Natural and human induced indicators in coastal vulnerability and risk assessment

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Abstract

Climate change has significant repercussions on the natural environment, triggering changes in the natural processes that might have a severe socio-economic impact on the coastal zone; where a great number of human activities are concentrated. So far, the estimation of coastal vulnerability has been based, primarily, on the natural processes and, secondarily, on socio-economic variables, which would assist in the identification of vulnerable coastal sectors. The present investigation proposes a methodology to examine the vulnerability of a highly touristic area in the Island of Crete to an expected sea level rise of up to ~40 cm by the year 2100, according to the A1B scenario of IPCC 2007. The methodology is based combination of socio-economic indicators and existing natural indicators, GIS-based, of the coastal vulnerability index (CVI) for sea level rise and related wave-induced erosion. This approach includes three sub-indices that contribute equally to the overall index. The sub-indices refer to coastal forcing indicators related to extreme natural events; (ii) socio-economic indicators, such as those of population, cultural heritage sites, transport networks, land use and protection measures; and, (iii) indicators of coastal characteristics that refer to both geological variables (i.e., coastal geomorphology, historical coastline changes, and regional coastal slope) and marine processes (i.e., relative sea level rise, mean significant wave height, and tidal range). All variables are ranked on a 1-5 scale with the rank 5 indicating the highest vulnerability. The socio-economic sub-index includes, as indicators, the population of the study area, cultural heritage sites, transport networks, land use and protection measures. The coastal forcing sub-index includes the frequency of extreme events, while the Coastal Vulnerability Index includes the geological variables (coastal geomorphology, historical coastline changes, and regional coastal slope) and the variables representing the marine processes (relative sea level rise, mean significant wave height, and tidal range). The main difficulty for the estimation of the index lies in assessing and ranking the socio-economic indicators. The whole approach was tested and validated through field and desktop studies, using as a case study the Elounda bay, Crete Isl.; an area of high cultural and economic value, which combines monuments from ancient and medieval times, with a very high touristic development since the 1970s.

Keywords: Sea level rise, adaptation, erosion, socio economics, vulnerability

Introduction

The expected accelerated sea level rise and the potential physical changes to the coastline can endanger coastal ecosystems, populations and infrastructure (McLean et. al., 2001). The sensitivity of the coastal zone to sea level rise, combined with the social, economic, and ecological value (e.g., Costanza et al., 1997; Agardy et al., 2005), has led to the proposal of a significant number of vulnerability indices developed for specific coastal areas (Gornitz et al., 1993; Hoozemans et al. 1993; Leggett and Jones, 1996; O'Riain, 1996; Cambers, 1998; Thieler and Hammar-klose, 1999; Mimura, 2000; Vafiadis et al 2008, Alexandrakis and Poulos 2014). The main objective of most of the existing indices is the classification of the coastline into areas with similar attributes or characteristics, while the majority uses multidisciplinary data related to natural processes. The need for the inclusion of socioeconomic variables has also been noted by Gornitz et al. (1993), which stated that the omission of socio-economic variables from their coastal vulnerability index could potentially limited evaluation of vulnerable areas. Likewise, indices reviewed by Cooper and McLaughlin (1998) and those examined since, reveal a general acknowledgement that there is a need to include socio-economic variables in the classification procedure (McLaughlin et al., 2002). Nevertheless, the estimation of coastal vulnerability related to climate change is still based, primarily, on natural processes and to a lesser extent on socio-economic considerations. This has led to criticism to vulnerability studies and to separation of the physical from the socio-economic aspects in vulnerability studies (e.g., Blaikie et al. 1994; Gough et al. 1998; IPCC, 2001; Nicholls and Small, 2002). The exclusion of the socio-economic variables derives from the difficulty in obtaining and ranking the data. Besides, socio-economic data can change over time (e.g. building of new houses and roads etc.) and perceptions of threat and of appropriate response may also change with time (Carter, 1993). Also, the fact that socioeconomic indicators are time constrained makes their use more difficult (McLaughlin et. al., 2002), while their ranking could be proved difficult, since it is not easy to assign an economic value to an attribute. The indicator-based approach proposed by Kaiser (2006) has accepted as one of the most appropriate approaches for intangible elements in ranking this kind of data. Despite these difficulties, the inclusion of socio-economic variables is of great importance, perhaps even essential, in the development of valid coastal vulnerability indices in order to mitigate hazards, and adapt to environmental and climate change (Birkmann, 2006; O'Brien et al., 2006). However, the evaluation of vulnerability involves diverse practical challenges, including political willingness, complexity of the problem, poor understanding of related issues and the importance of the results (Patt et al., 2009). Some coastal vulnerability studies have attempted more integrative assessment approach by combining both physical and socioeconomic vulnerability to an overall vulnerability index system (Wu et al.2002; Cutter et al. 2003; Boruff et al. 2005; Preston et al. 2008).

