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How to Define Priorities in Coastal Vulnerability Assessment

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Abstract: Awareness of coastal landscapes vulnerability to both natural and man-made hazards induce to monitor their evolution, adaptation, resilience and to develop appropriate defence strategies. The necessity to transform the monitoring results into useful information is the motivation of the present paper. Usually, to this scope, a coastal vulnerability index is deduced, by assigning ranking values to the different parameters governing the coastal processes. The principal limitation of this procedure is the individual discretion used in ranking. Moreover, physical parameters are generally considered, omitting socio-economic factors. The aim of the present study is to complement a geographical information system (GIS) with an analytical hierarchical process (AHP), thus allowing an objective prioritization of the key parameters. Furthermore, in the present case, socio-economic parameters have been added to physical ones. Employing them jointly, an integrated coastal vulnerability index (ICVI) has been estimated and its effectiveness has been investigated. To show how it works, the proposed method has been applied to a portion of the Adriatic coastline, along the Apulian region in southern Italy. It has permitted to identify and prioritize the most vulnerable areas, revealing its efficacy as a potential tool to support coastal planning and management.

Keywords: coastal morphodynamics; coastal vulnerability index; geographic information systems (GIS), analytical hierarchical process (AHP)

1. Introduction

Coastal regions worldwide provide important ecosystem services, such as fishing, aquaculture, tourism and high biological and ecological productivity. During the 20th century, increasing populations, urbanization and development activities have started altering littoral processes and thus the provisions of these services [1]. Although coastal zones represent a small part of the urbanized land, they are exposed to the continuous action of several factors, both natural and man-induced, operating on different time scales. Some of the most relevant natural factors are: wave height and direction, wind, tide, sediment transport, sediment supply from rivers to sea, soil subsidence, relative sea level change, rainfall, frequency and intensity of extreme climate events, including storms. As well, among the main factors induced by man we can group: maritime constructions and coastal defence such as ports and barriers, which interfere with the dynamics of sediments [2]; construction of housing, industrial, recreational infrastructures; interventions in river basin management and regulation of watercourses to provide water resources for drinking, irrigation and industrial use, which induce alteration of vegetation and forest drainage [1].

Moreover, most coastal environments around the world are experiencing the effects of climate change [3–5]. Among its major consequences is the global sea level rise, which will also contribute influencing the frequency and intensity of storm surge events [3,6]. In fact, sea level rise could cause permanent inundations of low-lying regions, amplification of episodic flooding events and increased beach erosion and saline intrusion, thus increasing the susceptibility of coastal populations and ecosystems [7,8]. These effects would be even more hazardous when coupled to high concentration of people and socio-economic activities [9–11].

Consequently, the detection and mapping of coastal areas particularly vulnerable to the impacts of hazards is a powerful decision tool, serving to promote the sustainable use of coastal resources and guarantee their conservation. Various methods have been proposed over the years to evaluate coastline vulnerability [12–14]. This assessment can be strengthened by integrating as much as possible all different types of risks to which a coastal area is exposed and embedding multiple dimensions of vulnerability, such as physical and socio-economics factors.

Most commonly used methods to assess coastal vulnerability to climate change are: index- or indicator-based methods; GIS-based Decision Support Systems (DSS); methods based on dynamic computer models [12].

Index- and indicator-based approaches are quite similar. Since its original formulation [15,16], the index-based tool expresses coastal vulnerability by means of a one-dimensional risk/vulnerability index (CVI, Coastal Vulnerability Index). When a set of independent elements are combined into a final summary indicator, the approach is named indicator-based. The CVI provides a discretization of the coastline in various segments, assigning ranking values for each of them, based on different parameters evaluation. The resulting CVI is a simple numerical basis for ranking sections of coastline in terms of their potential for changes. Generally, the CVI is expressed as the square root of the product of the ranking factors divided by the number of parameters considered [17,18]. Similarly, Vittal Hegde and Radhakrishnan Reju [19] used the sum of the value of each variable divided by the number of variables. Later, Nageswara Rao et al. [20] calculated the CVI by taking the sum of the considered variables with the rank of each multiplied by their corresponding weights.

DSS addressing climate change are meant to support decision makers in the sustainable management of natural resources and in the definition of possible adaptation and mitigation measures [4]. A key role in these systems is played by GIS (Geographic Information System), that is, set of computer tools that can capture, integrate and display spatial data. As an example, among these GIS-based DSS are DESYCO DEcision support SYstem for Coastal climate change impact assessment [4] and DITTY approach [21]. As an example, DESYCO is an open source software able to combine different scenario data resulting from climate models and high-resolution hydrodynamic, hydrological and biogeochemical models with vulnerability analysis of environmental and socio-economic features of the territory. It provides GIS-based maps, identifying hot-spot areas. DITTY-DSS incorporates mathematical and analytical models for separately handling biogeochemical, hydrodynamic, ecological and socio-economic aspects of vulnerability.

Computer based dynamic models can be roughly divided into sector models and integrated assessment models. The first category is related to a particular coastal process (e.g., coastal erosion or saltwater intrusion in freshwater systems). The second group, including for example, DIVA Dynamic Interactive Vulnerability Assessment [22] or REGIS Regional Impact Simulator [12], analyses multiple impacts.

The principal limitations of index- and indicator-based approaches is the incapacity to address socio-economic aspects. Consequently, they need to be extended/modified, by adjusting not only the number but also the typology of the key variables [12,23], which can be properly customized to better adapt to the specific coastal zone or region. The second weakness of these approaches is that the weights used in the ranking scale of evaluation are assigned based on individual discretion. The advantage to adopt more complex tools, such as GIS-based DSS, is in their flexibility, as they can fit different models/scenarios, identifying and prioritizing areas and targets at risk. On the other side, building and implementing the model chain requires great initial efforts in terms of time and resources. As well, also computer based dynamic models allow generating many scenarios but they often have limited resolution, thus are not appropriate for local scale application. Moreover, they generally require medium-high expertise to carry out intensive testing and validation.

For a scoping or 'first look' assessment, these models result even much sophisticated and time-consuming. Therefore, we aim to illustrate a relatively simple but efficient method to assess coastal vulnerability, which allows: i) overcoming of the restrictions of index-based models and ii) to take advantage from GIS support in processing and visualization. Our proposal is strengthened by the presence of socio-economic issues in the estimation [24,25] and by an objective hierarchy of the involved parameters, to go beyond the hastiness and arbitrariness of index-based methods. Specifically, some selected key parameters, both physical and socio-economics, have been implemented in a geographical information system (GIS) and have undergone a multi-criteria evaluation method, named Analytical Hierarchy Process AHP. Finally, the Integrated Coastal Vulnerability Index (ICVI) has been computed [26,27] using a formulation different from the classical one by Gornitz et al. [15] and mapped to identify priority of vulnerable coastal areas.

We have verified the applicability and reliability of the proposed methodology in the analysis of a part of the Adriatic coast in southern Italy, which is very vulnerable and subjected to strong erosion and human activities.

