Coastal Zone Vulnerability Analysis in East Mediterranean Basin: Greece, Cyprus and Montenegro

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Abstract The coastal zone is a vital natural resource extensively used by the population for various activities. Given the human pressures and climate change, it is crucial to comprehend the modifications occurring in the coastal environment and its exposure to erosion. The InVEST Coastal Vulnerability Model is employed to qualitatively assess vulnerability based on an erosion exposure index, which combines information from the physical environment and population. The methodology for calculating the index is developed holistically, considering technical data, climate parameters and theoretical background. Geographic information software is used to apply the methodology to specific parts of the coastal zone in Lesvos, Cyprus and Montenegro. These regions share common vulnerability issues but also exhibit differences in coastal management approaches, socio-economic characteristics, geological features and potential impacts. The study emphasizes the need to understand biological and geophysical factors influencing coastal erosion and flooding to facilitate effective future planning and management. By assessing coastal vulnerability and considering the impact of tourism, this study can provide insights for sustainable coastal zone management and informe decision-making tools regarding protection and development.

Keywords: Coastal Vulnerability, InVEST model, Lesvos, Cyprus, Montenegro

1. Introduction

Beaches play a crucial role in safeguarding coastal ecosystems, infrastructure, and valuable assets against the impacts of marine flooding. Additionally, they offer significant recreational opportunities (Monioudi and Velegrakis, 2022). These dynamic environments undergo constant changes in their shape and structure due to processes operating across different scales. One notable aspect of beach morphology evolution is shoreline adaptation, where sediments move along and across the beach driven by coastal wave/current fluctuations, resulting in visible beach profile rotation (Chatzipavlis et al., 2019). Coastal ecosystems contribute to job creation, economic development and quality of life, serving as a global sustainable environment. However, human and natural activities pose significant threats to coastal environments, with coastal erosion being a major consequence. Shoreline erosion weakens coastal resilience, making ecosystems vulnerable to various factors like wave forces, storms and sea-level rise. While coastal ecosystems can mitigate some pressures, excessive stressors can exceed their capacity, leading to the loss of services and the displacement of environmental stressors toward developed urban areas. Proactive coastal management and conservation strategies are urgently needed to ensure long-term sustainability.

The objective of the current study is to assess and compare the vulnerability of selected coastlines using the InVEST Coastal Vulnerability Index in three Eastern Mediterranean regions. These regions exhibit relatively similar climatological characteristics but differ in their geological and geomorphological conditions.

2. Material and Methods

2.1. Study Area

2.1.1 Lesvos, Greece

The area of interest covers the region from Gavathas (lat. 39.28, long. 25.96) to Molivos (lat. 39.36, long. 26.16) (Figure 1) and is located in the northeastern part of Lesvos Island, covering a total coastline length of 44.45 km. The average annual rainfall is 617 mm, while the average annual temperature is 18.5 ℃ (HNMS, 2023). The geological substrate in the area is primarily composed of Quaternary deposits, as well as of basalts and ignimbrites.

2.1.2 Cyprus

The study area encompasses the coastal stretch from Akamas (lat. 35.04, long. 32.30) to Limassol (lat. 34.68, long. 33.03) in the western part of Cyprus, with a total coastline length of 185.4 km (Figure 2). The average annual rainfall is equal to 503 mm. Regarding the geological characteristics, the study area primarily consists of volcanic bedrock (lava) and terrace deposits.

Figure 1. Study area (in red) in Lesvos Island

Figure 2. Study area (in red) in Cyprus Island

2.1.3 Montenegro

The area of interest spans 335.7 km along the Montenegro coastline, ranging from Njivice (lat. 42.42, long. 18.52) to Gornji Štoj (lat. 41.85, long. 19.36) (Figure 3). The average annual precipitation in Montenegro is 1320.5 mm and the average temperature during winter remains mild, with January temperatures averaging around 9 °C (ICPDR, 2010). It is characterized by diverse geological formations, including flysch formations such as sandstones, shales and other sedimentary rocks, as well as Quaternary deposits like fluvial sediments and alluvial and colluvial deposits (Radusinovid and Abramovid, 2016).

