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Assessment of the Vulnerability of the Lucana Coastal Zones (South Italy) to Natural Hazards

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Abstract: Coasts are highly dynamic and geo-morphologically complex systems that are exposed to several factors such as waves, extreme meteorological events and climate change. It is also well-recognized that coastal zones, characterized by an increasing population growth, are vulnerable to climate change. In addition, coastal erosion, resulting from natural environment changes and human activities, acts worldwide. Consequently, it is necessary to quantify coastal hazards vulnerability and develop tools to monitor coastal risks and support making targeted climate adaptation policies. In this paper, a framework to estimate coastal vulnerability to flooding and erosion has been developed for the Ionian Basilicata coast. It is based on two methods: the integrated vulnerability index (flooding and erosion) and the CeD physical vulnerability index (multi-risk assessment). Our results are in agreement with the recent shoreline evolution: the integrated coastal risk of the Ionian Basilicata coast is generally medium to high, while the “physical erosion vulnerability” is generally high to very high. In addition, the results highlight a spatial variability of the vulnerability, probably due to the morphology of the beach, which requires developing a strategic approach to coastal management and defining mitigation measures, considering relevant risk aspects as the vulnerability and exposure degree.

Keywords: erosion and flooding hazards; coastal integrated vulnerability index; physical vulnerability index; coastal management



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1. Introduction

Coasts are highly dynamic and geo-morphologically complex systems that are exposed to several factors such as waves, tides, relative sea level changes and extreme meteorological and climate events, including storm surge attacks [1–4]. Coastal floods are considered among the most dangerous and harmful natural disasters [5,6], while coastal erosion is one of the most important natural phenomena, with socio-economic impacts that challenge the capabilities of management authorities [4,7–10]. Whether it is due to natural or anthropogenic factors, coastal erosion causes significant economic losses, social problems and ecological damage. Furthermore, [11] indicates that more than half of the world's population lives in areas subject to at least one hazard at a significant level, and about 13% of the world's population lives in areas characterized by a high exposure to two or more different hazards. Recently, AR6 [12] estimated that 680 million people currently live in the low-lying coastal zone and projected this number to reach more than one billion by 2050.

As a consequence, the increased probability of natural hazards occurrence, associated with the growing concentration of people and activities on the coastal zone, such as those along the Mediterranean coastal zones, requires information updates and a better understanding of coastal zones' vulnerabilities and risks at the local/regional scale [13].

Ref. [14] also report that the selection of appropriate vulnerability and risk evaluation approaches depends on the decision-making context and ranges from global and national quantitative assessments to local-scale qualitative participatory approaches.

According to [6,15], the risk analysis related to coastal hazards involves the evaluation of two main components: hazard and vulnerability. Hazard corresponds to an event or phenomenon with the potential to cause harm such as loss of life, social and economic damage or environmental degradation, while vulnerability represents the propensity or predisposition of a community, system or asset to be adversely affected by a certain hazard [12,15]. In this context, vulnerability is often expressed in a number of quantitative indices and is a key step toward risk assessment and management [4,16].

The Basilicata coastline, facing the Ionian Sea, is characterized by low sandy beaches with a wide coastal plain. Coastal flooding and erosion cause extensive damages [2], and, consequently, an evaluation of the vulnerability and risk of the coastal area is urgent, along with the creation of operative tools, e.g., decision support systems, for coastal risks monitoring and assessment, helping local authorities in the planning and management of littoral areas [17].

The detection and mapping of coastal areas vulnerable to the impacts of hazards is a powerful decision tool, particularly for protecting coastal resources. Different methods may be used to assess these hazards' impacts. Ref. [4] defines four different approaches to check the susceptibility or vulnerability of a coastal area, while [18] reports two main approaches: the multi-hazard risk assessment [19] and the multi-risk assessment [19–23]. The first approach, the multi-hazard risk assessment, analyzes different hazards and aggregates them in a multi-hazard index, resulting in the assessment of a total territorial vulnerability (i.e., no hazard-dependent vulnerability). The second approach, the multi-risk assessment, is more complex because both multi-hazard and multi-vulnerability concepts take into account possible hazards and vulnerability interactions. In this approach, risks are analyzed separately and then aggregated to obtain a multi-risk index evaluation. In addition, one of the most commonly used methods to assess coastal vulnerability to hazards is index- or indicator-based methods [23,24]. The application of such methods provides a discretization of the coastline in various segments, assigning ranking values for each of them based on different parameters' evaluation.