2. Study Area

The study area is located along the Apulian region facing the Adriatic Sea, included between the Gulf of Manfredonia and the city of Barletta, for a total length of about 40 km, while its planimetric width is around 5 km landward (Figure 1). Other two coastal towns in this region are Zapponeta and Margherita di Savoia. In geo-lithological terms, this coastline was formed on the Quaternary deposit due to the sediment transport of the Ofanto river (Figure 2), the most important river of the region. North of Margherita di Savoia's port the coast has low and mainly sandy beaches (92%), sometimes pebbly, limited inland by marshy areas, whereas offshore submerged bars and groins are present. The alongshore sediment transport is northward. The greatest part of this coastal strip has significantly retreated due to strong erosion phenomena, also intensified by flood risk. The coastline between Margherita di Savoia and Barletta's port consists of low sandy beaches (mainly due to the Ofanto river's solid supply), with dunes, wetlands and salt marshes. This coastal sector is subjected to predominant NNW and SSE winds and the annual wave climate is characterized by a bimodal regime with a clear predominance of waves from N-NNE and E-ESE [28].

It is worth noting that in the last two centuries, the inland region and the coastline have suffered remarkable transformations. The hydrographic basins of the rivers flowing into the Gulf of Manfredonia (including the Ofanto river) have been involved in restoring works aiming at remediating marshy areas and distributing water in reclaimed basins with connected canalizations. Moreover, the urbanization of the coastal strip has started in 1960. Consequently, the solid supply from land to sea has diminished, contributing to a widespread erosion, still occurring today along the entire coast from Manfredonia to Margherita di Savoia.

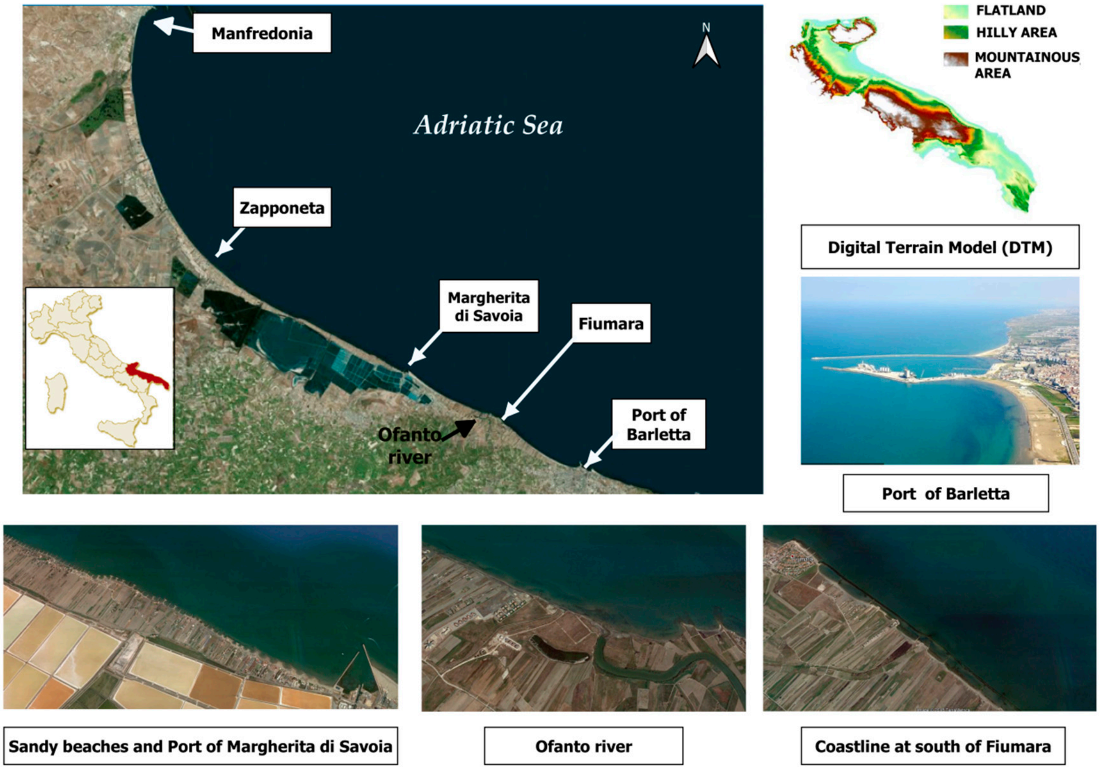

Figure 1. Map of the study area.

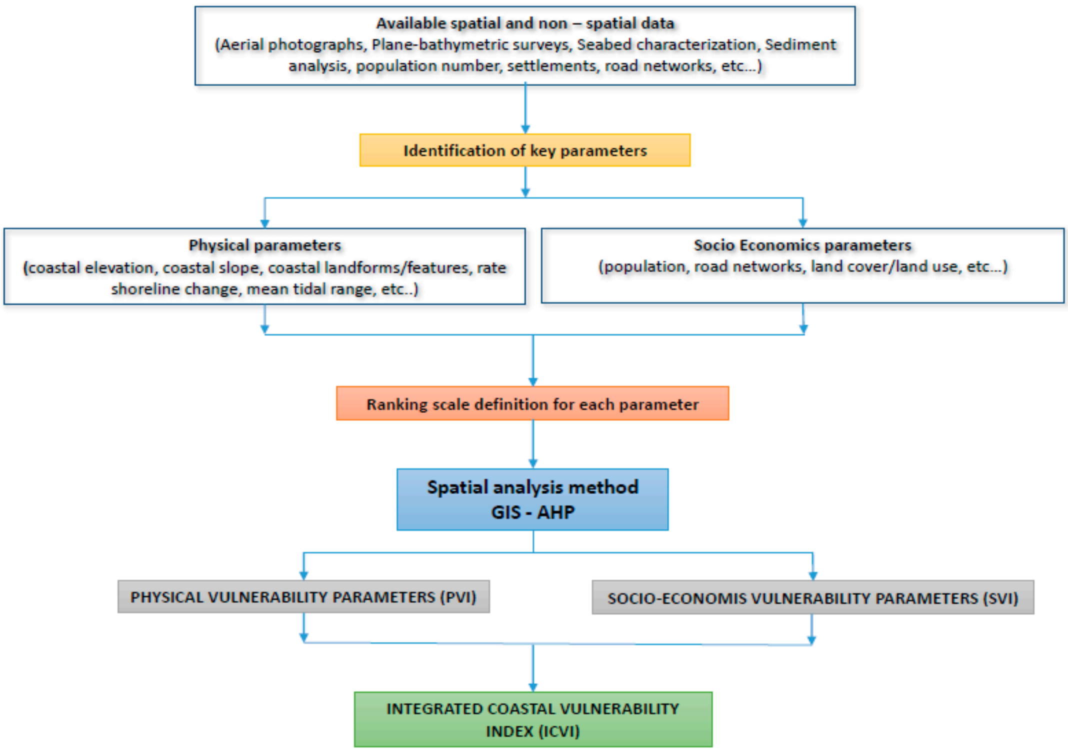

Figure 2. Flow diagram summarizing the methodology adopted in this study for the computation of the Integrated Coastal Vulnerability Index (ICVI).

3. Materials and Methods

The identification of more vulnerable coastal strips, where potential risks may be relatively high, has been faced in literature by applying different methodological approaches, as previously written. Among the first and widely adopted methods is the index-based one, which provides a Coastal Vulnerability Index (CVI) [15,29–33] usually according to the following steps. Firstly, key parameters are identified, that is, those ones linked to the hazard, which potentially could cause an adverse effect and those ones linked to susceptibility, which make the system prone to the effects of the hazard factors [15,34]. The number and typology of the key parameters can be modified according to the study area, the specific needs and the available data [12–14]. The second step consists in rating the key parameters, generally based on a semi-quantitative score, from low to high vulnerability. Finally, the key parameters are integrated in the single index, which represents the general vulnerability of the coastal area.