The present investigation proposes a methodology to examine the vulnerability to wave-induced erosion and sea level rise, of a highly touristic area in the Island of Crete with the introduction of socio-economic indicators into a GIS-based Socio-economic Coastal Vulnerability Index (SocCVI) and compares the results with those produced by the CVI of Thieler and Hammar-Klose (1999). This approach includes three sub-indices: coastal forcing, socio-economic, and coastal characteristics. All variables are ranked on a 1-5 scale, with 5 indicating higher vulnerability. The socio-economic sub-index includes the population of the study area, cultural heritage sites, transport networks, land use and economic activities. The coastal forcing sub-index includes the variables representing the marine processes, while the CVI includes the geological variables. The main difficulty for the estimation of the index lies in assessing the socio-economic indicators. The whole approach was tested and validated through field observations and numerical studies, using as a case study the Elounda bay, NE Crete Isl.; an area of high cultural and economic value, which combines monuments from ancient and medieval times with a large touristic development since the 1970s.

Study Area

Elounda bay is located at the NE part of Crete Island, covering an area of about 10 km^2. It is a semi-enclosed bay with an eastward-facing entrance on the north side. Its southern end consists of a tombolo formation, which connects the island of Crete with the Kolokitha peninsula. The surrounding coastal area hosts various sites of archaeological interest, such as ancient cities and facilities, dating from the Minoan era (27th -15th century B.C.) to the recent historical monuments of the early 20^{th} century. Between them, the most important is the Spinalonga fortress, located on a small island at the centre of the gulf, which has recently been nominated as a UNESCO World Heritage site (Fig. 1a).

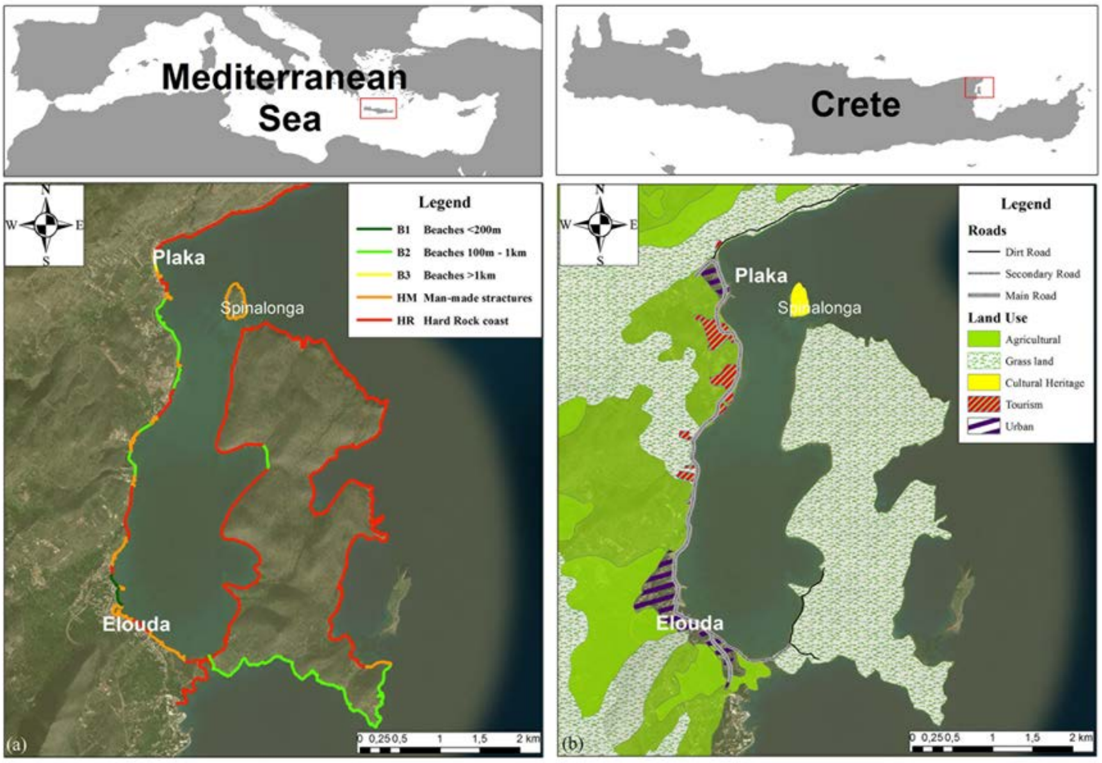

Figure 1: Coast classification (a) and land Use (b) in the study area.

