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Forecasting Impacts on Vulnerable Shorelines: Vulnerability Assessment along the Coastal Zone of Messolonghi Area—Western Greece

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Abstract: The coastal areas of the Mediterranean have been extensively affected by the transgressive event that followed the Last Glacial Maximum, with many studies conducted regarding the stratigraphic configuration of coastal sediments around the Mediterranean. The coastal zone of the Messolonghi area, western Greece, consists of low-relief beaches, containing low cliffs and eroded dunes, a fact that, in combination with the rising sea levels and tectonic subsidence of the area, has led to substantial coastal erosion. Coastal vulnerability assessment is a useful means of identifying areas of coastline that are vulnerable to impacts of climate change and coastal processes, highlighting potential problem areas. Commonly, coastal vulnerability assessment takes the form of an "index" that quantifies the relative vulnerability along a coastline. Here, the Coastal Vulnerability Index (CVI) methodology by Thieler and Hammar-Klose was employed, by considering geological features, coastal slope, relative sea-level change, shoreline erosion/accretion rates, and mean significant wave height as well as mean tide range, to assess the present-day vulnerability of the coastal zone of the Messolonghi area. In light of this, an impact assessment is performed under three different sea-level-rise scenarios. This study contributes toward coastal zone management practices in low-lying coastal areas that have little data information, assisting decision-makers in adopting best adaptation options to overcome the impact of sea-level rise on vulnerable areas, similar to the coastal zone of Messolonghi.

Keywords: coastal vulnerability index; coastal erosion; sea-level rise; flood maps; western Greece

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1. Introduction

Coastal areas are commonly low-lying landscapes that are affected by several dynamic and complex natural processes [1]. At the same time, they usually host a wide range of human activities such as agricultural, recreational activities, and urbanization as well as unique ecological habitats that are also crucial for human well-being.

There is now a growing worldwide concern regarding sea-level rise and its impact on coastal areas, especially on low-lying river deltas. Among others, it is anticipated that sea-level rise will accelerate shoreline erosion, inundation of wetlands, loss of land, and contamination of groundwater reservoirs, as well as impact socioeconomic activities and infrastructure. Sea-level rise is a major challenge for the Mediterranean coastal areas, where risks related to coastal erosion and coastal flooding are already a source of concern [2–5]. However, studies regarding sea-level changes in semi-enclosed basins are limited compared to open oceans, as such an assessment of coastal erosion and formulation of mitigation plans may be still problematic.

The term "vulnerability" is now widely used in many different contexts; however, a broad and consistent definition of vulnerability could be problematic, as its meaning changes in different policies and sets exposed to various hazards (e.g., [6]). Regarding climate change, however, the Intergovernmental Panel on Climate Change (IPCC), in its 6th Assessment Report (AR6) [7], has defined vulnerability as "the propensity or predisposition to be adversely affected. It encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt". This definition of vulnerability, due to changing climate, has been widely acknowledged by the scientific community (e.g., [8,9]). As long as coastlines and their populations are concerned, they are considered more vulnerable given the accelerated rising sea level and the ongoing urban developments. According to the IPCC's AR6, by 2050, at least one billion people will be affected by sea-level rise, and between seven to fourteen trillion dollars' worth of coastal infrastructure by 2100. The assessment of coastal vulnerability to sea-level rise is, therefore, of great concern at the European level.

In this respect, the European Environment Agency (EEA) has stressed the issue of sea-level rise in many of its reports (e.g., [10]), advising the EU members to carry out vulnerability and hazard assessments to address the effects of sea-level rise in their coastal zones. In this regard, there are several approaches ranging from vulnerability to risk assessments of coastal areas (e.g., [11–15]).

However, as a practical and fully quantifiable prediction approach of the coastal response to rising sea level has not been developed, the relative vulnerability of a coastline to sea-level rise may be quantified by assessing variables that dictate coastal evolution in a particular area. More recently, the Coastal Vulnerability Index (CVI), first proposed by [16,17], and its adaptations are among the most widely applied approach. The CVI developed by Thieler and Hammar-Klose [18] is one of the accepted and most commonly used indices for calculating the vulnerability toward coastal erosion and sea-level rise, as it has been proven to provide a reliable and consistent basis for coastal vulnerability evaluations, especially in low-lying coastal areas (e.g., [19–21] among many others). The CVI methodology, under a Geographic Information System (GIS) environment, combines and models a certain number of variables (coastal geomorphology, regional coastal slope, relative sea-level change, mean significant wave height, historical shoreline change rate, and mean tidal range) to assess the coastal system susceptibility to change and provides a relative measure of the coastal natural vulnerability to the effect of sea-level rise and erosion processes. Vulnerability is depicted in the form of a set of color-coded maps, permitting the most sensitive areas to be easily identified (e.g., [16,22–25]). In this regard, CVI has become a common tool that contributes to decision-making in the sustainable and responsible use of coastal resources, the planning and development infrastructure, and integrated coastal management.