The added value of the present study is in attributing a rating to the key parameters, jointly physical and socio-economic, based on the Analytic Hierarchy Process (AHP) proposed by Saaty [35] and Saaty and Vargas [36]. This is a robust and flexible multi-criteria decision analysis methodology, able to provide a better understanding of complex decisions by decomposing the problem into a hierarchical structure. Specifically, AHP employs a pairwise comparison procedure between the decision elements, successively ranking them according to their relative importance, thus enabling to obtain a scale of preference amongst the available alternatives [37]. Several studies have shown how the AHP methodology can be successfully used as a decision tool for the case of landslide hazard zoning, flood mapping and soil erosion danger mapping [30,38,39]. Nevertheless, few studies have applied the AHP methodology for the analysis of coastal vulnerability [32,33].

In the present study, as briefly sketched in Figure 2, starting from the available data, we have firstly recognized some key parameters. Seven physical parameters have been selected to detect the Physical Vulnerability Index (PVI). Among these, sea level rise, significant wave height and mean tidal range are the active ones linked to the hazard, which potentially could cause an adverse effect. On the contrary, coastal slope, coastal elevation, coastal landforms/features and shoreline change rate are the passive ones linked to susceptibility, which make the system prone to the effects of the hazard. Following a similar protocol, the Socio-economic Vulnerability Index (SVI) has been calculated using three parameters, which are susceptibility triggering: population, road networks and land use/land cover. Although the parameters considered for the SVI are not exhaustive, they are indicative of the socio-economic vulnerability status of the target region. All these parameters have been implemented in a GIS and have undergone the multi-criteria evaluation method AHP, used to calculate the parameters' weights. Finally, PVI and SVI have been joined to compute the ICVI with a new formulation, different from the classical one by Gornitz [15] and Gornitz et al. [16], which has been discussed.

The GIS implementation has been based on data collection and processing, by means of superposition, graphical visualization of the parameters and, finally, mapping of the results. The available data have been previously converted in vectorial format to be overlapped and made comparable each other.

3.1. Physical Parameters

The seven analysed physical parameters contributing to the PVI are listed in Table 1, together with the sources respectively providing these data and the time period covered by the same data. It is worth noting that the selection of these parameter is based on previous applications of the CVI method [17,18]. In any case, we remark that Thieler and Hammar-Klose [18] originally applied the index-based method to evaluate the potential vulnerability of the U.S. coastline at the national scale. Therefore, we have adapted our selection to the specific target site [12], taking into account its geographical and morphological peculiarities, especially referring to a low-lying area. The standard practice [40,41] is to assemble a list of variables using criteria such as suitability, availability of data, usefulness and ease of recollection.

As suggested by Payo [42], some of these parameters are dependent and exert reciprocal feedbacks. For example, if the shoreline rate change is negative, that is, the shore is eroding, it becomes wider and gentler. Consequently, the impact of waves is lower for the same given energy. It is difficult to quantitatively consider these interactions, thus the adoption of the AHP approach reveals very useful. In fact, the reciprocal influence of the variables is estimated in the procedure, by means of proper matrixes of comparison (as shown in the following Section 3.3).

In the adopted technique, the target coastline has been segmented into strips of equal lengths (500 m). For each strip and for each considered physical parameter a vulnerability ranking from 1 to 4 has been assigned, representing very low, low, high and very high vulnerability, respectively (Table 2). The thresholds chosen for the four classes shown in Table 2 are the same already used in previous classical studies. In particular, referring to significative wave height and shoreline rate change the limits by Thieler and Hammar-Klose [18] are replicated, to sea level rise those by Tragaki et al. [25], to tidal range those by Karimbalis et al. [43].

Table 1. Physical and socio-economic parameters investigated in the study.

	Variable	Data Source	Period of Reference
Physical	Coastal slope	Atlas of Italian beaches Data from Territorial Information Service–Apulian Region (www.sit.puglia.it)	2001
	Coastline landforms/features	Cartography and orthophoto from National Geoportal (http://www.pcn.minambiente.it)	2005; 2008; 2011; 2013
	Significant Wave height	European Centre for Medium-Range Weather Forecasts (ECMWF) model	2008–2013
	Shoreline change rate	Aerial photos (spatial), GPS measurements	1992; 1997; 2005; 2008; 2011; 2013
	Sea level rise	Literature data about the projections of global mean sea level rise over the 21st century (IPCC 2014; Galassi and Spada [5]; Lambeck et al. [44])	1990–2100
	Tidal data	Tide gauge data from National tide gauge network (https://www.mareografico.it/)	1999–2014
	Coastal elevation	Data from Territorial Information Service–Apulian Region (www.sit.puglia.it)	2015
Socio-economic	Population	Census sectors maps and Statistic data from National Institute of Statistics (https://www.istat.it/)	2017
	Road networks	ANAS (http://stradeanas.it/it)	2017
	Land use/Land cover	Cartography from Ortho-images from National Geoportal (http://www.pcn.minambiente.it) Data from Territorial Information Service–Apulian Region (www.sit.puglia.it)	2017 2011

Table 2. Vulnerability ranking assigned for physical parameters.

Parameter	Description	Coastal Vulnerability Ranking			
		Very Low (1)	Low (2)	High (3)	Very High (4)
Coastal slope (%)	Percentage of coastal slope	>2	1.3 ÷ 2	0.5 ÷ 1.3	0.1 ÷ 0.5
Coastal landforms/features	Coastal resistance capacity against erodibility and sea level rise	Rocky coast	Protection works	Dunes, estuaries and lagoons	Mudflats, mangroves, beaches, barrier-spits
Significant wave height (m)	Significant wave height can cause severe coastal erosion	<0.55	0.55 ÷ 0.85	0.85 ÷ 1.2	>1.2
Shoreline change rate (m/yr)	Mobility shoreline (positive accretion, negative erosion)	>+2	+2 to 0	0 to −2	<−2
Sea level rise (mm/yr)	Mean sea-level rise per year	<1.8	1.8 ÷ 2.6	2.6 ÷ 3.4	>3.4
Tidal range (m)	Difference between yearly mean high tide and low tide	<0.2	0.2 ÷ 0.45	0.45 ÷ 0.7	>0.7
Coastal elevation (m)	Surface elevation to mean sea level	>6	3 ÷ 6	0 ÷ 3	<0

3.1.1. Coastal Slope

Coastal slope, obtained as the ratio of the altitude change to the horizontal distance between any two points on the coast perpendicular to the shoreline, is a key factor in estimating the impact of sea level rise on a target coastline and thus in evaluating land loss from inundation. Coastal areas with gentle land slope are considered highly vulnerable, since they allow abundant penetration of seawater, whereas location with steeper slopes are assumed as areas of low vulnerability, providing greater resistance to inundation due to rising sea levels and storm surges [17,32].

Data provided by the Italian Atlas of the Beaches [28] and by the Territorial Information Service of the Apulian Region (www.sit.puglia.it) show that the coastline of the study area mainly consists of sandy beaches, with an average slope of the submerged beach equal to 1%. Submerged bars, both single and in series, are also present. The northern coastline is characterized by higher slopes, within the range 1.0–1.3%, while the southern coastline slopes are in the range 0.9–1.0%. These data have been determined from a topographic and bathymetric grid extending 5 km landward and seaward of the shoreline.