Six coastal types have been identified in the area: Hard rocky coasts (HR) occupying 58.89 % of the total shoreline length, soft rocky coasts (SR) (2.34 %), beaches with length <100 m (B1) (2.75 %), beaches with length <1 km, but >100 m (B2) (12.23 %), and a very small percentage (0.39 %) of beaches with length more than 1 km (B3); the latter are very narrow, rarely exceeding 10 m in width. A significant percentage (23.41%) of the shoreline hosts man-made structures (HM) i.e., ports and fishing shelters, coastal walls and groynes (Fig. 1a). In addition, there are several hotels and other leisure facilities, while tourist development is still growing. The main agricultural activity in the area is the production of olive oil from, while there aren't any forests or significant industries. In the surrounding areas, there are organized settlements and scattered farmhouses. The local transport network consists of a paved coastal road and some dirt roads that serve agricultural activities. The main road is of major importance, as it is the only road connecting the coastal town of Elounda with the inland villages, and it is supported by a coastal wall for most of its length (Fig. 1b). The area under investigation is exposed primarily to winds of northern directions (32.96 % annual frequency of occurrence) followed by western and south-western winds (20.58% and 13.25%, respectively). Wave regime is dominated mainly by NE and E wind-waves with relatively low frequencies of occurrence (7.37% and 3.44% respectively), while severe storm conditions (H_s >5 m) occur with an annual frequency <1% (Fig. 2).

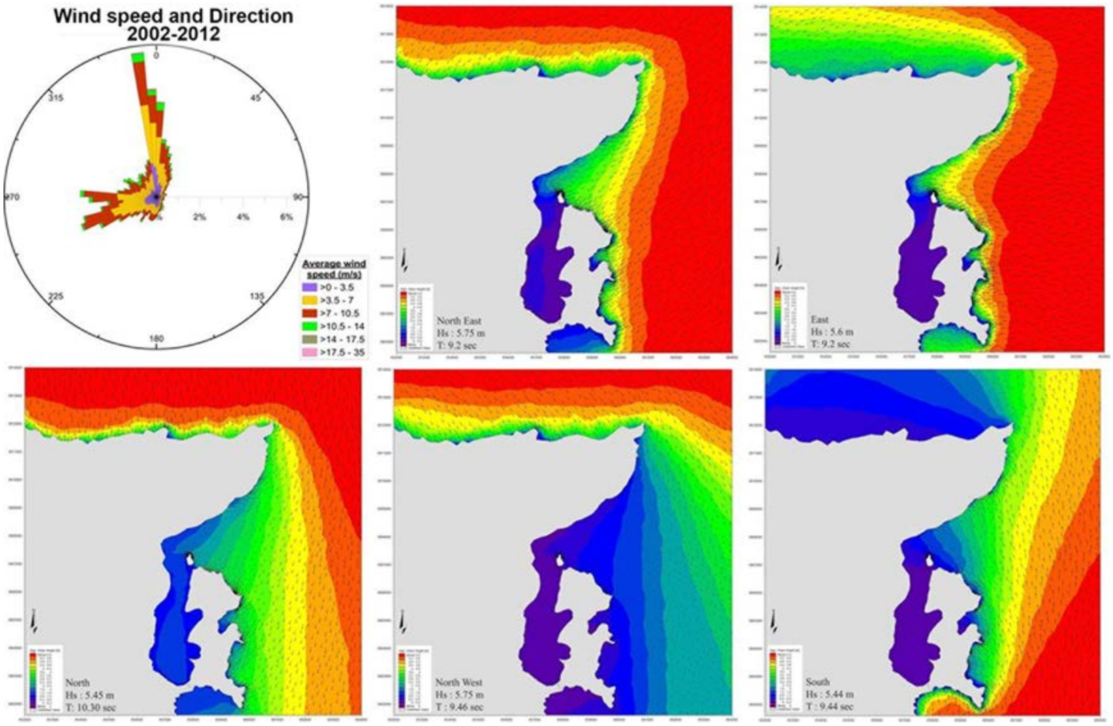

Figure 2: Wind frequencies and wave climate.

Methodology

Coastal Vulnerability Index

In order to estimate coastal vulnerability for the study area, the six physical variables (i.e., geomorphology; coastal slope; relative sea-level rise rate; shoreline erosion/accretion rate; mean tidal range and mean wave height) of the Coastal Vulnerability Index (CVI) of Thieler and Hammar-Klose (1999). In table 1 are listed, justified and ranked the variables used for the calculation of the Coastal Vulnerability index.

Socioeconomic Vulnerability index

For the calculation of the Socioeconomic Vulnerability índex, the variables of the CVI were integrated with socio-economic variables, on the basis of the work of McLaughlin et al. (2002). The socio-economic variables chosen as indicators has been selected in aiming to satisfy the criteria that must be easily obtained, and include, if possible, most the characteristics related to the economic growth and social development.. In this work the following social indicators were used: the presence and size of Settlements (SET), sites of Cultural Heritage (CH), Transport Network (TN), Land Use (LU) and Economic activities (E). From these variables, transport network and cultural heritage are easily to be obtained, while settlements, land use and economic activates as being time dependent, they are time limited and they must be reassessed after a certain period. The variables were ranked on a 1-5 scale, according to their perceived vulnerability (with 5 being the most vulnerable and 1 the least vulnerable).