Studies on the impact of sea-level rise on the Greek coastline (e.g., [19,20]) have identified the potentially flooded low-lying coastal areas (using the 50 cm contour line) and have estimated that ~13% of the total deltaic areas will be lost by 2100 [26]. The problem is more evident on the coastlines in southwestern Central Greece, where extensive coastal erosion is observed. This is mainly due to the increased rate of sea-level rise [27], the presence of extensive sandy beach zones and deltas, as well as the appearance of a low-relief coastal zone.

In this regard, this research focuses on the coastal zone of Messolonghi (SW Central Greece), where a significant part of its coastline has already been affected. The study area comprises the Messolonghi lagoon, the largest in Greece and one of the largest in the Mediterranean, covering over 220 km^2, and has been designated as a "Natura 2000 Special Protection Area" and protected under the Ramsar Convention [28]. The area is unique for its great biological, ecological, aesthetic, and scientific value. Here, the CVI approach proposed by Thieler and Hammar-Klose [18] is adopted, to assess the present-day vulnerability of the coastal zone of Messolonghi, but also an impact assessment on land-loss for the area is carried out under three different future sea-level rise scenarios.

2. Materials and Methods

The coastal zone of the study area (Figure 1) consists mainly of beaches of low-relief and unconsolidated sediments (gravel, cobbles, coarse, and fine sand), as well as eroded sand dunes [29], a fact that, in combination with the rise in the sea level and the tectonic subsidence prevailing in the area [30], has led to increased coastal erosion.

Figure 1. Study area showing the main geology.

The methodology adopted here follows closely the approach proposed by Thieler and Hammar-Klose [18] and employs the CVI equation (Equation (1)).

$$\mathrm{CVI} = \sqrt{\frac{a \times b \times c \times d \times e \times f}{6}} \quad (1)$$

where a: geomorphology; b: coastal slope; c: rate of shoreline erosion/accretion; d: rate of relative sea-level change; e: mean significant wave height; f: mean tide range.

Data for the six variables used were derived from (a) geomorphology: the geological map of the study area (Institute of Geology and Mineral Exploration of Greece, at the scale of 1:50,000), as well as field observations; (b) coastal slope: the European Union-Digital Elevation Model v1.0 (EU-DEM) [31]; (c) rate of shoreline erosion/accretion: aerial photographs of the year 1945 and 2018 to assess temporal changes in the coastline; (d) rate of the relative change in sea level: eustatic sea-level rise data [32,33] as well as local tectonic regimes [30]; (e) mean significant wave height: the Wind and Wave Atlas of the Greek Seas-Poseidon System [34]; (f) mean tidal range: published information (e.g., [35]), for the study area. All data were processed with the ArcGIS 10.7.1 software and visualization of the results was achieved by using the ArcMap software. Five classes for coastal vulnerability were used, where 1= Very low; 2 = Low; 3= Moderate; 4 = High; 5 = Very high vulnerability, as suggested by [36,37] and presented in Table 1. All variables were subsequently classified into a single coastal vulnerability scale, so that the estimation of the CVI became possible.

Furthermore, a GIS-based approach was used to produce inundation (land-loss) maps under three different sea-level rise scenarios of 0.5 m, 1 m, and 2 m. The EU-DEM as well as the difference in sea level between each future sea-level scenario and current sea level in the area were used to produce inundation maps. Additionally, to assess the impacts that a future sea-level rise will have on the socioeconomic activities in the study area, land-use type was defined using the "Corine Land Cover map" for the year 2018 [38]. Subsequently, the flooded areas (under each sea-level-rise scenario) per land-use category were calculated.

Table 1. Ranges for vulnerability ranking of the six variables used, shown together with their thresholds according to [17,18] approaches.