The appropriateness of a specific method depends on the adaptation or risk management issue to be addressed, including, for instance, the spatiotemporal scale, the number and type of actors and economic and governance aspects. Therefore, a relevant challenge is developing suitable approaches to assess hazard-induced impacts at the regional scale, considering the best available geographical information for the case study area, in order to highlight the most critical regions and support the definition of operational adaptation strategies.

This paper aims to compare two methods that have been used to assess potential marine flooding and erosion impacts along the Basilicata littoral in order to define a monitoring approach for coastal managers. The first methodology follows a multi-hazard risk assessment and is centered on the combination of several indices focused on both flood and erosion risk assessments. The second method follows a multi-risk assessment and has been developed using three factors, requiring easily obtainable data and avoiding calculations demanding a high processing capacity. This paper is divided as follows: Section 2 describes the study area, Section 3 illustrates the data and the methodological approaches and the results are presented in Section 4 and discussed in Section 5.

2. Study Area

The study area, oriented NNE-SSW, is located along the Ionian littoral of the Basilicata Region (Italy). The coastline is interrupted by five rivers: Bradano, Basento, Cavone, Agri and Sinni (Figure 1). Several dams and barrages, built since the end of the 1950s, have strongly reduced the sediment transport into the sea [25]. Indeed, before the 1960s, the mean discharge of the Bradano river was about $10.5 \text{ m}^3/\text{s}$, with an annual suspended load

of about 3.5 million tons [26]. After the construction of the S. Giuliano dyke in 1956, the mean discharge reduced to $2.5 \text{ m}^3/\text{s}$ and the suspended load reduced to 271,000 tons. The extraction of sand and pebble from the riverbeds had also contributed to the reduction of the fluvial discharge [25]. For instance, $5 \times 10^6 \text{ m}^3$ of material were extracted from the Bradano river between 1965 and 1977, and almost $8 \times 10^6 \text{ m}^3$ were extracted from the Basento [26].