Settlement size is used as a proxy for the estimation of the population in the study area. Population is not commonly used variable in published coastal vulnerability indices, but it is acknowledged that an area with greater population would have an increased economic value (Hughes and Brundrit, 1992). Settlement size can be considered as an economic variable because in larger settlements more people are affected and act to protect their properties from erosion (Dilley and Rasid, 1990; Rivas and Cendrero, 1994). Settlement size can also be considered as a direct "erosion-inducing" variable because the presences of large numbers of people near the coast can have a more severe impact on the coastal area (e.g. larger coastal structures). Both aspects of settlement size are complementary in relation to coastal vulnerability, as each one enhances the effect of the other in increasing or decreasing vulnerability. Settlement data are time dependent, since the size of the settlements can change with time and need to be re-evaluated periodically. The settlement size is ranked on a 1-5 basis, with the assumption that, larger settlements are affected more by erosion; therefore they are directly correlated with increasing vulnerability.

The value and vulnerability of *cultural heritage* sites (i.e. Archaeological and historical monuments) in the coastal zone, as part of cultural resource, are irreplaceable. This makes them important in not only economic terms, but also in social and cultural terms Thus, even if coastal retreat due to a rising sea level is unavoidable in some areas, protection measures are necessary for cultural heritage sites (Hopley, 1992).. Even though it is to identify a cultural heritage site, it is, difficult to assign an economic value on a cultural heritage resource. Even if one site is better preserved than another, this does not mean that it is more important. Therefore, any method of ranking this variable is subjective. To address this problem, the ranking of the sites in the present study was made in terms of global importance. Hence, sites of global interest are considered as most vulnerable, while less important sites are assigned a lower vulnerability value.

Transport network is to incorporate into an index, because they have well-defined geometrical characteristics (length and width), which can be measured, and the cost of their protection or replacement can be calculated. Also, transport networks present very little variations with time. Herein, the TN variable is ranked based on the size of the roads, with larger roads to be considered as more vulnerable.

Land Use type is very significant in determining vulnerability, because protection measures for a vulnerable area will be considered only if it has sufficient economic, cultural or environmental value to justify protection. Land value can be defined in different ways, such as financial terms, or replacement cost or in aesthetic or conservation value. Other indices that incorporate Land Use as a variable include those of McCue and Deakin (1995), and O'Riain (1996). Ranking of Land Use variables, should consider the characteristics of the given area in terms of economic growth (Hughes and Brundrit, 1992). For the purposes of this study, Land Use types were grouped and then ranked according to EUROSION 2004, with urban and industrial sites to be considered as more vulnerable.

Economic activities variable represents the financial value related to the land use type of the areas. In this study as most vulnerable is considered the coastal sectors that are used for tourism purposes, since tourism is the main factor that drives the economic growth, not only of the specific area but Greece, followed by agriculture (Manasakis et al., 2013). In table 1 the ranking of all variables is presented.

Table 1: Indices variables and their rankings.

VARIABLES		Categories				
		1	2	3	4	5
		Very Low	**Low**	**Moderate**	**High**	**Very High**
Geomorphology	**GEO**	Rocky, Cliff coasts	Medium cliffs coasts	Low cliffs, alluvial plains	Lagoon, Cobble Beaches	Beaches, deltas
Shoreline Erosion (%)	**ERO**	>2.0	from 1.0 to 2.0	from -1.0 to 1.0	from -2.0 to -1.0	<-2.0
Coastal Slope (%)	**CS**	12	12 - 9	9 - 6	6 - 3	<3
Relative Sea-Level Rise(mm/a)	**RSLR**	<1.8	1.8 - 2.5	2.5 - 3.0	3.0 - 3.4	> 3.4
Mean Wave Height (m)	**Hs**	<0.55	0.55 - 0.8	0.85 - 1.05	1.05 - 1.25	>1.25
Mean Tide Range (m)	**T**	>6.0	4.0 - 6.0	2.0 - 4.0	1.0 - 2.0	<1.0
Settlement	**SET**	Absent	Village	Small Town	Large Town	City
Cultural Heritage	**SH**	Absent	Local	Regional	National	Global
Transport Network	**TN**	Absent	Secondary	National road	Ports	Highway
Land Use	**LU**	Bare rocks	Grasslands Coastal areas	Forest	Agricultural	Urban , Industrial
Economic activities	**E**	Absent	Agricultural	Commercial	Industrial	Tourism

Calculation of indices

CVI

First, the Coastal Vulnerability Index of Thieler and Hammar-Klose (1999) was used, which includes six physical variables that are related in a quantifiable manner (GEO: Geomorphology; CS: Coastal slope, RSLR: Relative sea-level rise rate; ERO: Shoreline erosion/accretion rate; T: Mean tide range and Hs: Mean wave height).

$$CVI = \sqrt{\frac{GEO \cdot CS \cdot RSLR \cdot ERO \cdot T \cdot Hs}{6}} \quad (1)$$

SocCVI

The socioeconomic index (SocCVI) was estimated after the calculation of the three sub-indices: CC: Coastal Characteristics related to the resistance of the coast to erosion; CF: Coastal Forcing (CF) that quantifies the forcing variables; and, SE: Socio-Economic that identifies the potential risk of the existing infrastructure. Each sub-index contributed equally in the final index score (i.e. each by one third).