Variable	Categories				
	Very Low (1)	**Low (2)**	**Moderate (3)**	**High (4)**	**Very High (5)**
Geomorphology	Rocky cliffed coasts, Fjords	Medium cliffs, Indented coasts	Low cliffs, Glacial drift, Alluvial plains	Cobble Beaches, Estuary, Lagoon	Barrier beaches, Sand beaches, Salt marsh, Mud flats, Deltas, Mangrove, Coral reefs
Coastal slope (%)	>1.2	1.2 to 0.9	0.9 to 0.6	0.6 to 0.3	<0.3
Shoreline erosion (−)/accretion (+) (m/yr)	> (+2.0)	(+1.0) to (+2.0)	(−1.0) to (+1.0)	(−2.0) to (−1.0)	<(−2.0)
Relative sea-level change (mm/yr)	<1.8	1.81 to 2.5	2.51 to 3.0	3.01 to 3.4	>3.4
Mean wave height (m)	<0.55	0.55 to 0.85	0.86 to 1.05	1.06 to 1.25	>1.25
Mean tide range (m)	>6.0	4.0 to 6.0	2.0 to 4.0	1.0 to 2.0	<1.0

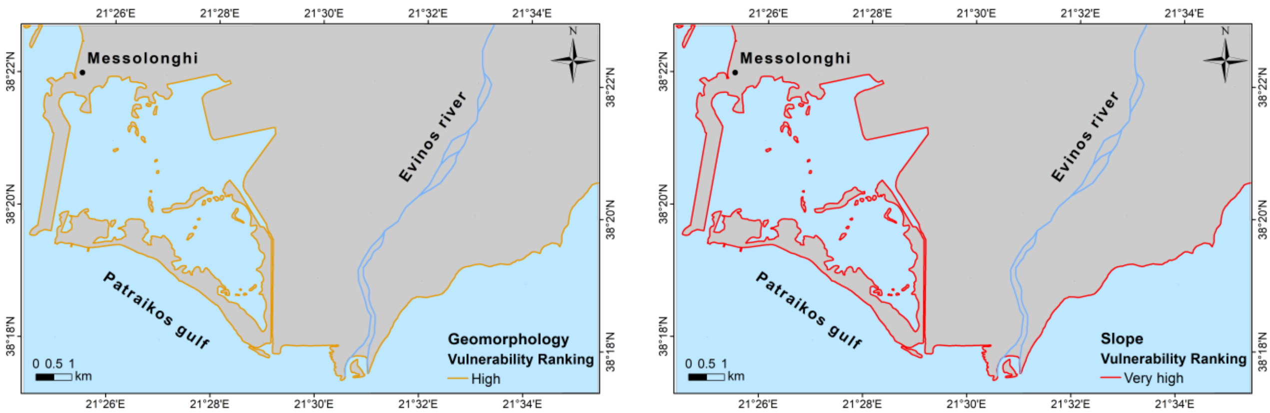
3. Results and Discussion

3.1. Calculation of the CVI and Coastal Inundation

3.1.1. Calculation of Coastal Vulnerability

The vulnerability of the coastal zone of Messolonghi, based on every single variable, is depicted below.

The geological map of the study area, as well as data from field observations, were used to assess the vulnerability of the coastal zone, based on geomorphic features. Based on the characteristics of the geological formations, a vulnerability map (Figure 2a) was developed. The study area is made mainly of coastal and lagoonal deposits covering a total length of 77.5 km (76.65%) as well as fluvial deposits and scree occupying a total length of 23.6 km (23.35%). The map revealed that the total length of the coastline is classified as high vulnerability.