In Table 2, referring to percentage slope values, four classes of vulnerability are identified, from high (coastal slope less than 0.5%, that is, very gentle slope) to low vulnerability (coastal slope greater than 2%, that is, steep slope). Following this classification, the map of coastal slope vulnerability has been implemented and is displayed in Figure 3.

3.1.2. Coastal Landforms/Features

Coastal landforms/features deal with the coastal morphology due to marine processes and landscape evolution. They represent the response of the coast to both erosion and sea level rise. Landforms offer a certain degree of resistance to erosion: for instance, rocky cliffs and wave-cut benches offer maximum resistance and therefore are much less vulnerable than sandy and muddy forms such as dunes, mudflats and so forth, offering the least resistance and so being extremely vulnerable to sea level rise [17]. These behaviours have been considered to classify the vulnerability ranking for this physical parameter, as written in Table 2. Orthophotos and satellite images (Table 1) have shown that landforms in the study area are prevalently beaches, sand dunes, tidal flats and estuaries. The northernmost coast, from Manfredonia to Margherita di Savoia (Figure 2) is characterized by low and mainly sandy beaches (sometimes pebbly), with marshy areas inland. Along the coastline from Margherita di Savoia to Fiumara (Figure 2) a low sandy coast with dunes, wetlands and salt marshes is settled. The detailed map of coastal landforms/features vulnerability based on this data is shown in Figure 3.

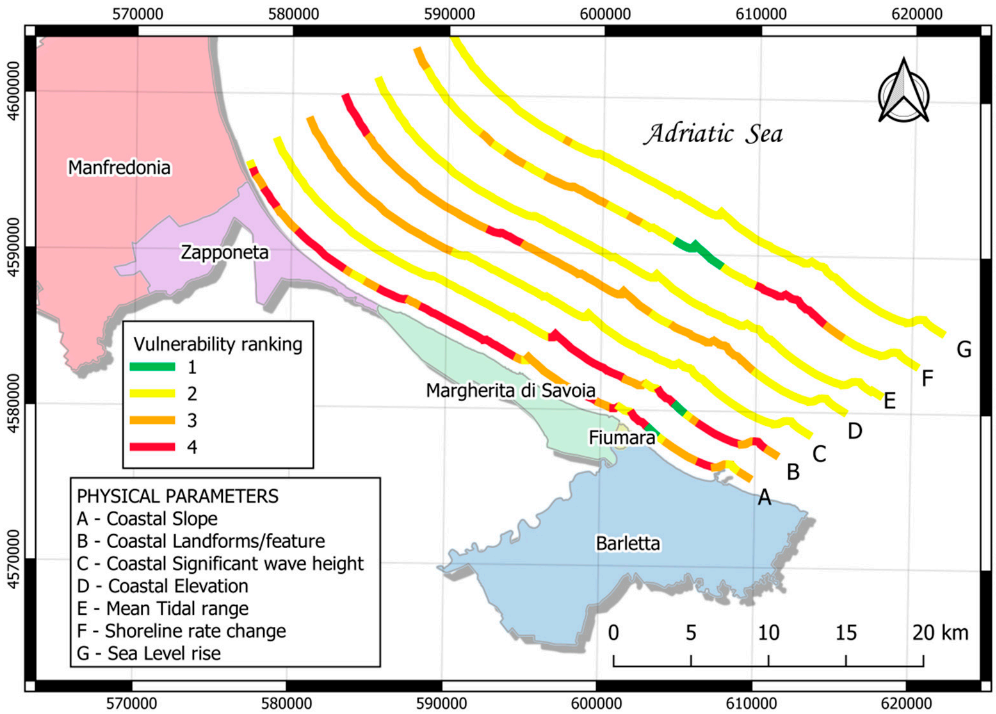

Figure 3. Vulnerability ranking map of physical parameters.

3.1.3. Significant Wave height

The mean significant wave height is a pivotal parameter in many aspects of coastal evolution, especially considering that wave energy is directly related to the wave height, as $E = 1/8\,\rho g H^2$, being E the energy density, H the wave height, ρ the water density and g the gravity acceleration.

Increasing wave energy results in an increased intensity of coastal processes (more often erosion than accumulation), wave set-up and inundation along the coast, finally causing loss of land. Coastlines experiencing high wave heights are thus considered more vulnerable than those exposed to low wave heights [17,45], assuming that higher waves breaking has a stronger impact on the beach and mobilizes and transports coastal sediments (refer to Table 2 for ranking values). Furthermore, the wave action may endanger the cultural heritage and the infrastructures in low-lying areas [46].

The significant wave height data used in the present study come from a previous work by Armenio et al. [47], where wave hind-casting was executed, starting from the results of the European Centre for Medium-Range Weather Forecasts (ECMWF) model. For the coastline from Margherita di Savoia town to the port of Barletta (Figure 2) the mean significant wave height is equal to 0.77 m, with a wave propagation direction of 227° N and a wave period of 4.23 s. The coastline northward Margherita di Savoia's port is characterized by a significant wave height equal to 0.92 m, with a wave period of 5.33 s and a wave propagation direction of 244° N. The deduced map of wave height vulnerability is plotted in Figure 3.

3.1.4. Shoreline Change Rate

Shoreline changes are the result of coastal processes which mainly depend on wave characteristics, near-shore circulation, littoral transport and beach forms. Accreting coastlines are considered less vulnerable because they benefit from the accumulation of land areas. As well, coastlines in erosion are considered highly vulnerable due to the loss of natural and man-made resources. Four categories of vulnerability have been identified for shoreline rate of change, corresponding to high erosion, low erosion, low accretion and high accretion (Table 2).

The historical shoreline positions have been detected from geo-referenced aerial photographs, digital orthophotos and field surveys (Table 1). Specifically, shoreline data referring to the years 1992, 1997, 2006, 2008, 2011 and 2013 have been digitized and superimposed for comparison. The shoreline rate of change has been successively computed using the ArcGIS© GIS-Digital Shoreline Analysis System (DSAS) tool [47], which applies a linear regression rate method, starting from the shoreline position along specified perpendicular transects (more details [29]). Much of the target coastline is in strong retreat due to advanced erosion and is also subjected to flood risk, as resulting from the Coastal Plan of the Apulia Region [28]. The obtained vulnerability map is shown in Figure 3.

3.1.5. Sea Level Rise

The variation in sea level is based on global and local environmental and physical factors, with a strong temporal variation. Its effects, depending on the coastal site morphology, lithological composition, hydrodynamic regime and extension of anthropogenic pressure [48,49] can be mainly: accelerated erosion at sedimentary coasts; intrusion of saline water into groundwater, thus impacting ecosystems; changes in tides, affecting coastal flooding [50–52]. Sea level change is one of the most important consequences of climate change. From the Intergovernmental Panel on Climate Change data [3,52]) a global rise in the sea is expected, ranging from a minimum of 53 cm to a maximum of 97 within 2100.

The historical level of the sea in the Mediterranean and in the Adriatic Sea shows wide interannual and multi-year fluctuations, mainly due to meteorological conditions [50–52]. For the present study, data of sea level variation are referred to studies focusing on the Mediterranean Sea [5,44]. Considering their results, across the whole Mediterranean Sea, a minimum sea-level rise around 2.4–2.5 mm/year has been taken as reference. Four vulnerability classes related to the mean annual sea level rise have been identified, based on Tragaky et al. [25] and consequently a low vulnerability value has been applied to the study area.