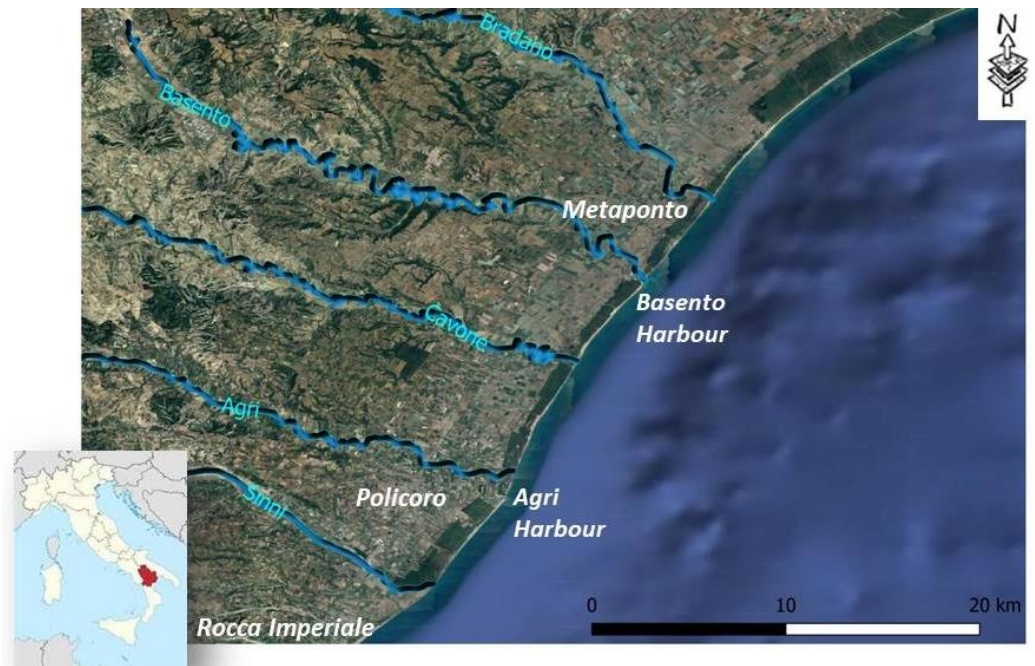


Figure 1. Case study area of the Lucana coast (Basilicata region, South Italy) (adapted from Google Earth).

The climate is classified as thermo-Mediterranean, with a mean annual temperature above $16 \text{ }^\circ\text{C}$ and a mean annual rainfall less than 500 mm [27]. Dominant winds are from 90° N to 180° N . The sea storms are produced by the SE-SSE winds that represent more than 50% of the wind conditions [28]. The significant wave's heights mainly range from 0.25 to 1.25 m for 49% of the wave's conditions, from 1.25 to 2.25 m for 13% of the waves and reach 2.25 to 3.75 for 27% of the waves. Furthermore, the most severe sea storms (force 5 to 8, from SE and SW) generally occur in January and October [25,29]. Finally, the Lucana coast experiences semi-diurnal tides with a mean tidal range ranging from 0.20 to 0.45 m [30].

The shoreline, about 38 km long, can be divided in two sectors whose boundary can be placed at Policoro. The beaches of the southern sector (about 11 km) are mainly composed of pebbles in the southern part and by sand in northern part. The beach width ranges from 30 m to more than 100 m at Nova Siri Lido. The northern sector (27 km) includes the fluvial mouths of the Agri, Cavone, Basento and Bradano rivers. The coastline is sinuous, with the apex extending offshore at the river mouth [2,29,31]. From Policoro to Ginosa (Figure 1), the beaches are composed of dark coarse sands that become gradually thinner and lighter towards Ginosa Marina, while the pebbles gradually disappear toward NE. The beach width ranges from less than 5 m between Metaponto Lido and the Bradano river mouth to more than 70 m between Basento and Cavone rivers. Furthermore, erosion affects this coastal stretch, and marine floodings occur through the formation of breaches in the coastal dune during sea storms. In other terms, coastal inundation and erosion risks are strongly related: as erosion increases, inundation hazard increases as a consequence of the reduction of the self-defense capabilities [32].

The evolution is strongly controlled by the fluvial systems, especially on the variations between the sediment fluvial discharge, the waves and the longshore drift [25,33]. The long-term evolution of the Ionian coast can be described in two main phases [29,30,34,35]:

- From 1873 to 1949/1954: Coastal accretion with a value ranging from +0.7 to +5.5 m/yr, with the highest values being observed at the river mouths.
- After 1955: Coastal erosion, especially between the Bradano and Basento rivers, related to the reduction of the fluvial sediment supply from river catchments due to human activities, land use changes and coastal protections. Coastal accretion still persists between Capo Spulico and Rocca Imperiale due to the presence of different torrential rivers.

At the beginning of the 21st century, the construction of two tourist harbors, located respectively at the right side of the Agri and Basento river mouths, strongly affected the coastal evolution. In fact, the river mouths were historically oriented northward [36]. From 2008, the coastline data exhibit a reverse trend of the above-mentioned morphological process; for instance, the Basento river delta deflects to the south with increasing channel width and depth. Such process is probably related to the construction of the harbor jetties on the updrift side of the Basento river, which has induced shoreline accretion upward and shoreline erosion downward [36]. In addition, the reduction of the sediment supply has caused severe erosion at Metaponto Lido, which is associated with increasing flooding hazards [37].