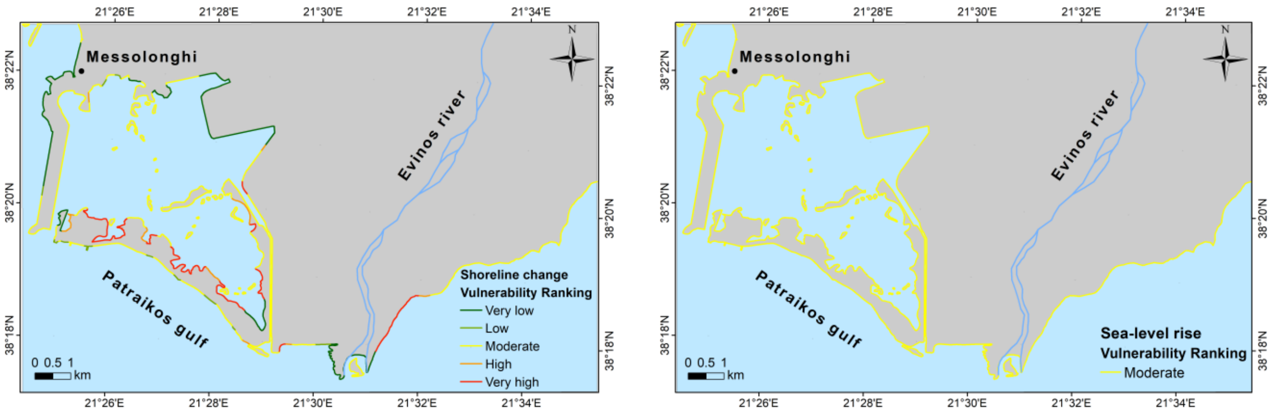
(**a**) (**b**)

Figure 2. Assigned vulnerability classes in response to (**a**) geomorphology and (**b**) coastal slope.

To calculate the vulnerability of the study area based on coastal slope, the EU-DEM with a pixel dimension of 30 m was used. The entire coastal zone is a low-lying area and is characterized as very highly vulnerable to inundation (Figure 2b).

To examine diachronic changes on the coastline, the ArcGis software was used along with the extension "Digital Shoreline Analysis System" (DSAS) v5 software [39], which is freely available from the US Geological Survey (USGS). Initially, the position of the coastline of the study area, in two different years (aerial photographs of the year 1945 and Google Earth for the year 2018), was digitized and then two coastlines were compared using the

ArcGis software. The produced vulnerability map (Figure 3a) revealed that the largest part of the coastline was classified as moderate (61.07 km, 60.42% of the coastline). High to very high vulnerability was classified as 17.04% (17.22 km) of the total length of the coastline, while low and very low vulnerability were classified as about 2.92 km and 19.86 km of the coastline, respectively, which do not collectively exceed 23% of the total coastline length.



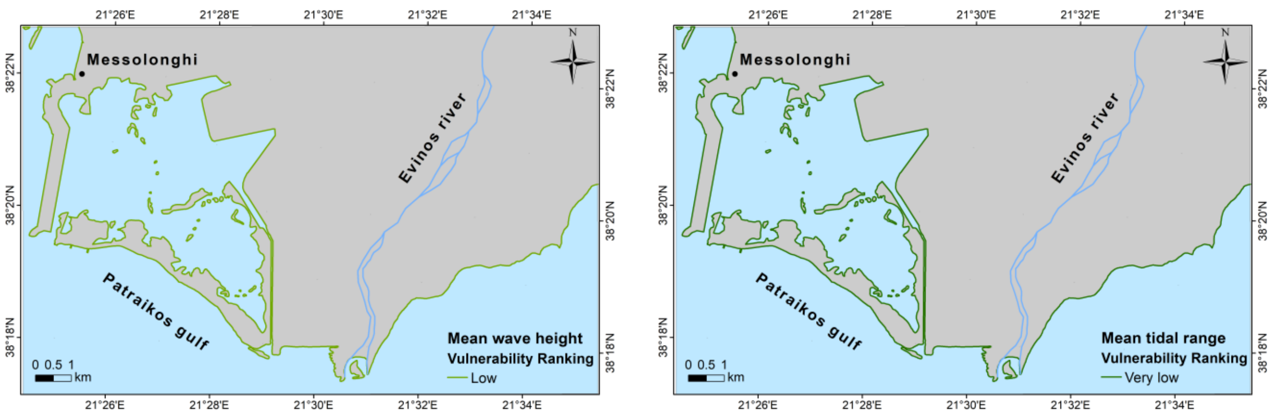
(**a**) (**b**)

Figure 3. Vulnerability ranking maps based on (**a**) diachronic shoreline change and (**b**) relative sea-level change.

Relative sea-level changes take place as a result of the interaction between eustacy and isostasy, and/or tectonism. The estimation of the relative sea-level change in the coastal zone of Messolonghi was based on both the rate of sea-level rise and the tectonism in the area, where tectonic subsidence is evident due to the active faults found in the area. Based on Lambeck's eustatic curve [32,33], a value of 1.12 mm/yr was used as a rate of sea-level rise, where the tectonic subsidence in the area has been estimated between 1 and 2 mm/yr [30] and, thus, an average subsidence of 1.5 mm/yr was considered.

