EVALUATION OF COASTAL VULNERABILITY USING THE INVEST MODEL – CASE STUDY: SE CHIOS ISLAND

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Abstract
Beaches are widely recognized as valuable natural habitats, since they provide protection from marine flooding to the coastal environments, infrastructures and activities they front. Beaches are also particularly vulnerable to climate change. Therefore, the identification of the most vulnerable coastal areas that require immediate protection is essential for decision makers and coastal managers. In the present contribution a general framework for the coastal zone vulnerability assessment was examined, using the southeastern coast of Chios Island (Greece) as a case study area. The aim is to provide a combinational approach for the evaluation of coastline susceptibility and the calculation of coastal erosion. The main stages of the approach include: (i) first, the identification of the erosion-prone areas using the InVest Coastal Vulnerability model and (ii) then the assessment of the shoreline retreat under various sea level rise scenarios, for the beaches found to face the greatest erosion risk, using ensembles of numerical and analytical models. The examined approach gives promising results suggesting that it can be used as an effective tool for a rapid assessment of coastal vulnerability.
Keywords: *Invest Coastal Vulnerability, Sea-level Rise, Erosion, Coastal Zone Management*
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1. Introduction

Beaches (the low-lying coasts built on unconsolidated sediments - sand and gravel) are not only important ecological habitats in their own right, but they also protect from marine flooding (a) very significant transitional coastal habitats (e.g. wetlands and lagoons) which are protected by international conventions and the EU Legislation and (b) valuable economic assets/infrastructures (e.g. urban, industrial and touristic developments, coastal roads, railways and airports). The sea level rise (SLR), both long-term and short-term, threatens the coastal zone due to the expected significant retreat and/or even beach drowning (when beaches are backed by coastal cliffs and/or human assets) (IPCC, 2013). During the last decades, beaches have been shown to be under increasing erosion and a permanent flood risk (IPCC SREX, 2012). Taking also into consideration the rapid growth of touristic activities and services at the coastal zone, the design/application of efficient coastal zone management plans has become extremely important in environmental and socio-economic terms. In Greece, the last few years, studies regarding coastal erosion and beach retreat, take place more systematically, since they are considered as a major environmental problem, affecting coastal population, infrastructures and assets (i.e. Velegrakis et al., 2008, 2017; Alexandrakis et al., 2013; Poulos et al., 2013; Valaouris et al., 2014; Monioudi et al., 2016, 2017).

In this context, the aim of this contribution is to test the InVest Coastal Vulnerability model, which was used for the evaluation of the susceptibility of coastal zones, to a small area along the coastline of south-eastern Chios (Fig. 1) and also to estimate the potential future retreat of particular (mostly touristic) beaches under short and long-term SLR. The study area is about 8 km long and extends from about one kilometer north of the port of Ag. Ermioni to the south of Kataraktis beach (Fig. 1).

The Natural Capital Project (2006–2017) developed the "Integrated Valuation of Ecosystem Services and Tradeoffs" (InVEST) model, as an open-source modelling toolbox that allows users to assess the current and future responses of ecosystem services by coupling bio-geophysical and economic models. The Invest Coastal Vulnerability sub-model of InVEST produces a qualitative estimation of coastal vulnerability through a vulnerability index, which indicates the areas with relatively high or low exposure to erosion and storm-induced floods. By combining these results with demographic data, the model can present, along a particular coastline, locations where the population is more vulnerable to storm surges. The vulnerability index is based (except from population) on the spatial distribution (GIS polygon and raster files) of seven bio-geophysical variables: geomorphology, relief/bathymetry, natural habitats (biotic and abiotic), sea level change, wind exposure, wave exposure and surge potential. The model generates raster files (of specific pixel size) for each variable and provides absolute values for each pixel along the coast of the study area. For each variable the pixels are ranked from very low exposure (rank 1) to very high exposure (rank 5) (Hammar-Klose and Thieler 2001). The model then calculates the exposure index along the shoreline as the geometric mean of all the variable ranks. In addition, the model computes an erosion index.