3. Methods

In this study, two index-based approaches expressing coastal vulnerability were applied and compared. The first method is based on the combination of complex indices for the assessment of the flooding risk and erosion risk [2], without considering the value of the triggering factor. The second methodology has been developed to help managers to quickly characterize the relative vulnerability of coastal areas to natural hazards.

The events considered in this study were related to four return periods (Tr) in agreement with the different policies (directive 2000/60/CE, 2007/60/CE and the legislative decree DLgs 49/2010):

- Tr = 1 corresponding to a very high probability
- Tr = 10, high probability
- Tr = 25, medium probability
- Tr = 100, low probability.

3.1. Division of the Littoral in Homogeneous Stretch and Recent Evolution

The first step consists of the division of the coastal zone into a number of littoral cells, considered as closed systems. Indeed, the concept of littoral cells or sediment cells is generally applied in coastal management, and the cells represent units of coastline within which the natural processes are relatively self-confined [38]. The delimitation of the macro-cells was based on morphological-geographical criteria using the river mouth and harbor jetties. For each macro-littoral cells, two or three cross-shore profiles have been obtained from the Lidar dataset [2].

Furthermore, the recent shoreline evolution was assessed using georeferenced aerial photos from 2011, 2012, 2013 and 2015. The shoreline position was defined as the water line, and the Digital Shoreline Analysis System (DSAS), a freely available extension to ESRI's ArcGIS [39], was used to evaluate the shoreline changes.

3.2. ICC: Multi Hazard Risk Assessment—Flooding and Erosion

In the present study, starting from the available data, we first recognized some key parameters related to coastal flooding and erosion. Two indices have been elaborated upon, which are the Coastal Flooding Index (ZPI) and the Coastal Erosion Index (ZPE).

3.2.1. Coastal Flooding Index

The definition of the coastal flooding risk is related to the product of the morphological vulnerability (V) and the socio-economical vulnerability associated with an exposure (people and economic assets [40]).

a. Morphological vulnerability

The morphological vulnerability considers different probabilities of the weather-marine event associated with different return periods (1, 10, 25 and 100 yr). The impact index (I_i) represents the morphodynamic interaction of the event with the coastal system, as defined by [40]:

$$I_i = I_{Ru} + I_R + I_D + E_{LT} \tag{1}$$

where I_{Ru} : the index of the distance of the wave run-up; I_R and E_{LT} : the long- and short-term coastal erosion, respectively; I_D : the efficiency of the protection structures.

The I_{Ru} index is the horizontal distance X_{max} associated with the level of the maximum wave run-up related to the mean sea level without set-up. It depends on the percentage of “flooded” beach computed along the cross-shore profiles per each macro-area, as reported in Table 1 and ranges from 0 to 4.

Table 1. Classification of the run-up according to the percentage of beach affected by the wave run-up.

	Horizontal Run Up %				
	$X_{max} < 20$	$20 \leq X_{max} < 40$	$40 \leq X_{max} < 60$	$60 \leq X_{max} < 80$	$X_{max} \geq 80$
Runup Index I_{Ru}	0	1	2	3	4

The erosion index I_R corresponds to the short-term shoreline erosion due to wave impacts, and it is calculated using the Kriebel & Dean convolution method [41] through the ratio:

$R_{max} = R(t)/R_{\infty}$ with the following scoring: $R_{max} \leq 15\% = 1$; $15 < R_{max} < 30 = 2$ and $R_{max} \geq 30 = 3$.

The long-term erosion index E_{LT} represents the beach erosion observed from 1997 to 2008 (11 yr). It ranges from 0 to 1, considering a threshold value of 2 m/y [41].

The I_D index accounts for the efficiency of the structural protections along the coast, and it is defined according to the stability of the structures in relation to the incident wave’s height. I_D is equal to 0 if no damage occurs and to 1 in the case of damages or the absence of protecting structures.

Thus, the classification of the morphological vulnerability is defined through the value of the impact index (I_i), ranging between the interval 1–9, and is assumed to be classified as reported in Table 2.

Table 2. Morphological vulnerability classes.