Consequently, an average sea-level rise rate of 2.62 mm/yr was adopted along the entire length of the coastline of the study area (moderate vulnerability-class 3).

To estimate the average significant wave height, data were drawn from the "Atlas of Winds and Waves of the Greek Seas" [34] of the Hellenic Center for Marine Research. For the study area, the average significant wave height is 0.4 to 0.5 m. Based on the produced vulnerability map (Figure 4a), the entire length of the coastline is classified as low vulnerability.



(**a**) (**b**)

Figure 4. Assigned vulnerability classes in response to (**a**) mean wave height and (**b**) mean tidal range.

The average tidal range for the Greek coastline is between 0 and 0.2 m [35]. Consequently, the coastline of the study area, along its entire length (Figure 4b), is classified in category 1 (very low vulnerability).

To calculate the CVI for the study area, the ArcGIS "Raster Calculator" tool was used. The final CVI map for the coastline of Messolonghi is shown below. The calculated CVI values for the coastline of Messolonghi range from 4.47 to 10. The median CVI value for the area is 7.75, while the standard deviation is 1.63. The coastal vulnerability classification for the study area is presented schematically in Figure 5.

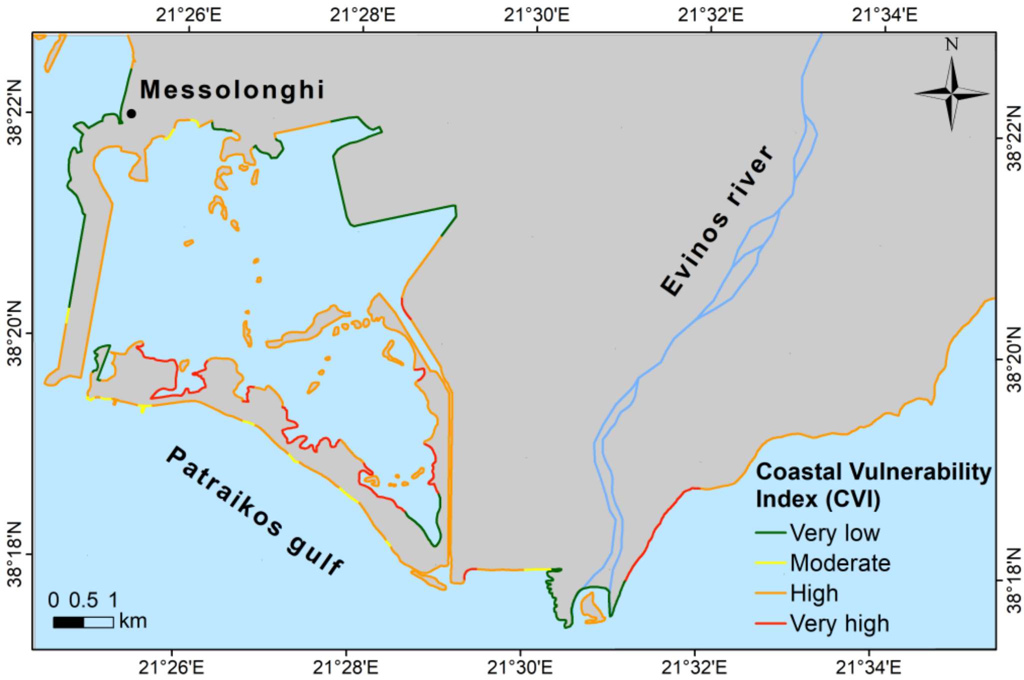


Figure 5. The results of the vulnerability assessment for the study area: Coastal Vulnerability Index (CVI) using all variables.

By applying the CVI methodology, it appears that the largest part of the coastline of Messolonghi is classified as having high vulnerability. However, there are also quite a few parts that present very high vulnerability. Based on a quantitative analysis of the CVI, the length of the coastline showing the lowest vulnerability stretches some 19.83 km (19.62% of the total length), that of moderate vulnerability is 3.02 km (2.99%), that of high vulnerability is 65.48 km (64.79%), and that of very high vulnerability is 12.74 km (12.6%).