3.1.6. Tidal Level

Tidal range could origin occasional inundation hazards. For the present study, the mean tidal range in the southern Adriatic Sea has been estimated based on the tide gauge station of the National tide gauge network (https://www.mareografico.it/) located in Bari, for the period 1999—2014. Numerical filters have been applied to obtain the annual mean tidal range value [53]. Four classes of vulnerability ranking have been defined, as shown in Table 2, correlating tidal ranges to both permanent and episodic inundation hazards, causing erosion and transport of sediment. Therefore, macro-tidal coasts (>4 m) are the most vulnerable ones, while coastal areas characterized by low tidal ranges are designated to be of low vulnerability [15]. In terms of mean tidal range, the entire study area coast falls into the low vulnerability category (Figure 3), being a region with limited extension, characterized by a mean tidal value around 0.30 m (Bari station).

3.1.7. Coastal Elevation

Coastal elevation is defined as the average height of an area above the mean sea level. High-resolution topographic mapping is necessary to quantitatively assess coastal areas at risk from flooding and future sea level rise. High elevations make the coast less susceptible, whereas low elevations make it highly vulnerable (Table 2).

In this study, data of coastal elevation have been derived from Digital Elevation Models (DEM) of the Territorial Information Service of the Apulia Region (www.sit.puglia.it), from gridded topographic and bathymetric elevation at 1 m vertical resolution for 8 m grid cells. The results of the vulnerability evaluation are provided in Figure 3, where low coasts with sandy beaches are mainly observed, hence being very vulnerable.

3.2. Socio-Economic Parameters

The changes of coastal systems due to social, economic and built-environment variables occur frequently and rapidly, even more than those due to physical processes, thus their contribution cannot be disregarded in the coastal vulnerability assessment [54]. The variables here selected for the estimate of the SVI are: population number, land use/land cover and road networks (Table 1). In this study case, the target area has been segmented every 500 m and assigned a vulnerability rank ranging from 1 (very low vulnerability) to 4 (very high vulnerability) as shown in Table 3.

All the vulnerability rankings assigned to the socioeconomics parameters are grouped with thresholds based on previous studies [12,14,24]. Consequently, the vulnerability ranking map following these socioeconomics parameters has been implemented.

Table 3. Vulnerability ranking assigned for socioeconomics parameters.

Parameter	**Description**	**Coastal Vulnerability Ranking**			
		Very Low (1)	**Low (2)**	**High (3)**	**Very High (4)**
Population	Number of residents in the coastal municipality.	0–5000	5000–10,000	10000–50,000	>50,000
Road networks (distance in km)	Presence of roads in coastal areas in terms of distance from the shoreline.	>1.5	1.5–1.0	1.0–0.5	<0.5
Land use/Land cover	Land use refers to purposes served by land (i.e., recreation, tourism, agriculture, residence). Land cover refers to surface cover on the ground (i.e., vegetation, urban infrastructure, water, bare soil or other).	Barren land, water bodies, marsh/bog and moor, sparsely vegetated areas, bare rock	Vegetated land or open spaces, Coastal area (tidal flats, mangroves, salt pans, beaches), natural grassland	Agriculture/ fallow land	Urban, ecological sensitive regions. Urban and industrial area

3.2.1. Population

Most populated areas have increased economic value because people tend to protect their properties, especially from erosion [55,56]. On the contrary, areas where few people live may not experience the same attention on the coastal environment or have the same resources for protection [57]. Moreover, a greater number of resident people generally implies more residential or industrial building interventions, with consequent environmental impacts on the coast. Data on population density obtained from the Italian National Institute of Statistics (Table 1) show that areas with denser population are especially localized around Barletta and Margherita di Savoia (Figure 4). Based on the ranking criteria, four vulnerability classes have been derived (Table 3).

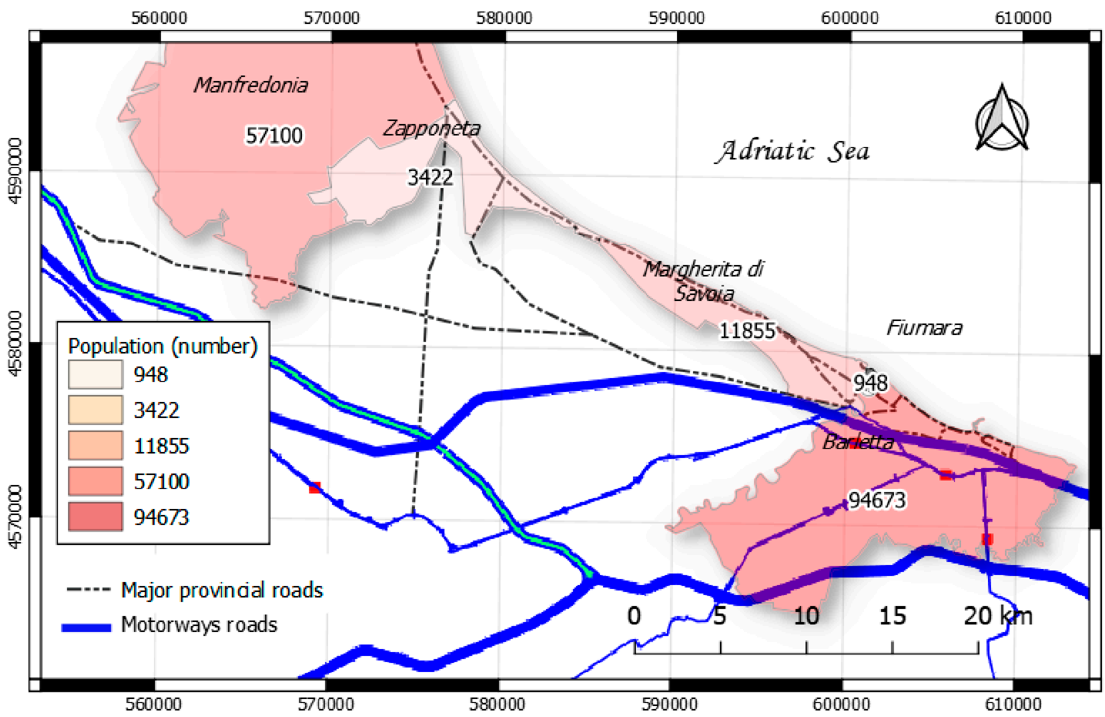

Figure 4. Distribution of population number, major provincial roads and motorways road in the study area.

3.2.2. Coastal Road Networks

The road network is a relevant socio-economic information to evaluate coastal vulnerability and risk, being directly referred to local accessibility, in terms of distance from cities and transport infrastructures (e.g., railways, roads). The spatial distribution and clustering of places and structures where people live and move is a key element in quantifying damages on human life, services and economies (mainly in terms of immediate effects from for example, inundation or surges). In addition, road networks are crucial during a natural calamity, to face emergencies and improve early warning systems. The road network data used in this study have been obtained from the Italian Ministry of Infrastructure and Transport and local institutions (Table 1). Figure 4 shows the major provincial roads and motorways roads. The classification has been done by selecting buffers within 1.5km from the shoreline. Based on this, the vulnerability ranking has been fixed, as written in Table 3.