Impact Index	Vulnerability Level	Classes
$I_i < 5$	Low vulnerability	V1
$5 \leq I_i < 6$	Medium vulnerability	V2
$6 \leq I_i < 8$	High vulnerability	V3
$I_i \geq 8$	Very high vulnerability	V4

b. Socio-economical vulnerability

The socio-economical vulnerability means the potential loss of exposure or human lives due to a disaster. It corresponds to the products of the exposure’s susceptibility to a damage (D) and the exposure in terms of economic, social and environmental value [40,42–45].

The coastal damage index (IDC) represents the potential damage D per each macro-area:

$$IDC = P_M + U_M + E_M + U_{10km} \tag{2}$$

where P_M : population of the macro-area M; U_M : percentage of urbanized or industrial area of the macro-area M; E_M : percentage of the high ecological value area of the macro-area M; U_{10km} : percentage of the increase of urbanized area in the macro-area M in the last decade. The values of the quantities P_M , U_M , E_M and U_{10km} are determined through Table 3.

Table 3. Scoring of P_M , U_M , E_M and U_{10km} .

Score	0	1	2	3
P_M	0	<5000 resident	5000–20,000 resident	>20,000 resident
U_M	<10%	10–20%	20–40%	>40%
E_M	<5%	5–20%	20–30%	>30%
U_{10km}	<5%	5–10%	10–15%	>15%

The definition of the potential damage level is based on the IDC value according to the following classification:

- D4: very high damage ($IDC \geq 10$);
- D3: high damage ($7 \leq IDC \leq 9$);
- D2: moderate damage ($4 \leq IDC \leq 6$);
- D1: low damage ($IDC \leq 3$).

c. Index of Coastal flooding

Finally, four classes of flooding risk have been defined by crossing the values of the morphological vulnerability with the socio-economical values (Table 4), which are:

- ZPI 1: Very high flooding risk;
- ZPI 2: High flooding risk;
- ZPI 3: Medium flooding risk;
- ZPI 4: Low flooding risk.

Table 4. Levels of flooding risk. The colours indicated the levels of flooding risk with red indicating very high flooding risk and green low flooding risk.

		Socio-Economic Vulnerability			
		D4	D3	D2	D1
Morphological vulnerability	V4	ZPI1	ZPI2	ZPI3	ZPI4
	V3	ZPI2	ZPI3	ZPI4	ZPI4
	V2	ZPI3	ZPI4	ZPI4	ZPI4
	V1	ZPI4	ZPI4	ZPI4	ZPI4

3.2.2. Coastal Erosion Index

The coastal erosion index indicates the level of natural and/or human pressures, including the actual climate change conditions, on the coastal area. The morphological and socio-economical shoreline erosion vulnerability was defined by calculating different indicators (Table 4 and supl.mat Table S1), which were aggregated into three groups:

- H: erosion rate, shoreline evolution, exposition and intensity of the sea storms;
- V: presence of coastal dunes, defense structures, variation of the coastal dune length, submerged slope, protected areas, lithological characteristics and harbor structures, coastal waterproof level and distance from the shoreline to the active zone;
- E: loss of the soil value, touristic and productive activities and population.

Regarding the indicators related to the erosion rate, harbor structures, coastal water-proof level and distance from the shoreline to the limit of the active zone, the analysis has been performed taking into account the storm-surge wave height corresponding to different return times ($Tr = 1, 10, 25$ and 100 yr) [2]. The wave climate data were referred to a re-analysis of the atmospheric and wave conditions by the hindcasting method WAVE-WATCH III (WWIII) for the whole Mediterranean Sea [46]. This model allows the climate wave analysis to refer to several case studies related to heavy storms observed in this basin in the last twenty-five years. Wherever available, the simulation results have been validated using buoy data provided by different official sources. The simulated and observed data are compared through statistical error measures such as Normalized Bias (NBI), Normalized Root Mean Square Error (NMRSE), also known as Scatter Index, and Correlation Coefficient (CORR). The waves data for each Tr have been derived through the omni-directional analysis, which generates a general overestimation of the wave height [46].