The CVI determination is very important for the study area, as it hosts unique biological, ecological, aesthetic, and scientific values. Although the magnitude of the coastal vulnerability in the study area, due to sea-level rise, cannot be straightforwardly assessed, due to several interacting factors (e.g., sediment budget availability, hydrodynamics, and near-shore runoff events, which are not always predictable), the application of the CVI methodology provides a holistic tool for the determination of current coastal vulnerability for the area. The employment of the CVI approach in the study area allowed the identification of those coastal spots that are particularly threatened by climatic hazards, something that is crucial for the development of effective long-term coastal zone management and adaptation strategies.

Although the current sea-level rise rate in the area is considered low (1.5 mm/yr), the CVI determination strikingly indicates that 77.4% of the study area (78.2 km of coastline) is highly to very highly vulnerable. The main reasons that could explain this finding are associated with the presence of particular coastal geological formations in the area (lagoonal and fluvial deposits), as well as the presence of low-gradient beaches.

Similar studies that make use of the CVI approach have been implemented in several countries with reliable results. For example, Boumboulis et al. [40] applied the CVI approach using only physical factors in the Gulf of Patras in Western Greece, in order to give prominence to the importance of geotechnical evaluation and shoreline evolution in CVI calculations. Widura and Mardiatno [41] used the same model to assess coastal vulnerability in some coastal tourism areas in Gunungkidul, Yogyakarta—Indonesia, while Oloyede et al. [42] quantified and classified the vulnerability of the Nigerian coastline using an analytical hierarchical approach, which involved calculating the CVI by employing physical and geomorphological variables as well as socioeconomic indicators. The CVI methodology has also been applied in Barcelona Province—Spain, where four different CVI computation approaches were employed, and the results were compared and contrasted [43]. The extensive number of studies in the literature using the CVI approach signifies that coastal vulnerability assessments, based on indexes and backed by the employment of Geographical Information Systems, are among the most widely used and reliable practices. However, the CVI methodology does not include the socioeconomic characteristics and the interactions between natural hazards and human activities. The IPPC's AR6 stresses the importance of vulnerability assessments that encompass both social and biophysical orientations. Thus, the present study serves as a basis for future investigations, which will incorporate the socioeconomic characteristics of the study area, thus allowing for a complete understanding of the local vulnerability to climate change and sea-level rise.

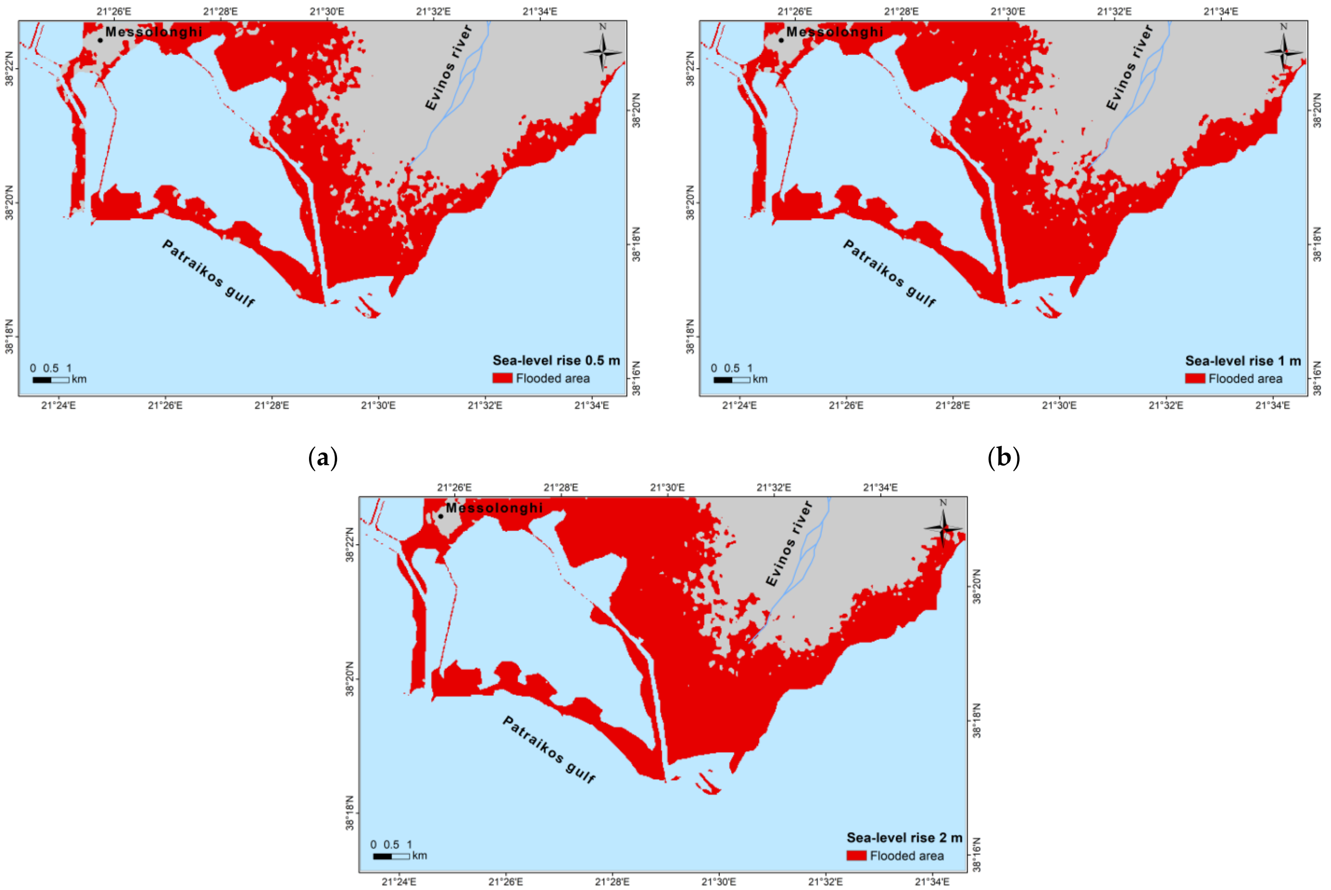
3.1.2. Sea-Level-Rise Scenarios and Coastal Inundation