The Coastal Characteristics sub-index (CC), which is related to the rate of relative sea-level rise, mean tide range and mean wave height, is calculated by using equation 2.

$$CC = \sqrt{\frac{RSLR \cdot T \cdot Hs}{3}} \quad (2)$$

Coastal Forcing sub-index, which includes the variables of geomorphology (GEO); coastal slope (CS), shoreline erosion/accretion rate (ERO) is given by of equation (3).

$$CVI = \sqrt{\frac{GEO \cdot CS \cdot ERO}{3}} \quad (3)$$

Finally, the Socio-Economic sub-index, which includes the socio economic variables (presented in detail above) is estimated by equation (4).

$$SE = \sqrt{\frac{SET \cdot CH \cdot TN \cdot LU \cdot E}{5}} \quad (4)$$

The final index is estimated by equation 5

$$SocCVI = \frac{CC + CF + SE}{3} \quad (5)$$

The resulting scores were normalised by converting them to a range of the maximum and minimum scores. The ArcView GIS system (ESRI) was used to calculate the index and map the results. Variables were selected and ranked on a 1-5 scale according to their perceived vulnerability to wave-induced erosion (with 5 being the most vulnerable and 1 least vulnerable).

Results

Ranking of indices' variables

The variables controlling both CVI and SocCVI were determined and assessed on the basis of existing information (e.g. EUROSION 2004), which are combined and interrelated spatially. The *geomorphological variable* has found to be Very Low vulnerable for the 80.5% of the coastline and Very High vulnerable for the 11.8%., with the remaining vulnerability ranks to refer to small percentages (0.3% Low, 4.2% Medium, 3.2% High) of the coastline. For the *Shoreline Erosion* variable the 45.5% of coastline is presented as Low vulnerable, while the 53.3% as Medium vulnerable. Very low, High and Very High ranks present very small percentages, 0%, 0.2%, and 0.4%, respectively.

The *coastal slope* was estimated by the distance between isobaths of 5m and the 5 m elevation contour line, while for its ranking the limits of the five classes in table 1 were utilised. Thus, the 9% of the coast presents very High vulnerable, the 0.8% (High vulnerability), the 1.2% Medium vulnerability), the 16.3% Low vulnerability, and the 72.8% Very Low Vulnerability (cliffs)

Relative Sea Level Change and the Tidal variables are considered to have the same values in the whole area. Thus, according to Table 1, Relative Sea Level Change variable in ranked as Medium Vulnerability, while the Tidal range variable as Very High Vulnerability.

The majority of the coastline is ranked as Low Vulnerable (40.2%) and Very High Vulnerable (45%) with respect to The Mean Wave Height variable. The remaining coast presents Very Low Vulnerability (5.2%), Medium the 9.3% and only the0.2% High vulnerability.

For the *Settlement variable*, the majority of the coastline is ranked as Very Low (91.3%) since there are no settlements in these areas. The remaining 6.1% that corresponds to coastline in front of villages and tourist infrastructures is ranked as High and 2.6% that represents the coastal front of the town of Elounda Very High.

For the Cultural Heritage variable, 54.1% of the coastline is ranked as Very Low, 36.1% as Low, since there are cultural heritage sites of local importance in these areas, and 9.4% as Very High, representing the Spinalonga Island. Regarding the *Transport Network* variable, 56.4% of the coastline is ranked in the Low category, since it hosts secondary roads mainly dirt roads; 27.1% hosts roads of national importance and is ranked in the Medium Vulnerability category; in the 15% of the coastline there is no road network and it is ranked in the Very Low category, while 0.7% of coastline is ranked in the High and Very high categories, which represent ports and highways.

For the Land Use variable, the 56.4% of the coastline belongs to the Low category representing coastline in front of grasslands, and the 35.6% in the Very High category since it hosts urban structures. The remaining 9% being in front of bare rocks is ranked as Very Low vulnerable.

Finally, for the Economic Activities variable the majority of the coastline (59.3%) belongs to the Very Low category, as there are no economic activities in those areas, the 3.7% to Low category as it incorporates agricultural activities, the 17.9% having commercial activities to Medium category, the 17.2% to Very High category as it hosts tourism activities and only a very small percentage of the coastline (2%) to the High category as it hosts small scale industrial activities. All variable ranking is presented schematically in figure 3.