Figure 3. Study area (in red) in Montenegro

2.2 Coastal Vulnerability Model

The InVEST Coastal Vulnerability Model generates an exposure index for each point along the selected study coastline, representing the relative vulnerability of different sections to erosion and storm-induced flooding. The model considers up to seven bio-geophysical variables and incorporates the density of the coastal population on the same scale as other indices. This information aids in creating maps depicting the relative vulnerability of human populations to coastal storms. The model calculates the exposure index and population density using spatial representations of various factors, including topography, natural habitats, wind and wave exposure, bathymetry, geomorphology, and sea-level rise. The output file provides ranks indicating the degree of vulnerability, ranging from very low (Rank=1) to very high (Rank=5) exposure. By employing a combination of criteria, users can determine the vulnerability level. This ranking system is based on methods proposed by Gornitz et al. (1990). The exposure index (EI - Equation (1)) is calculated for each coastal point as the geometric mean of all variable ranks, offering a comprehensive assessment.

$$EI = (R_{Geomorphology} * R_{Relief} * R_{Habitats} * R_{WindExposure} * R_{WaveExposure} * R_{Surge})^{1/7} \quad (1)$$

3. Results

3.1 Lesvos

According to Figure 4, Lesvos coastline faces varying pressures. The majority of the coast is highly to very highly vulnerable, with a significant portion having moderate vulnerability. Factors reveal high vulnerability on Quaternary deposit beaches and lower vulnerability on basalt and andesite areas. The prevailing northeast wind results in high to very high vulnerability in the central coastline, while sheltered points have low (Rank=2) to very low vulnerability (Rank=1). Hard geological substrates exhibit low vulnerability regardless of strong wind and wave intensity, while soft substrates show high vulnerability. Natural habitats provide minimal coastal protection, concentrated in the highest indices (Rank 4 and 5). Terrain relief and distance from the shoreline also affect vulnerability. The farthest area from the mainland exhibits the highest vulnerability (Rank =5), while areas closer to the mainland have lower vulnerability indices.

Figure 4. Exposure of the coastline according to the vulnerability index in Lesvos

3.2 Cyprus

Figure 5 reveals Cyprus' vulnerable coastline with exposure characterized as high (Rank = 4) and very high (Rank=5). The northern region exhibits low vulnerability

(Rank=2), while volcanic areas with lava formations show moderate vulnerability (Rank=3). Terrace deposits demonstrate higher vulnerability indices (Rank=4 and 5). Fine sediment grain size greatly contributes to the high susceptibility (Rank=5). The southwest coastal area has rocky parts with interesting shapes and structures, while the inland portion consisting of mud, results in intermediate vulnerability (Rank=3). Alluvial deposits primarily occur near rivers and salt lakes. Prevailing westward winds contribute to high vulnerability along the surveyed coastline. Strong winds, wave conditions, and fine sediments make the study area highly vulnerable (Rank = 4 and 5). Natural habitats provide limited coastal protection, concentrated in higher vulnerability indices (Rank=4 and 5). Topography and proximity to the mainland shape vulnerability, with lower-elevation beaches exhibiting higher vulnerability.

Figure 5. Exposure of the coastline according to the vulnerability index in Cyprus

3.3 Montenegro

According to Figure 6, the Montenegrin coastline is subjected to significant pressures, resulting in high (Rank=4) and very high vulnerability (Rank=5). Moving from North to South, vulnerability index values remain consistently high, influenced by formations such as flysch and Quaternary deposits. Conversely, regions with limestone rocks, including limestones, dolomitic limestones, dolomites, and the Budva zone, exhibit moderate to very low vulnerability due to their erosion-resistant nature. The prevailing north-northeastern winds contribute to the overall vulnerability, ranging from high to very high along the coastline.