In order to assess the land-loss of a possible future rise in sea-level, three different sea-level rise scenarios of 0.5 m, 1 m, and 2 m were studied. Assessment of the IPCC's AR6 [44] was used to acquire a comprehensive knowledge of the possible effects of climate change impacts on sea-level trends and to evaluate possible sea-level scenarios. According to the different climate change scenarios (following the phrasing in the AR6, the scenarios can be considered as follows in terms of future Greenhouse Gas Emissions: SSP1–1.9: Very Low; SSP1–2.6: Low; SSP2–4.5: Intermediate; SSP3–7.0: High; SSP5–8.5: Very High), the projected values of sea-level rise for the year 2150 range between 52 cm (SSP1–1.9) and 193 cm (SSP5–8.5). Because of the relatively broad range of future sea levels, scenarios used in this study (sea-level rise of 0.5 m, 1 m, and 2 m) could be seen as general (approximate) projections of the minimum, mean, and maximum sea-level rise in western Greece for the year 2150.

Additionally, to assess the impacts that each of the sea-level-rise scenarios will have on the socioeconomic activities in the study area, land-use type was defined using the Corine Land Cover map of the year 2018. In the study area, twelve different land use categories were identified. Subsequently, flood inundation maps (Figure 6), based on the three different future sea levels, were developed and the flooded areas per land-use category were calculated (Table 2). Due to the coarser resolution of the Corine Land Cover map data compared to the EU-DEM, some cluster grid cells may protrude into the open sea. In order to avoid such artifacts, we retain only those parts of a Corine Land Cover grid cell that lie behind the coastline or that overlap with an EU-DEM cell that shows a positive elevation above the current mean sea level.

The largest part of the study area is covered by permanently irrigated land and beaches, dunes, and sands. They are followed by smaller areas of non-irrigated arable land, salines, coastal lagoons, rice fields, as well as discontinuous urban fabric. There are smaller scattered water courses, industrial or commercial units, and salt marsh areas. A small portion is occupied by complex cultivated lands and continuous urban fabric.

The total loss of land after a sea-level rise of 0.5 m covers an area of ~28.5 km^2; for a 1 m rise, an estimated land of ~31.1 km^2 will be flooded; while after a rise of 2 m, the area expected to be lost extends over ~37 km^2. In all three sea-level-rise scenarios, the most affected areas are those covered by permanently irrigated land, followed by beaches, dunes and sands, and non-irrigated arable land.