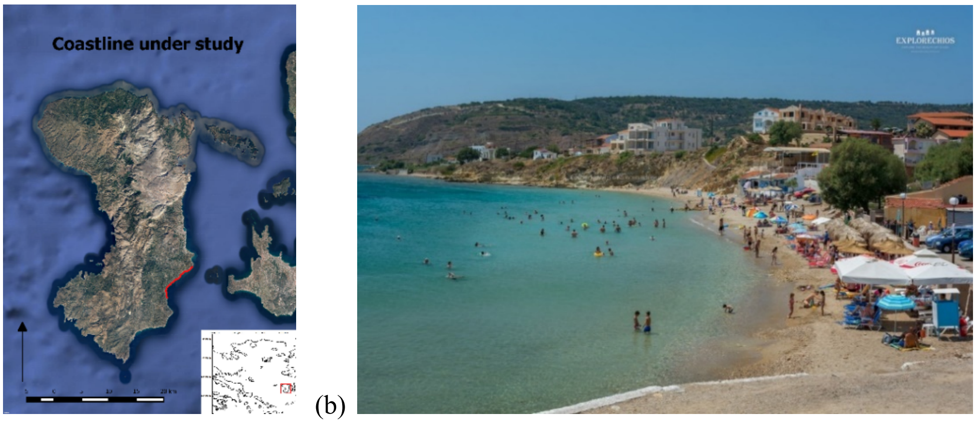
(a) (b)


Figure 1: (a) Location of Chios Island (inset map) and the coastline under study (red line) and (b) photo of the beach of M. Limnionas.

2. Material and Methods

Field data were collected (Fig. 2), including detailed topography (Topcon Hipper RTK-DGPS), bathymetry (digital Hi-Target HD 370 hydrographic echo-sounder), habitat mapping (StarFish 450F side-scan sonar) and sediment (both onshore and inshore) sampling from Ag. Ermioni and Kataraktis. Bathymetry and topography for the entire stretch of the studied area was created using also data from the European Marine Observation and Data Network (EMODnet 2009-2017) and local DEMs. Waves were hindcasted from the available wind data of the Chios meteorological station (Hellenic National Meteorological Service) for the period 2010-2015. The study area is mainly affected by E, SE and S winds and waves. For each beach, the significant wave height (H_s) and peak period (T_p) were calculated, on the basis of the effective fetch length (Koutitas, 1994), using the JONSWAP method. The beach sediments are moderately well to well sorted graded, with D_{50} ranging from 1 to 4 mm.

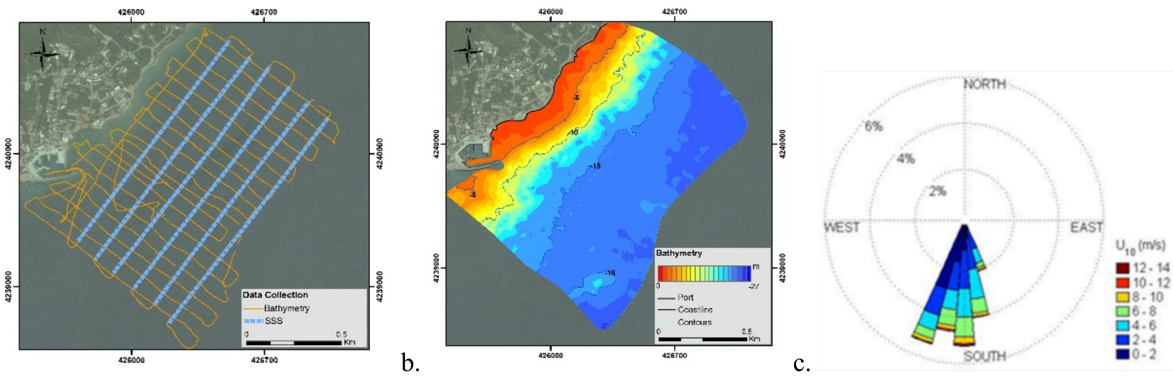
a. b. c.


Figure 2: Examples of (a) data collection grid and (b) detailed bathymetry along Ag. Ermioni coastal area. (c) Rose diagram for the south winds in Chios Island for the period 2010-2015.