3.2.3. Land Use/Land Cover

The territorial information system of the Apulian region (www.sit.puglia.it) has provided information about the land use of the region, since 2011, as shown in Figure 5, together with indications of land covering. The northern part is characterized by irrigated areas inland and residential areas along the coast. In the centre, salt plants are close to the coast, while fruit orchard and vineyard are prevalent inland. The agricultural area also dominates the southern zone, where densely populated residential areas are also present in the coastal strip. Urban centres are Margherita di Savoia and Barletta towns, hence classified with very high/high vulnerability. Considering the monetary value due to land use/cover, four vulnerability classes have been identified, as shown in Table 3.

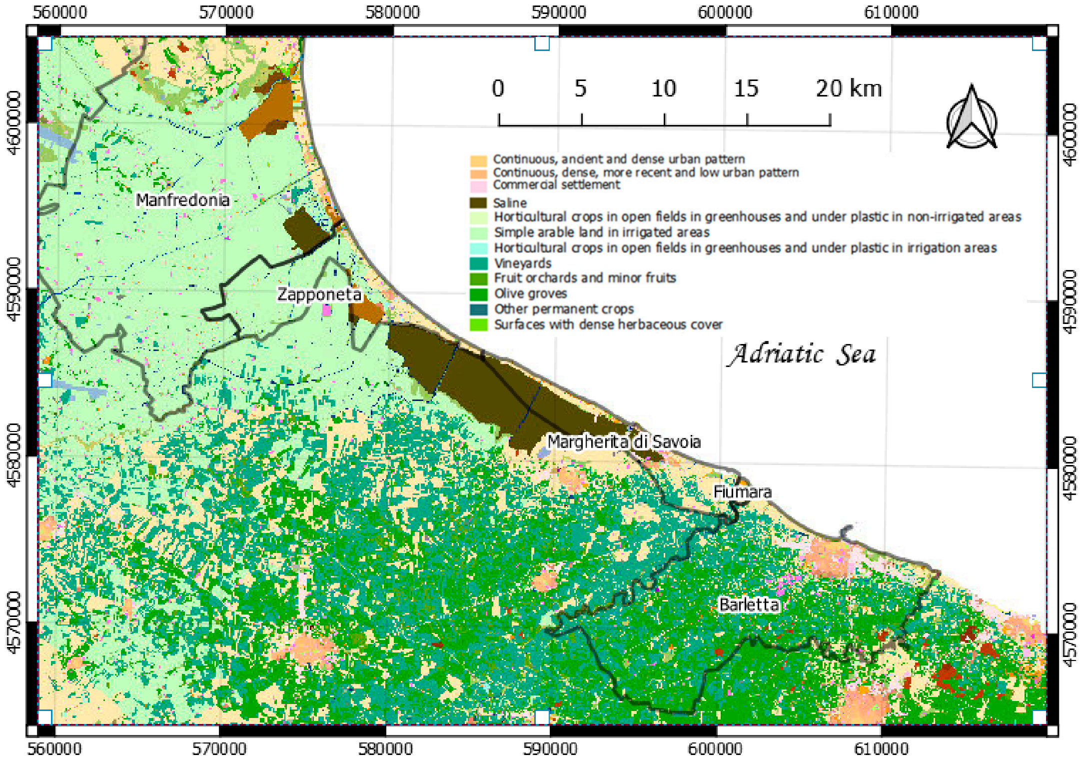

Figure 5. Map of land use/land cover.

3.3. Analytical Hierarchical Process

The Analytical Hierarchical Process (AHP) is a multicriteria decision analysis method that solves decision-making problems by ranking possible alternatives according to several criteria [35,36].

The AHP evaluates the needed weighting factors by means of a preference matrix, where all the selected parameters, considered relevant for the specific study, are compared against each other. Firstly, pairwise comparisons are carried out for all the parameters involved in the definition of both PVI and SVI and the matrix is completed using scores based on their relative importance. In the construction of the pairwise comparison matrix, each parameter is rated against every other one by assigning a relative dominant value between 1 and 9, according to Saaty rating scale [35] as shown in Table 4. In this way, qualitative evaluations are transformed into a quantitative assessment.

In the present study, referring respectively to physical and socio-economic parameters, a score has been assigned to each couple of compared parameters, following the Saaty scale (Table 4) and two different pairwise comparison matrixes have been derived (Tables 5 and 6). This operation in any case involves a certain arbitrariness, even if deductions on the relative importance of the parameters have previously been made, as summarized in Figures 3 and 6.

Table 4. Saaty rating scale [35].

Intensity of Importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favour one over the other
5	Much more important	Experience and judgment strongly favour one over the other
7	Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice
9	Absolutely more Important	The evidence favouring one over the other is of the highest possible validity
2,4,6,8	Intermediate values	Compromise is needed

Table 5. Pairwise comparison matrix of physical variables.

Variables	Coastal Slope	Coastal Landform/Feat	Rate of Shoreline Change	Mean Tidal Range	Mean Sign. Wave Height	Coastal Elevation	Sea Level
Coastal Slope	**1**	**3**	**6**	**9**	**9**	4	7
Coastal landform/feature	1/3	1	5	9	8	3	6
Rate of shoreline change	1/6	1/5	1	5	4	1/3	3
Mean tidal range	1/9	1/9	1/5	1	1/2	1/7	1/3
Mean sign. wave height	1/9	1/8	1/4	2	1	1/5	1/3
Coastal elevation	1/4	1/3	3	7	5	1	4
Sea level	1/7	1/6	1/3	3	3	1/4	1
Column Total	2.11	4.94	15.78	36	30.5	8.92	21.66

Table 6. Pairwise comparison matrix of socioeconomics variables.

Variables	Population Density	Land Use/Land Cover	Roads Network
Population density	1	4	8
Land use/Land cover	1/ 4	1	4
Roads network	1/8	1/4	1
Column Total	1.38	5.25	13

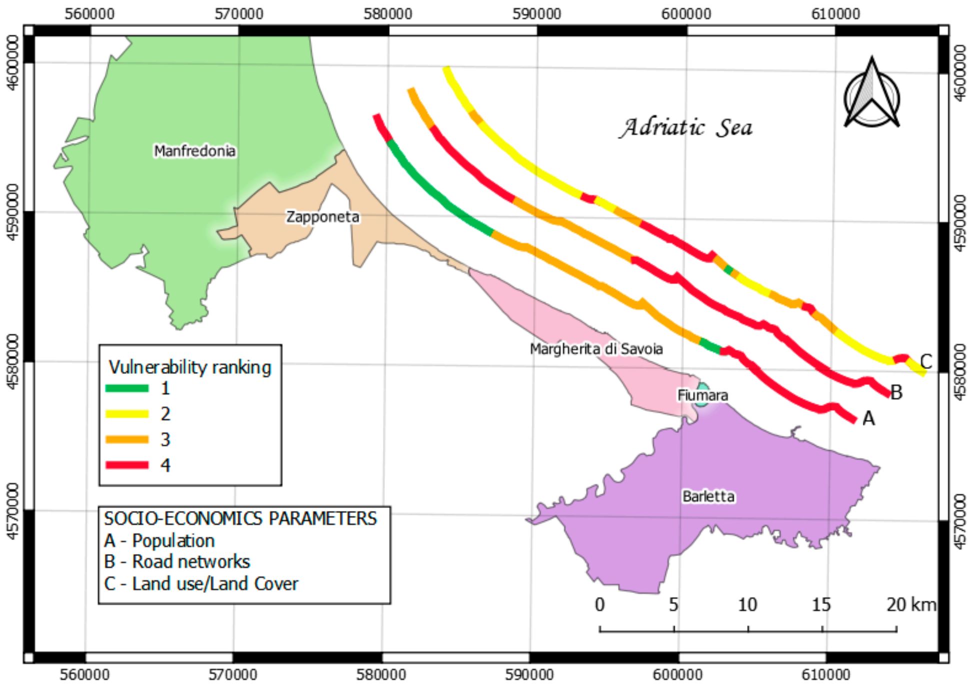

Figure 6. Vulnerability ranking map of socio-economic parameters.