(**a**) (**b**)

(**c**)

Figure 6. Flood inundation maps for (**a**) 0.5 m, (**b**) 1 m, and (**c**) 2 m sea-level-rise scenarios. The red color represents underwater areas.

Table 2. Land-use categories and flooded area per land-use category for each sea-level-rise scenario (land-use data were obtained from Corine Land Cover map, of the year 2018).

	Sea-Level-Rise Scenarios					
	0.5 m		**1 m**		**2 m**	
	Flooded Area					
Land-Use Type	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
Permanently irrigated land	15.88	55.51	18.77	58.06	24.1	62.76
Beaches, dunes, sands	3.81	13.32	4.1	12.68	4.29	11.17
Non-irrigated arable land	3.12	10.91	3.17	9.81	3.2	8.33
Salines	1.38	4.82	1.41	4.36	1.42	3.70
Coastal lagoons	1.31	4.58	1.34	4.14	1.36	3.54
Rice fields	1.14	3.98	1.16	3.59	1.16	3.02
Discontinuous urban fabric	0.53	1.85	0.79	2.44	1.16	3.02
Water courses	0.34	1.19	0.36	1.11	0.38	0.99
Industrial or commercial units	0.12	0.42	0.16	0.49	0.2	0.52
Salt marshes	0.8	2.80	0.84	2.60	0.84	2.19
Complex cultivation patterns	0.08	0.28	0.1	0.31	0.1	0.26
Continuous urban fabric	0.01	0.03	0.04	0.12	0.1	0.26
Total flooded area	27.51		31.1		37.07	

The assessment of land-loss under the three future sea-level-rise scenarios has pointed out the need for better preparation to mitigate the impacts of sea-level rise as well as the development of effective adaptation strategies and actions to reduce risk exposure and vulnerability. Currently, there are no mitigation or adaptation strategies for the study area, most probably due to the uncertainty about the extent and rate of sea-level rise as well as the diversity of the physical and the socioeconomic environment in the area. In this regard, the IPCC's AR6 [7] provides guidance and emphasizes that an adaptation strategy should be "effective, feasible, [. . .] conform to principles of justice" and capable of reducing risks for both societies and ecosystems. This could be achieved using "adaptation pathways" and following sequencing and mixing adaptation responses. That is, planning a range of strategies and actions that can be adjusted according to economic, environmental, sociocultural, institutional, or technical objectives. These should include protection (e.g., dikes), accommodation (draining systems), advancing (land reclamation), or managed retreat (relocation of activities), and should be adaptable over time.

4. Conclusions

Climatic changes and their associated effects, including the rise in sea levels, flooding, and extreme storm events, require immediate consideration and action. This study presents an approach for coastal vulnerability assessment that can assist relevant stakeholders in identifying vulnerable spots on the coastline, thus facilitating effective planning and mitigation strategies to be developed. In this regard, the present study assessed the temporal coastline position changes that have taken place in the coastal zone of Messolonghi and revealed the vulnerability of the coastal zone, based on the CVI methodology, by considering geomorphological features, coastal slope, relative sea-level change, shoreline erosion/accretion rates, and mean significant wave height, as well as mean tide range in the area. The employment of the CVI approach in the study area allowed the identification of those coastal spots that are particularly threatened by climatic hazards, something that is crucial for the development of effective long-term coastal zone management and adaptation strategies. CVI values along the shoreline vary between 4.47 and 10, signifying that the largest part of the coastal area of Messolonghi experiences high vulnerability. Furthermore, based on three scenarios, sea-level rise will have a detrimental effect on the majority of the coastal zone, mainly due to the fact that the area has very low elevation, and is made of sandy beaches and lagoon deposits and is experiencing tectonic subsidence. A land area of 27.51 km^2 will be lost if the sea level rises by 0.5 m, 31.1 km^2 in the case of a 1 m sea-level rise, while the land area that will be flooded in a 2 m sea-level-rise scenario has been estimated to cover 37.07 km^2. Taking into account that the area presents a unique ecological habitat but also hosts agriculture and tourist activities, sea-level rise will have significant environmental and socioeconomic impacts. Thus, the results of this study signify an urgent need to monitor regularly the area and develop mitigation plans to reduce both socioeconomic and ecological damage in the region.

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