An impact value has been assigned to each indicator according to a set of attributes defined as:

- RA: representation of the environmental state (Incidence 5);
- FP: facility of population (Incidence 1);
- SI: easiness of interpretation (Incidence 2);
- SC: sensitivity to variation (Incidence 5);
- DF: applicability at different scales (Incidence 1);
- VS: comparability with the threshold value (Incidence 2).

The value of classification is obtained by summing the products of the five attributes, in terms of incidence, and the judgment assigned to each indicator, classified as:

- High 4;
- Moderate 3;
- Good 2;
- Low 1.

Then, a coefficient of significance (CS) normalized to the maximum value (equal to 1) has been assigned to each indicator. A value of 1 has been assumed for the last group (E) since no accurate and complete data are available (supl.mat Table S2).

Finally, the coastal risk erosion index, ZPE, has been calculated as:

$$ZPE = H \cdot V \cdot E \tag{3}$$

and the level of risk to erosion ranges from 0 to 1, as follows:

- ZPE1 [0.75–1] VERY HIGH RISK;
- ZPE2 [0.50–0.75] HIGH RISK;
- ZPE3 [0.25–0.50] MEDIUM RISK;
- ZPE4 [0–0.25] LOW RISK.

3.2.3. Integrated Coastal Risk Index

The global assessment of the erosion and flooding risk can be evaluated through the integrated coastal risk index, ICC, which is a combination of the two previous indices (flooding and erosion). It allows for the obtention of a complex zonation of the coast and provides a complete vision of the risk level along the Basilicata littoral (Table 5).

Table 5. Level of integrated coastal risk. The colours indicated the levels of flooding risk with red indicating very high flooding risk and green low flooding risk.

	ZPE1	ZPE2	ZPE3	ZPE4
ZPI1	ICC11		ICC2	
ZPI3	ICC1	ICC2		ICC3
ZPI2	ICC2		ICC3	ICC4
ZPI1	ICC2	ICC3		ICC4

The values of the ICC, ranging from 0 to 1, indicate:

- ICC1 [0.75–1]: very high coastal risk
- ICC2 [0.50–0.75]: high coastal risk
- ICC3 [0.25–0.50]: medium coastal risk
- ICC4 [0–0.25]: low coastal risk

3.3. CeD—Multi-Risk Assessment (Physical Vulnerability Index)

The second method has been developed in collaboration with local authorities to support them in terms of coastal monitoring and management. Therefore, we decided to follow the procedures used by [47] to determine the physical vulnerability of the Basilicata coastlines to environmental hazards. We also started by determining the key parameters. Moreover, the vulnerability of the coastal zone to natural hazards such as erosion or “marine” flooding is determined by using geological and physical process variables that strongly influence coastal evolution. It is based on the shoreline concept that is also used to define set-back lines. At a regional scale, the physical process variables are almost “constant” and therefore were not directly considered. Past and present geomorphological characteristics (considering historic shoreline change rates and beach slope) represent variables that account for a shoreline’s relative resistance to erosion and its susceptibility to flooding. Considering the almost constant general morphology along the Ionian Basilicata coast, we decided to use two parameters, which are:

- the beach width (beach slope) that limits or prevents coastal marine flooding and
- the medium and long-term shoreline evolution.

The beach width was therefore measured along distant transects 250 m apart on the 2010 aerial photos and integrated with in situ measurements. Then, according to the 10-year return period wave run-up, three situations may occur:

- dramatic for a beach width less than 35 m;
- adequate for a beach width ranging between 35 and 60 m;
- excellent for a beach width greater than 60 m.

The shoreline positions were mapped using the 1954, 1997, 2006, 2010 and 2015 aerial photographs considering an error of 5 m. All of the photographs were geo-referenced within ArcGIS 9 in the WGS84/UTM 33 projection system. As reported by different authors, when the aerial photographs or satellite images are used, the reference line chosen should be characterized by spatiotemporal continuity [48,49]. The present study was based on the high-water line, also called the high-water mark, which is the most commonly used indicator for the study of shoreline variations [48,50]. Topographic surveys were also performed in 1997, 2006, 2010 and 2015.