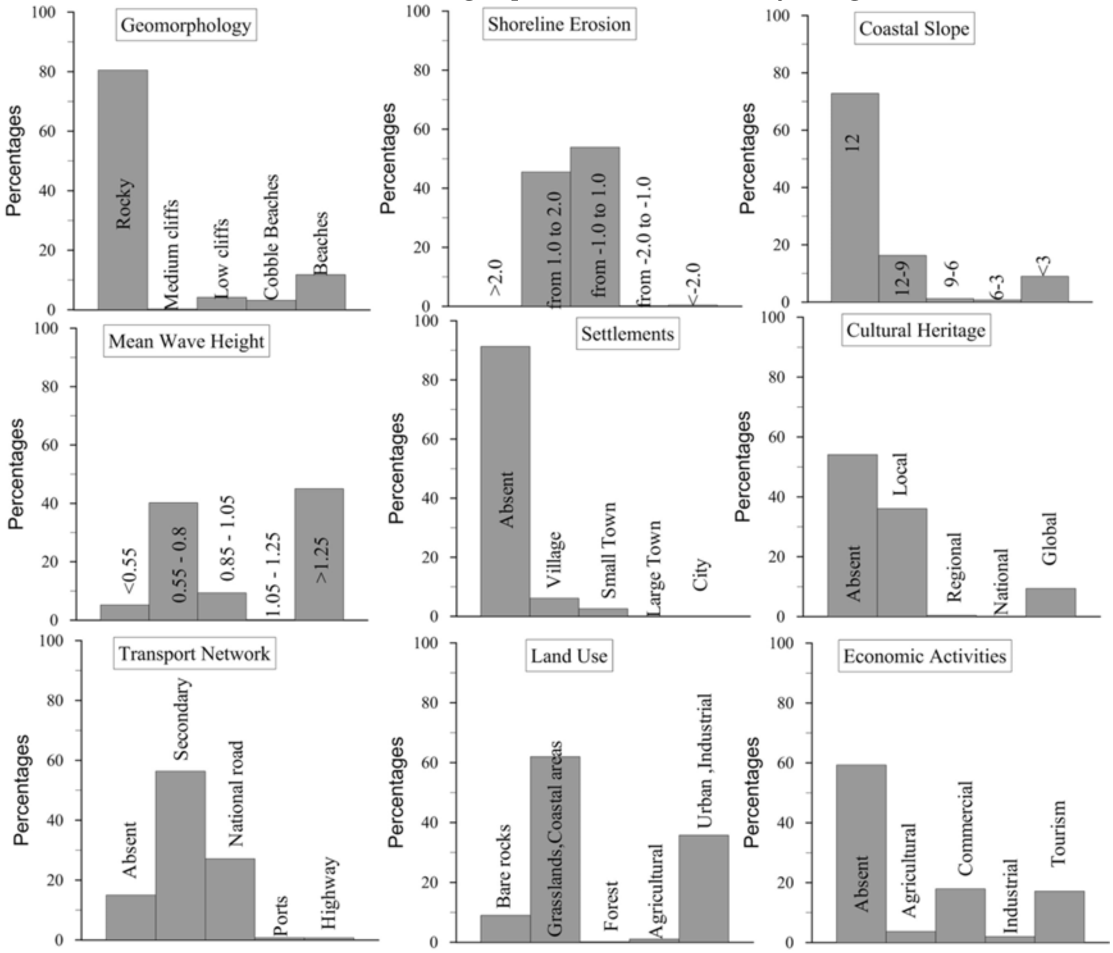

Figure 3: Schematic representations of the variable ranking.

Indices calculation

CVI

Estimations using CVI show that, the majority (85.55%) of the coastline is characterized as Low vulnerability areas, mainly rocky coasts, steep slopes, and man-made structures. A very small percentage (0.28 %) is classified as Medium vulnerability areas. High and Very High vulnerability areas correspond to 7.81 % and 5.84 % of the total coastline length respectively, being mainly beaches and soft rocky coasts that are located mostly at the northern part of the Elounda bay. The schematic presentation of the CVI classification is shown in figure 4a.

SocCVI

According to the results of the index SocCVI, there aren't any areas with Very Low vulnerability, while 78.51 % of the coastline is characterized as Low Vulnerability coasts. They consist mainly of areas with steep slopes, hard bedrock and human constructions. A very small percentage of the coastline (0.8%) is ranked in the Medium Vulnerability category; 11.71% and 8.9% of the coastline are ranked in the High and Very High Vulnerability categories, respectively; these areas correspond mainly to beaches and to areas with bedrock consisting of loosely connected conglomerates, mainly in the northern part of the bay. The schematic presentation of the SocCVI classification is shown in Figure 4b.