Coastline response to long- and short-term SLR was projected using ensembles of cross-shore (1-D) analytical (Bruun, Dean, and Edelman) and numerical (Leont'yev and SBEACH) morphodynamic models (GUIs) (Monioudi et al., 2017) respectively. The models were set up/forced on the basis of the observed cross-shore profiles and sediment size and the estimated (through the JONSWAP method) wave characteristics. The simulation time, for all the numerical model runs, was the same (8000s). The short-term beach retreat models, were applied considering four scenarios (0.2, 0.4, 0.5, 0.6 m) of episodic (short-term) SLR due to extreme events and storm surges (Tsimplis and Shaw, 2010; Krestenitis et al., 2011). With regard to long-term SLR, the following scenarios were considered (projected for the Aegean Archipelago): 0.15 m (average of the RCP 4.5 and RCP 8.5 in 2050), 0.5 m (RCP 4.5 in 2100) and 0.75 m (RCP 8.5 in 2100) (Hinkel et al., 2014). In order to take into account the combined effect of both the short and the long-term SLR, a moderate episodic SLR scenario of 0.4 m superimposed on the 3 (previous mentioned) long-term SLR scenarios, was considered. Thus, the final combined SLR scenarios that were examined correspond to 0.55, 0.9 and 1.15 m. For these scenarios the 2 ensembles were used consecutively.

3. Results

The Invest Coastal Vulnerability model produced raster GIS files that illustrate the exposure to coastal hazards along the coastline of the study area (Fig. 3). The highest relief (coastal cliffs and steep beaches) is located between Kataraktis and Ag. Foteini. The shore exposure variable indicates that the coastline under consideration is in general protected except the shores of Ag. Foteini and Kerameia (Fig. 3a). High exposure to waves is detected south of Kataraktis, between Ag. Foteini and Ag. Ermioni and throughout the northern part of the coastline along the studied area (Fig. 3b). High probability of surge occurrence appears only on the coast south of Kerameia beach.

The exposure index along the shoreline (Fig. 3c) was derived from the combination of the corresponding rank values of each geophysical variable in each pixel of the coastline. This expresses the vulnerability across the studied coastline. The higher values of the vulnerability index appear mainly in the northern part of the studied coastline (from the beach of Ag. Foteini to Ag. Ermioni). These are the areas with the highest coastal population and the largest touristic activity. Finally, according to all input data, beaches that appear to have significant erosion problems are M. Limnionas, Kerameia, Ag. Ioannis (the southernmost part of Ag. Foteini) and Kataraktis.

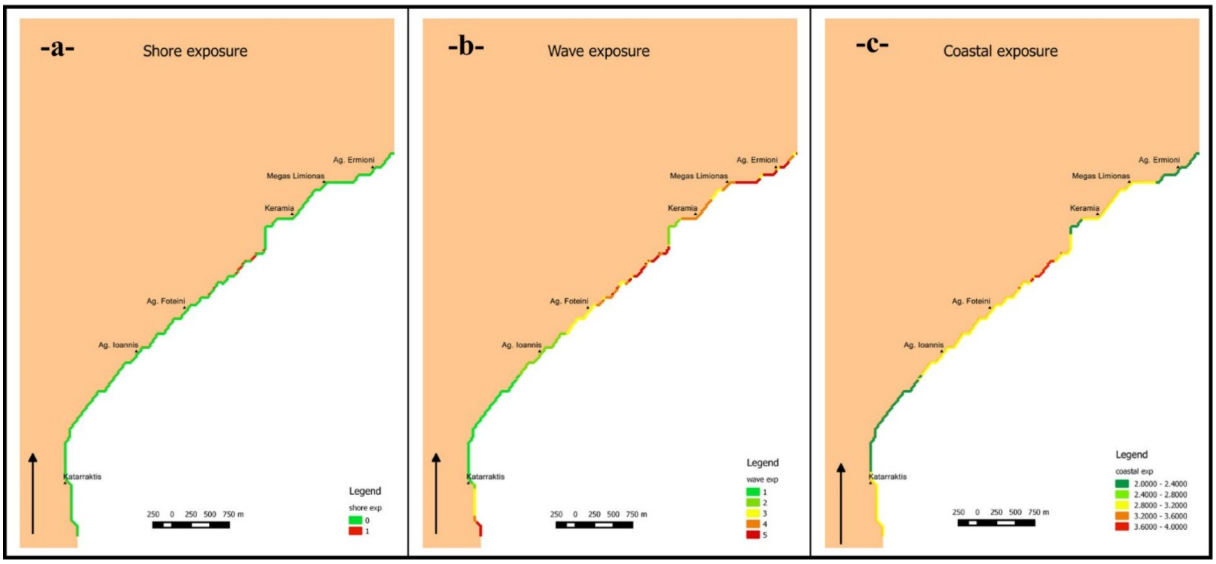


Figure 3. Examples of InVest coastal vulnerability model results.