Then, the long-term (1954 to 1997) and medium-term (1997–2010 and 2006–2020) shoreline evolution was calculated using the Digital Shoreline Analysis System program DSAS tools [39]. The stability of the beach evolution was determined by comparing the long-term trend with the medium-term trend using four classes, which are:

- A: positive when the long and medium-term trends are positive
- B: mainly positive when the long term is negative and the medium term is positive
- C: mainly negative when the long term is positive and the medium term is negative
- D: negative when the long- and medium-term trends are both in erosion.

A value was assigned to each class of the beach width and of the shoreline evolution (Table 6). It must be noted that we decided to use the 2010 beach state because the 2015 data were not entirely available. The CeD index, reflecting the actual coastal configuration and its probable evolution, was obtained by combining the two parameters (Table 6).

Table 6. Parameters used for the CeD approach.

	Class	Value
BEACH WIDTH	<35 m	1
	35–60 m	2
	>60 m	3
Shoreline evolutive trend	+	
	+ for 1954 to 1997 and for 1997–2010	0.25
	– for 1954 to 1990 and + for 1997–2010	0.50
	+ for 1954 to 1990 and for 1997–2010	0.75
	– for 1954 to 1997 and for 1997–2010	1
CeD	=	
	<1.50	Not relevant/low
	1.50–2.50	Not negligible/medium
	2.50–3.50	Significative/high
	>3.50	Important/very high

It must be noted that, because it was not possible to reconstruct tidal conditions at the moment of the photo, we assumed that the daily water line position was subjected to a maximum uncertainty of ± 4 m.

4. Results

4.1. Macro-Areas and Recent Shoreline Evolution

The division of the coastal zone in the macro-area, based on a geographic-morphologic criterion (river mouths and harbor jetties), allowed for the individuation of seven macro-areas along the Ionian coastal zone (Figure 2). The extension of the macro-area ranges from 9.8 km² (macro-area 1) to 70.8 km² (macro-area 4), corresponding to a shoreline length from 1.1 km to 8.2 km, respectively (Table 7).

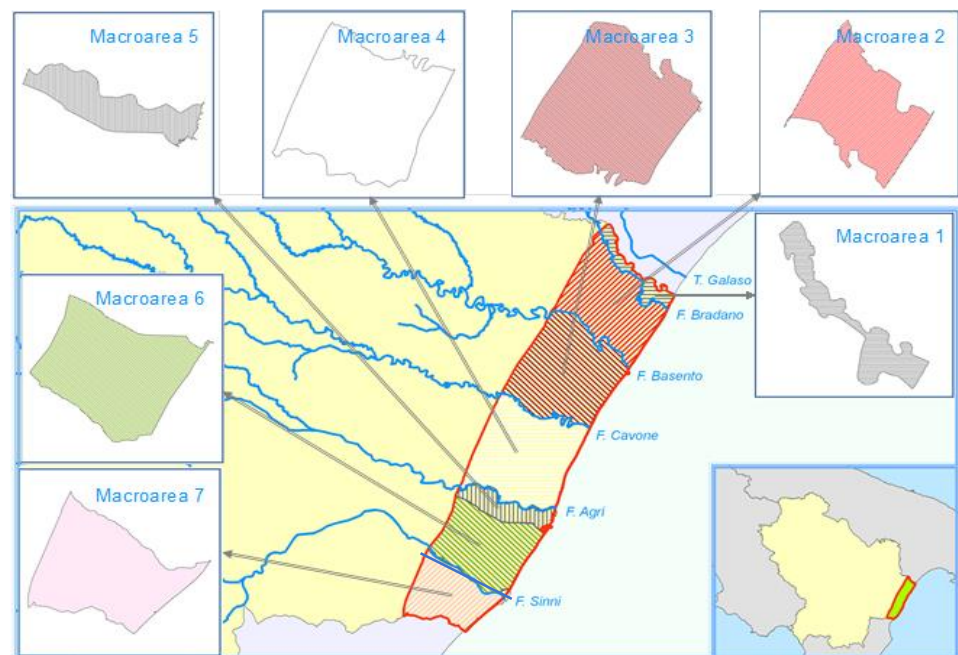


Figure 2. The macro-areas of the Ionian Basilicata coastal zone and the different transects used in this study.