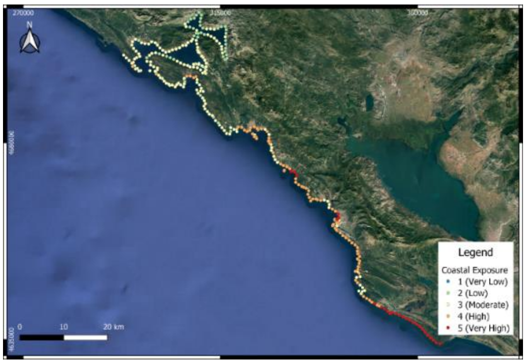

Figure 6. Exposure of the coastline according to the vulnerability index in Montenegro

Within the bay, vulnerability levels are consistently low, irrespective of the geomorphology. Areas with a hard geological substrate and protection from severe weather conditions exhibit lower vulnerability, while those with a soft substrate and exposure to intense weather demonstrate higher vulnerability. Natural habitats, particularly those associated with seagrass, offer some coastal protection. The distinct geomorphology and distance from the continental shelf boundaries contribute to the vulnerability characteristics of the Bay of Kotor.

4. Conclusion

Coastal erosion and vulnerability in the Mediterranean region, particularly in tourist destinations and residential areas, have been extensively studied (i.e., Andreadis et al., 2021). However, the In VEST Coastal Vulnerability model is underutilized in Greece, Cyprus and Montenegro (Arkema et al., 2013; Chalazas et al., 2018; Zhang et al., 2021; Al Ruheili and Boluwade, 2023). By using a vulnerability index, combined with data of coastal populations, infrastructure mapping and natural habitats, strategies for coastal disaster management and habitat protection can be developed (Arkema et al., 2013). These strategies address the retreat of coastlines and the significance of preserving natural habitats.

Montenegro, situated along the Adriatic Sea, is renowned for its coastline adorned with numerous bays, beaches, and cliffs. The coastal areas of Montenegro are vulnerable to erosion, floods and storm surges, which are enhanced due to the rapid development, inadequate infrastructure and tourism activities that have all exerted increased pressure on the coasts, exacerbating their vulnerability. The northern part of Lesvos Island in the Aegean Sea is exposed to various coastal vulnerabilities. The island features rocky shores, sandy beaches and coastal wetlands, which are significant for biodiversity and local livelihoods. Lesvos is susceptible to coastal erosion and flooding that can be caused by severe weather events due to its topography and prevailing weather conditions. Low elevation signifies higher susceptibility to erosion, leading to increased vulnerability (Zhang et al., 2021). Cyprus, located in the Eastern Mediterranean, is renowned for its diverse coastal landscapes ranging from sandy beaches to rocky shores. The coastal areas are vulnerable due to a combination of natural and human-induced factors. Erosion, floods and storm surges pose potential threats, worsened by factors such as climate change, rapid development and tourism activities. Notable areas of high vulnerability include the estuaries of the Ezousa and Asprokremos rivers (Tzoraki et al., 2018) and the Western Cape, which exhibit very high vulnerability (Rank=5).

These coastal regions share similarities in terms of vulnerability, including erosion, floods and storm surges. They are also impacted by factors like climate change, rapid development, and tourism activities. However, there are differences in approaches to coastal management, socio-economic characteristics, geological features, and potential impacts. Understanding these similarities and differences can help inform effective strategies and policies for coastal management tailored to the characteristics of each region, aiming to reduce vulnerability and enhance coastal resilience. The findings of this comparative analysis can provide valuable information for coastal area managers and other stakeholders in effectively addressing coastal vulnerability and strengthening shoreline resilience in these areas. Accordingly, proposed approaches for addressing and managing coastal areas include nature-based solutions, infrastructure upgrading, climate-informed land-use planning, early warning systems, sustainable tourism practices and education and awareness. These strategies aim to address the specific vulnerabilities and challenges faced by each coastal region, promoting sustainable and resilient coastal management practices. For more accurate and representative results, further research could be conducted on individual beaches within the study area, using numerical models and field investigations to generate a methodology that integrates the models.

Acknowledgments

This work was mainly supported by the research project BEACHTECH, co-funded by the European Union (ERDF) and national funds of Greece and Cyprus under the Cooperation Programme "INTERREG V-A Greece-Cyprus 2014-2020". S. Papasarafianou is funded by the Ph.D. program "Phenomena and Environmental Risk" of the University of Naples, Parthenope, and A. Gkaifyllia's research is part of ERASMUS Plus.

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