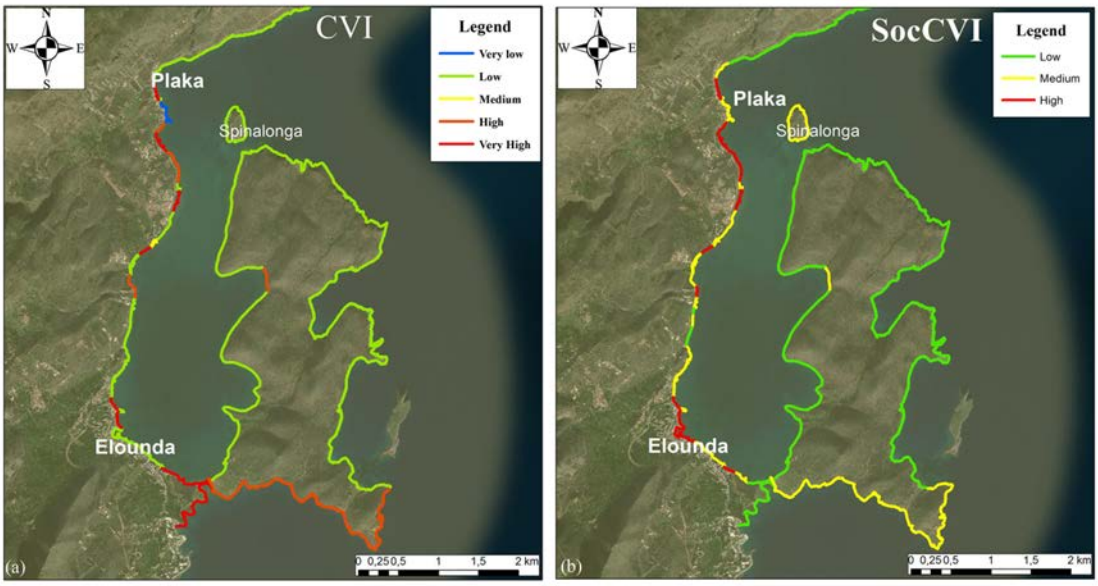

Figure 4: Vulnerability ranks for CVI (a) and SocCVI (b).

Discussion

The comparison of the results of the two indices (Fig. 5) shows that the CVI ranks most of the coastline to the category of Low vulnerability with the remaining part to the extreme categories i.e., Very Low and Very High. It seems to be controlled mainly by the morphological variables. On the other hand, the SocCVI characterises the coastline mainly as of Medium vulnerability. This is explained by the addition to the natural variables those expressing the socioeconomic value related to man-made structures and heritage sites. In areas where there are no human activities, the ranking is lower even if the area is more vulnerable in terms of its environmental setting (e.g. the south area of the Elounda bay).

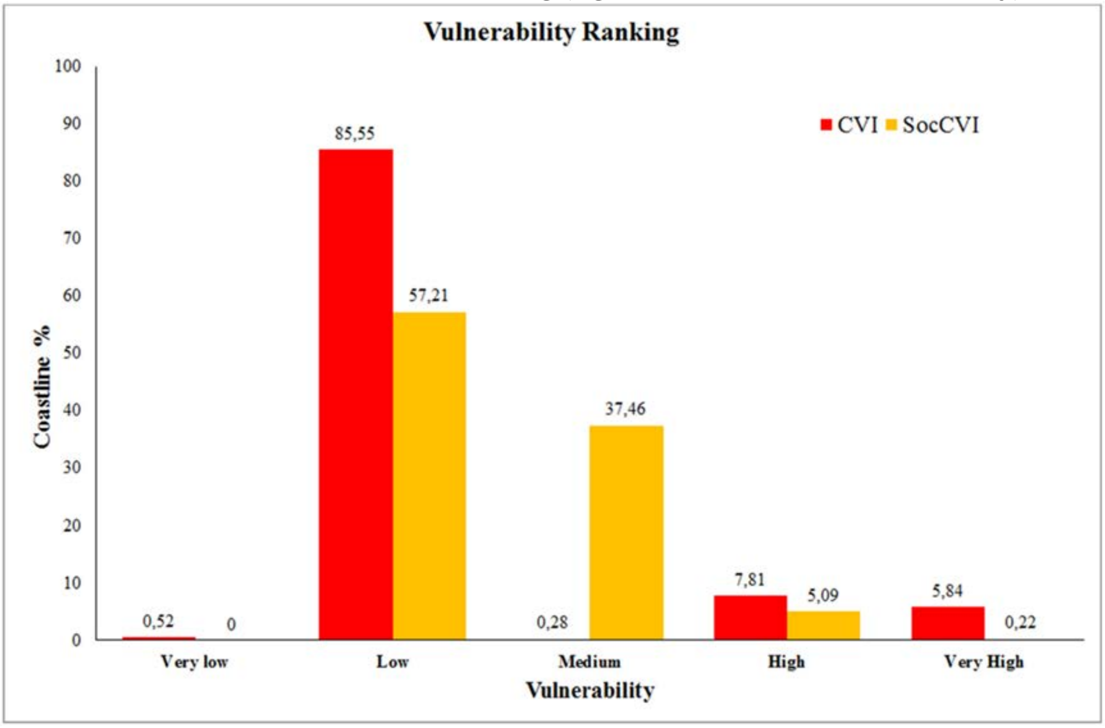

Figure 5: Vulnerability percentages for the two indices ranks.