To overcome this subjective evaluation, the method by Saaty [35] explains that the matrix must be consistent and thus an index of consistency, known as consistency ratio *CR*, must be computed with the following formula:

$$CR = CI/RI \tag{1}$$

where *CI* is the consistency index and *RI* means a random index.

The consistency index *CI* is expressed as:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \tag{2}$$

where λ_{max} is the principal eigenvalue of the matrix and n is the order of the matrix.

The *RI* values for different values of n can be obtained by Saaty and Vargas [36], as shown in Table 7.

If $CR < 0.10$, the matrix is consistent, otherwise if $CR > 0.10$ we need to re-evaluate the pairwise comparisons and test again the consistency by AHP. This procedure ensures the correct prioritization of the involved variables [58].

Operatively, we have summed the values in each column of the pairwise matrix and have normalized each value by its column total, thus generating a normalized pairwise matrix (as shown in Tables 8 and 9 respectively for physical and socio-economic parameters). The mean value of each row of this normalized matrix is the weight to be used for the row entry parameter, if consistency is verified.

In the present case, following Equations (1) and (2) we have obtained the consistency ratios less than 0.1 (Table 10) for both physical and socio-economic matrixes, consequently these weights derived using AHP have been used to compute the *PVI* and *SVI*.

Specifically:

$$PVI = W_1X_1 + W_2X_2 + W_3X_3 + W_4X_4 + W_5X_5 + W_6X_6 + W_7X_7 \tag{3}$$

$$SVI = W_8X_8 + W_9X_9 + W_{10}X_{10} \tag{4}$$

where W_i is the weight value of the i-th variable and X_i is its vulnerability score (with $i = 1 \div 10$).

Table 7. Values of *RI*, with *n* order of the matrix [36].

n	1	2	3	4	5	6	7
RI	0	0	0.58	0.9	1.12	1.24	1.32

Table 8. Normalized matrix of physical variables.

Variables	Coastal Slope	Coastal Landform/ Feature	Rate of Shoreline Change	Mean Tidal Range	Mean Sign. Wave Height	Coastal Elevation	Sea Level
Coastal slope	0.474	0.608	0.380	0.250	0.295	0.448	0.323
Coastal landform/feature	0.156	0.203	0.317	0.250	0.262	0.336	0.277
Rate of shoreline change	0.081	0.041	0.063	0.139	0.131	0.037	0.139
Mean tidal range	0.052	0.022	0.013	0.028	0.016	0.016	0.015
Mean sign. wave height	0.052	0.025	0.016	0.056	0.033	0.022	0.015
Coastal elevation	0.118	0.067	0.190	0.194	0.164	0.112	0.185
Sea level	0.066	0.034	0.021	0.083	0.098	0.028	0.046

Table 9. Normalized matrix of physical variables.

Variables	Population Density	Land Use/Land Cover	Roads Network
Population density	0.7273	0.7619	0.6154
Land use/Land cover	0.1818	0.1905	0.3077
Roads network	0.0909	0.0476	0.0769

Table 10. Computation of the consistency ratio (CR).

Variables	Physical Variables	Socioeconomic Variables
λ_{max}	7.50	3.05
N	7	3
CI	0.08	0.03
RI	1.32	0.58
CR	0.06	0.04

4. Results and Discussion

As a result, Figure 7 maps the computed physical and socio-economics vulnerability indexes, where PVI and SVI are displayed for each segmented and examined sector. From the comparison of PVI and SVI in Figure 7, it can be noticed that the coastal stretch of Barletta is almost entirely classified as highly vulnerable in physical terms. On the contrary, from the socio-economic point of view, its vulnerability is more variable and is very high in a very limited stretch around Fiumara. The opposite situation occurs in the northern section of the coast. The coastline of Zapponeta shows an extended section with low vulnerability considering PVI and a high vulnerability considering SVI.

After these considerations, we have observed that a further step is necessary to have the most complete vulnerability assessment of the coastline. To this, firstly, the classical and mostly used formulation has been applied [15], even if it differs from the classical CVI formula because of the inclusion of the socio-economic variables. In fact, we have computed the square root of the product of the estimated contributions of each variable, based on Tables 2 and 3 in our case, divided by the total number of criteria [15,45]:

$$\mathrm{ICVI\_1} = \sqrt{(X_1 \cdot X_2 \cdot \ldots \cdot X_i \cdot \ldots . X_{10})/i} \quad (\text{with } I = 1, 2, \ldots, 10) \tag{5}$$

This option is the geometric average of the numerical values of the criteria [15,59] consequently the resulting ICVI_1 tends to smooth out single large values of some criteria (damping extreme ranges) and to particularly highlight cases when most of criteria have above average levels. It has been widely used at local, regional and supra-regional scale. As an example, the U.S. Geological Survey (USGS) used this formulation to evaluate the potential vulnerability of the U.S. coastline at the national scale [17,18]. They limited this expression to only physical parameters. In the present case, the socioeconomic parameters have been also taken into consideration (i.e., X_8, X_9 and X_{10} variables in Equation (5)). It is worth noting that this expression may be quite sensitive to small changes in individual factors. Furthermore, the X_i values used in Equation (5) are not objectively weighted by means of any AHP procedure. Therefore, a second formulation has been investigated [32,57], directly combining both PVI Equation (3) and SVI Equation (4) to compute:

$$\mathrm{ICVI\_2} = \frac{\mathrm{PVI+SVI}}{2} \tag{6}$$

In this way, both physical and socio-economic factors have equal contribution in the coastal vulnerability assessment. Moreover, the ranked parameters used in Equations (3) and (4) are weighted by the AHP method.

For each ICVI index, the obtained scores have been equally divided into 4 classes, attributing very low vulnerability to the lowest values class and very high vulnerability to the highest values class. Figure 8 shows the map of the examined area where ICVI_1 and ICVI_2 are both plotted along the coast, with their corresponding classification.