The four beaches (M. Limnionas, Kerameia, Ag. Ioannis and Kataraktis) that emerged from the model as the most prone to erosion were studied in more detail; the effective fetch length, the wind and wave characteristics the beach morphology and the sediment texture were estimated in order to apply the short- and long-term model ensembles and assess the SLR-induced shoreline retreat (Monioudi et al., 2017). The beaches of M. Limnionas and Kerameia are protected from the eastern winds and are exposed (long fetch distances) to the south and southeast directions. Waves generated by the southeast winds are small, whilst those from the south have higher heights and periods. The beaches Ag. Ioannis and Kataraktis are protected from the southern winds and have a small fetch in the east direction and large fetch in the southeast. The waves created by the southeast and eastern winds are of low heights and periods.

Comparisons between the beach retreat projections of the ensemble modeling and the observed maximum beach widths (Table 1), have shown that, in the case of a combined SLR of 0.55m the four examined beaches will retreat more than the 20% (up to 45% at Kerameia) of their maximum width. For the worst case scenarios projected for the year 2100, the analysis showed that a SLR of 0.9 m will induce beach retreats of more than 47%, with the Kerameia beach losing about 85% of its width, whereas in the case of 1.15 m SLR Kerameia beach will be completely drown and the M. Limnionas and Kataraktis beaches will lose about 90% of their maximum widths.

4. Discussion

The present study highlights the effective use of the InVest Coastal Vulnerability model, which was accompanied by the application of morphodynamic model ensembles (analytical and numerical) in order to identify vulnerable beaches along a stretch of the coastal zone of the SE Chios Island and to estimate beach retreat under projected SLR scenarios, respectively. Although the available field data were limited, the InVest model performed very well, using supplementary information from available databases and finally managed to detect segments along the coastline that are more susceptible to wave forcing and thus to erosion problems. The indicated as more vulnerable coastal segments coincide with well-known beaches (i.e. M. Limnionas, Kerameia), which according to anecdotal information, have faced, in the past, issues regarding shoreline retreat during extreme events. For these areas, the application of ensembles of cross-shore morphodynamic models provided a first assessment of coastal erosion risk under numerous scenarios of SLR.

Table 1. Projections of the cross-shore beach retreat and % in relation to the current max. width in the study area for different SLR scenarios.

		Beach retreat							
	SLR (m)	M. Limnionas		Kerameia		Ag. Ioannis		Kataraktis	
		m	%	m	%	m	%	m	%
Long-term	0.15	2.3	14	2.9	19	2.4	12	1.9	12
	0.50	7.9	46	8.9	59	7.7	39	6.2	39
	0.75	11.7	69	13.2	88	11.5	58	9.3	58
Short-term	0.0	0.7	4	0.7	5	0.05	0.3	0.02	0.1

	0.2	2.8	16	2.6	17	0.8	4	1.0	6
	0.4	4.2	25	3.9	26	1.7	9	4.8	30
	0.5	4.7	28	5.5	37	3.1	16	6.7	42
	0.6	5.2	31	6.0	40	3.6	18	8.5	53
Combined	0.55	6.5	38	6.8	45	4.1	20	6.7	42
long +	0.90	12.1	71	12.8	85	9.4	47	11.0	69
short-term	1.15	15.9	93	17.1	100	13.5	68	14.1	88

Taking into account the long length of the Greek coast, effective tools for the rapid assessment of coastal vulnerability are required in order to estimate the exposure at a large scale. Extensive literature research has shown that Invest Coastal Vulnerability model has a very limited application (i.e. Arkema, et al., 2013; Langridge et al., 2014). Throughout the current work, the results of the InVest model successfully pointed out beaches prone to erosion, so as to estimate their retreat under projected SLR. Future work should combine the vulnerability indicator with coastal population data, the attractiveness of beaches, as environments of leisure, and the economic evaluation of the potential technical adaptation options, in order to promote integrated and efficient coastal management plans (Arkema, et al, 2013; Liquete et al., 2013).

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