In addition to the above, the relative influence of each of the three sub-indices of the SocCVI index is presented graphically in the ternary diagram in Figure 6. As it is shown the three sub-indices presents only small differences between the sub-sections of the coastline. Moreover, the sub-indices of coastal forcing (CF) and coastal characteristics (CC) seem to dominate the overall SocCVI score. The latter is more pronounced in hard rocky areas with no human activities (e.g. north side of bay and Kolokitha Isl.), where the Socio-Economic sub-index (SE) has the least influence.

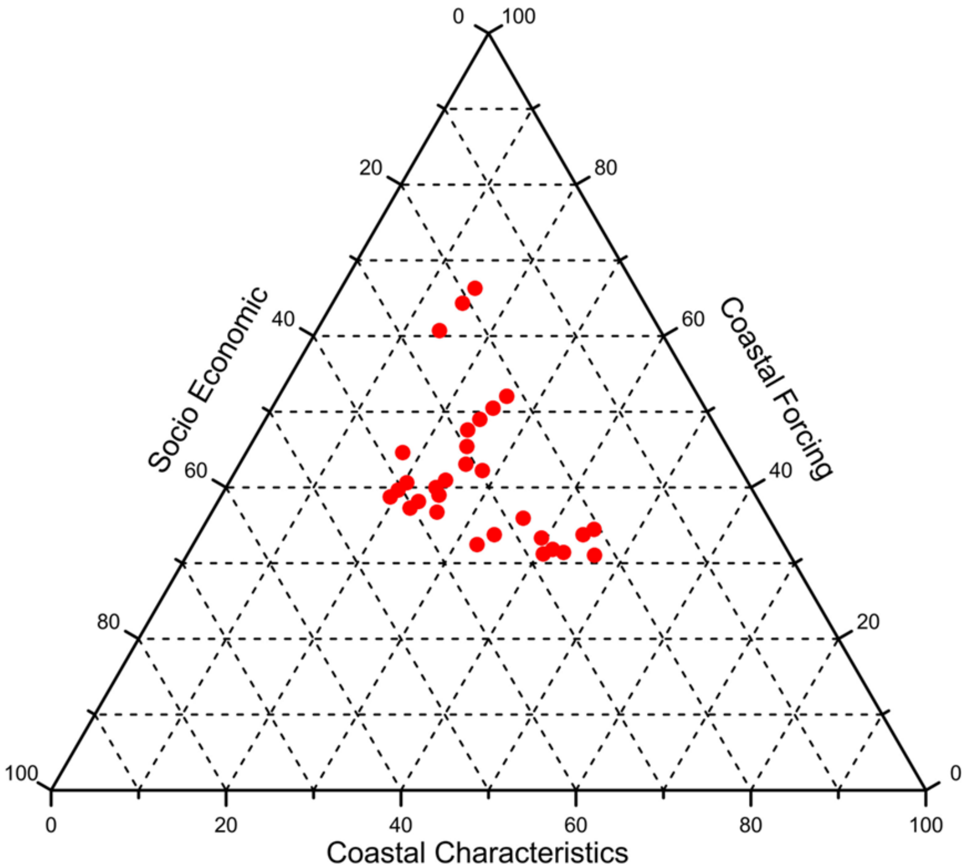

Figure 6: Ternary diagram showing the relative contributions of the three sub-indices of SocCVI

In terms of validation of the three sub-indices of the newly formed SocCVI index were tested against site assessment validation studies and found correlate well. However, a problem noted during the breakdown of the overall SocCVI index scores into their component sub-indices was the low values of the socio-economic sub-index in its contribution to the overall index score in some sites. In contrast, in the areas near Elounda and Plaka, the Socio-Economic sub-index had a significant contribution to the overall index score. This can be explained by the fact that the rest of the coastline is relatively undeveloped in socio-economic terms, and the index is in fact reflecting reality. Another factor explaining the low contribution of the Socio-Economic sub-index may be an artefact related to the subjectivity in estimating the cultural heritage indicator. A possible solution to the aforementioned difficulties could be an alternative approach, according to which instead of developing an overall vulnerability index to develop a vulnerability “profile”. This could be achieved by using the three sub-indices as being independent, instead of combining them into one. By this way, the distinction between the sub-indices will be clearer and also the identification of the dominant sub-index. In this way, the quantification of socio-economic data will best represented in the Socio-Economic index, minimising human perceptions of vulnerability. For example, many hotels put their gardens into unstable dune systems (a profound vulnerable area) for reasons of scenic view.

The paradox is that if the gardens were located farther to inland, in a safer and less vulnerable position, it would be perceived as less attractive and therefore less "valuable".

Conclusions

The indicators that are selected for the coastal vulnerability analysis can strongly influence its final justification.. The addition of socio-economic variables in coastal vulnerability indices based initially only on natural processes is of high importance, even though the accurate quantification of most of them remains a serious challenge. The input of socio-economic variables in a coastal vulnerability assessment studies could be proved a useful tool for making coastal management decisions more focused to the actual needs of the society.

Acknowledgments

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