned a rank of 3, eroding coasts a rank of 4 and accreting coasts a rank of 2, considering that nowhere rapid coastline evolution has been reported.

The rate of relative sea-level change is ranked using the modern rate of eustatic rise for the Eastern Mediterranean (1.8 mm/yr) as very low vulnerability (category 1), since the rate of relative sea level rise, according to recent studies for the Aegean Sea show a gross rate of SLR of about 1 mm/a for the past 5000 years. Subsequently, the CV index has been calculated adopting, for the offshore wave significant wave height the mean heights presented on Figure 5, ranked according to Table 1. The same has been applied to the mean tidal level (see Fig. 6); this does not reflect only the astronomically induced tidal oscillation but incorporates also the meteorological forcing.

5. Discussion and Conclusions

The calculation of the Coastal Vulnerability index for the coast of the Aegean Sea for SLR of category 1 (<1.8 cm/s) has shown (Fig. 7) that almost the half of the Aegean coast is of moderate vulnerability with the remaining being of high vulnerability (Fig. 8a). Thrace and Eastern Macedonia, Central most of Central Macedonia, Thessaly and Evia are less vulnerable, while the island of Crete and the has the highest vulnerability rank as most of the Southern Aegean coast including Attica; this is attributed to the coastal types which are mainly sandy and gravelly beaches as in the case of Crete and the incoming
higher waves compared to the northern part of the Aegean Sea.

Figure 7. Map showing the vulnerability of the Aegean coastline for SLR <1.8 mm/a.

In Figure 9, the various levels of vulnerability of the Hellenic coast are shown in the case of materialization of the IPCC latest prediction concerning a rhythm of sea level >3.5 mm/a for the next 100 years. As it can be seen with the exception of a part of Thessaly and Evia all the Hellenic Aegean cost will undergo high to very high vulnerability (see also histogram in Figure 8b). For the total length of the Aegean Coast the 1/3 is comparatively highly vulnerable, more than 50% highly and the remaining 7% medium vulnerable. Apart for the rate of increasing sea level that obviously plays an important role, again, coastal geomorphology (coastal types and slopes) and offshore wave climate are the controlling factors of CVI values.

Figure 8. Histogram showing the percentages of the coast of various administrative peripheries of Greece for the five categories of vulnerability due to SLR by <1.8 mm/a (a) and for >3.5 mm/a (b).

Figure 9. Map showing the vulnerability of the Aegean coastline for SLR >3.5 mm/a.

The outcome of the present assessment for the vulnerability of the Aegean (Hellenic) coast although provides a good tool for coastal zone management, it has to be used with precaution in the case of studies in coastal areas of smaller scale. Coastal Vulnerability Index applied to large scale studies, such as the whole of the Aegean Coast, it has the disadvantage that it does not include special characteristics that may play an important role to the evolution of a specific coastal region. For example, the islands of the Aegean Sea are mainly rocky, but there are numerous small (hundreds of meters long) pocket beaches that can not be identified in large scale studies. Also the wind and wave characteristics may change in value and direction in a smaller scale, as small obstacles, like small islands, may change the wave height and the direction of wave incidence at the shore. For complex geomorphologically
and hydrodynamically coasts, like the multimeferous Aegean coast it is better
to use such indexes in smaller scale studies. In addition, there are major
differences in the estimation of the index when it refers to beach zones, where
the evolution is controlled by different factors such as the granulometry of the
beach zone and the position of the breaking zone.

Thus, for more detailed investigation of shore zone evolution models
incorporating more complex assumptions regarding coastal processes (e.g.
nearshore hydrodynamics and sediment dynamics, coastal zone sediment
budget) like the Advanced Circulation Model (ADCIRC), the Regional Ocean
Modelling System (ROMS), the Delft3D, the Shoreface Translation Model
and the Geomorphic Model of Barrier, Estuarine, and Shoreface Translations
(GEOMBEST), have been developed during the past decades. Even though
these models are used widely as research tools to advance our understanding
of past and present shore zone behavior, most of them apply to specific
coastal morphological and/or sedimentological formations.

In conclusion, the CVI is a good tool for general estimations of the
vulnerability of an area to erosion due to SLR, but it is better to be used in
smaller scales and the results to be combined with field observations
supported by detailed geomorphological, sedimentological; and coastal
oceanographic data.

Related Chapters

Glossary

Alluvial plain: Relatively flat landform created by the deposition of
sediment over a long period of time by one or more rivers
coming from highland regions, from which alluvial soil forms

Barrier beaches: A long and narrow beach of sand and/or gravel that runs
parallel to the coastline and is not submerged by the tide.

Cliff: A tall steep rock face.

Coastal Slope: The mean slope of the beach zone

Coastal Zone: Relatively nutrient-rich, shallow part of the ocean that
extends from the high-tide mark on land to the edge of the
continental shelf

Coastline: The line that separates a land surface from an ocean or sea.

Delta: Large deposit of alluvial sediment located at the mouth of a
stream where it enters a body of standing water

Dredging: An excavation activity or operation usually carried out at
least partly underwater, in shallow seas or fresh water areas
with the purpose of gathering up bottom sediments and
disposing of them at a different location, mostly to keep
waterways navigable

Erosion: The wearing away of land or the removal of beach and/or
dune sediments by wave action, tidal currents, wave currents,
drainage, or wind. Erosion includes, but is not limited to, horizontal recession and scour and can be induced or aggravated by human activities.

Eustatic sea-level: Variations in sea-level that are related to changes in the volume of seawater in the oceans.

Isostasy: The buoyant condition of the Earth's crust floating in the asthenosphere. The greater the weight of the crust the deeper it floats into the asthenosphere. When weight is remove the crust rises higher.

Pocket beach: A small beach, between two headlands. In an idealized setting, there is very little or no exchange of sediment between the pocket beach and the adjacent shorelines.

Significant Wave Height (SWH): Is the average wave height (trough to crest) of the one-third largest waves.

Sea Level: The average surface elevation of the world's oceans.

Tide: Cyclical rise and fall of the surface of the oceans. Caused by the gravitational attraction of the Sun and moon on the Earth.

Tombolo: A deposition landform such as a spit or bar which is attached to the mainland by a narrow piece of land. They usually form because the island causes wave refraction, depositing sand and shingle moved by longshore drift in each direction around the island where the waves meet.

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.

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