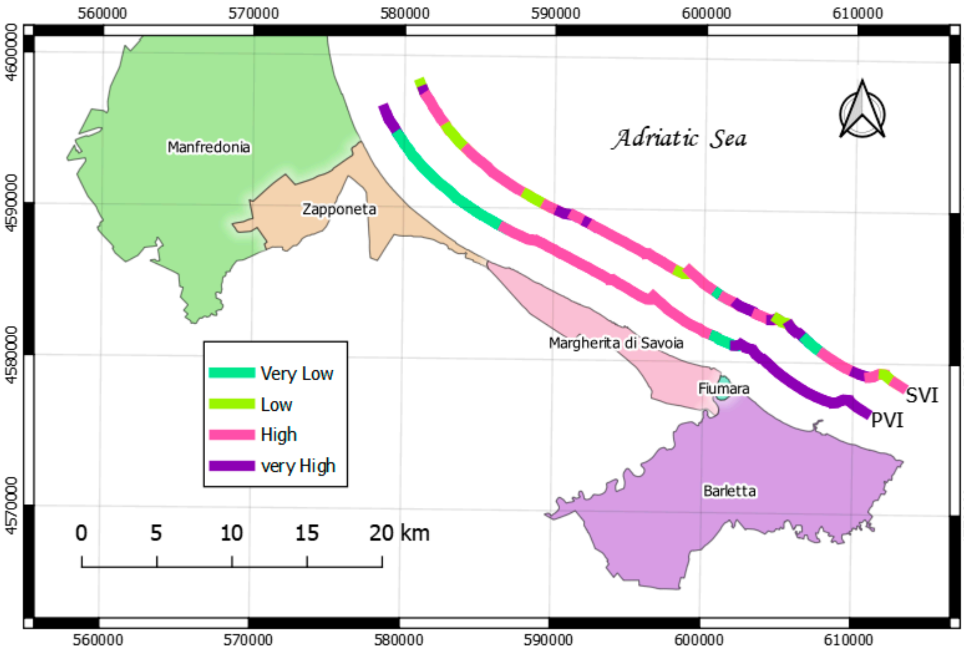

Figure 7. Physical and socio-economic vulnerability index map.

The shoreline length falling in each vulnerability class, for both ICVI_1 and ICVI_2, is shown in Figure 8. Following ICVI_1 result, a coastline length equal to 1.5 km (i.e., the 3.75% of the total coastline) is classified as very highly vulnerable, while following ICVI_2 result a coastline length of 6.0 km is very highly vulnerable (i.e., the 15% of the total coastline). Similarly, the length of coastline with very low vulnerability is equal to 21.0 km considering the ICVI_1 estimation and 5.0 km for the ICVI_2 estimation, which correspond to 52.5% and 12.5% of the total length, respectively.

Specifically, in Figure 8 we observe that ICVI_1 is characterized by very low/low vulnerability along mostly of the examined coastline, except for a very a limited area around Fiumara. By comparing Figure 8 with Figure 7, we note that ICV_1 distribution replicates the one of PVI in correspondence of very low and low PVI values, while the high and very high vulnerability elsewhere to both physical and socio-economic parameters is not evident in ICV_1 map. Therefore, we deduce that ICV_1 tends to underestimate the real coastal vulnerability, as a consequence of the flattening of the higher values due to Equation (5).

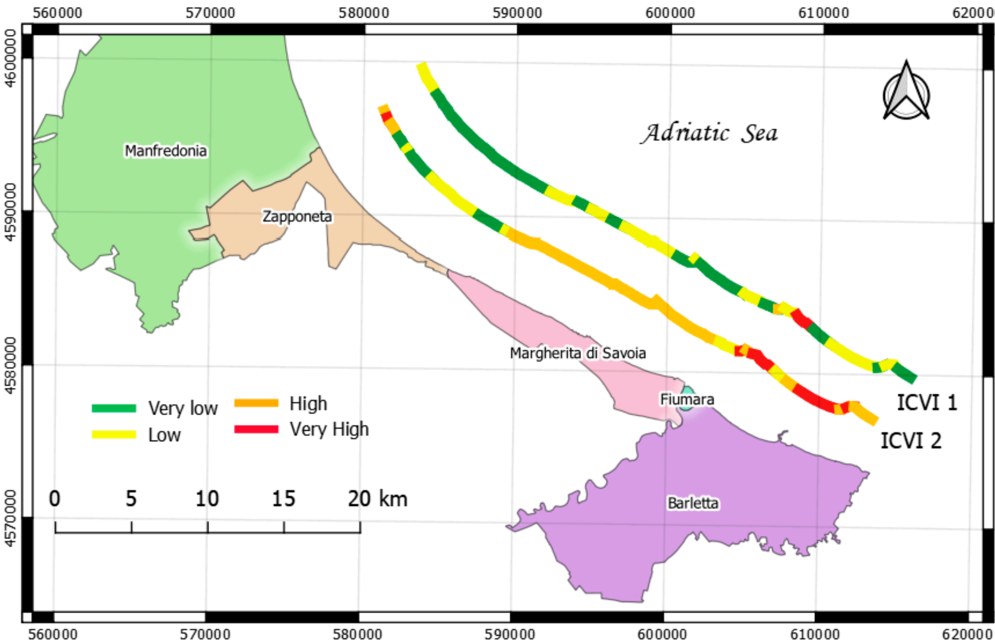

Figure 8. Coastal vulnerability index map.

Conversely, ICVI_2 index seems affected more by physical parameters than by socio-economic ones, when PVI score is higher than SVI one, as resulting along the southern coast. As well, along the northern coastline, where the scores of PVI are very low/low (Figure 7), ICVI_2 distribution is analogously more consistent with PVI distribution. Along the central coast, where both physical and socio-economic effects contribute to high vulnerability, even if with different weights as deduced by AHP, ICVI_2 shows high and very high scores. Thus, we can note that ICV_2 is more sensitive to physical parameters.

ICVI_2 map, more reliably than ICV_1 map, respond to the typical and known peculiarities of the target coastal environment, thus resulting in a more accurate and realistic vulnerability assessment. Finally, we note that the ICVI_2 index is also more conservative than the ICVI_1 one. A true validation of this result could be operated only based on the historical behaviour of the costal site and on the experience. A rough validation of ICV_2 approach could be done considering the strong erosion suffered in recent years along the coast northward Margherita di Savoia, because of different factors [53] and which seems to be consistent with the obtained ICV_2 distribution.

We can certainly observe that this proposed approach is quite simple to implement. Adjustments may be needed to address relevant characteristics in different regions and/or to make best use of available data. Nevertheless, it is a useful tool for "first look" assessment, in need of more detailed investigations, as it allows the identification of priority vulnerable coastal areas. It could be also very useful for communication purposes. If compared with DSS tools and dynamic models, which are much more complete but also much more complex to implement and time consuming, this procedure is feasible and telling piece of a system that is satisfactorily illustrated to stakeholders, representing a necessary step in coastal zone management plans.

5. Conclusions

The present study has proposed an objective methodology to evaluate coastal vulnerability based on some key parameters, both physical and socio-economic. The procedure is based on the implementation of this data in a GIS and on the following application of the analytical hierarchical process to derive the ranked weights for these parameters. In the present application, the obtained weights have been used to compute a physical index and a socio-economic index, successively joined into an integrated coastal vulnerability index.

A formulation different from the classical one has been used to this scope and it has revealed even more satisfactorily. In fact, the study has shown that the classical formulation (ICV_1) underestimates the coastal vulnerability. The new proposal (ICV_2) has illustrated that the examined Adriatic Apulian coast is more vulnerable to physical parameters than to human induced hazards. Particularly, a coastline length of 6.0 km is very highly vulnerable (i.e., the 15% of the total coastline) especially in the southern area, while a coastline length of 5.0 km (i.e., the 12.5% of the total length) has a very low vulnerability especially in the northern area.

The proposed procedure is quite simple to implement, repeatable and general and allows to rapidly obtain vulnerability maps for a 'first look' assessment. If compared with other more complete but also more complex methodologies and models, it is much more feasible in providing tools to prepare and respond to different impacts on people and settlements.

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