Table 7. Main characteristics of the macro-areas.

Macro-Area	Limits	Extension (Km ²)	Shoreline Length (km)	Width (km)	Urban Center	SIC-SAC/SPA
1	LH Bradano—Apulia Border	9.8	1.1	9.0		C type
2	RH Bradano—LH Basento (Porto Argonauti)	54.7	6.8	8.8	Metaponto Lido	C type B type
3	RH Basento (Porto Argonauti—LH Cavone)	70.3	6.6	8.2	Marina di Pisticci	B type
4	RH Cavone—LH Agri	70.8	8.2	8.2	Lido di Scanzano	B type
5	RH Agri—Porto Marinagri	14.2	2.2	8.6	Marinagri	B type
6	Porto Marinagri—LH Sinni	49.0	6.8	7.8	Policoro	C type
7	RH Sinni—Calabria Border	33.8	5.7	6.8	Nova Siri Rotondella	

The coastal zone of the macro-areas 1, 2 and 3 is generally flat and locally lies below the mean sea level. Coastal dunes may also be present. A steeper beach sloping gently offshore down to the marine escarpment characterizes the northern stretch of the macro-area 3. The macro-areas 4, 5, 6 and 7 are similar to the macro-area 3, with, however, a hilly hinterland morphology.

Urbanization is almost sparse in all of the macro-areas or is even absent, such as in the macro-areas 1 and 5. However, the macro-area 2 is characterized by the presence of a residential area “Metaponto Lido”, which is protected by eight breakwaters. Other protections have been realized along the littoral: a jetty at the Bradano river mouth, two groins at Lido Marinella, a seawall (dyke) protecting the southern extremity of the macro-4 in proximity of the Agri river mouth and four groins that are present on the opposite site of the Agri river mouth in the macro-area 5. The small harbor, Porto Argonauti, located in the macro-area 3, is protected by jetties, while two jetties protect the small harbor situated near the Agri river in the macro-area 5. Finally, the littorals of the macro-areas 1, 6 and 7 are unprotected.

The recent evolution of the shoreline (Figure 3) reveals that:

- A general shoreline retreat occurred almost along the entire coast between 2011 and 2012. Locally, shoreline advance may be observed in the macro-areas 2, 4, 6 and 7;
- A general shoreline stability or advance is observed between 2012 and 2013, but locally, shoreline erosion occurred. In addition, shoreline advance is locally important; for instance, at the right side of the Bradano and Cavone, the shoreline advances more than 50 m;
- From 2013 to 2015, shoreline retreat is generally observed in the macro-areas 2, 3, 5 and 7, especially near the river mouths. The macro-areas 4 and 6 are characterized by a shoreline advance, except at the river mouth area;
- From 2011 to 2015, the macro-areas 2, 3, 5 and 7 are characterized by a shoreline retreat, especially in the river mouth areas (Bradano, Basento, Agri and Sinni). The macro-area 4 is characterized by an alternation of shoreline advance and erosion, while shoreline advance is observed in the macro-area 6.

4.2. Integrated Coastal Risk to Flooding and Erosion

The morphological vulnerability has been defined for each profile of the macro-areas 2 to 7, considering the different morphological vulnerability classes (Supl.mat Table S3). The results indicate that the vulnerability is low to medium for almost all profiles when considering a 1-year return period, except for profiles 8 (MA 4, I_i 7), 10 (MA5, I_i 7) and 13 (MA 7, I_i 9), while the vulnerability is high to very high for a 100 year return period, except for profile 11 (MA 6, I_i 4). The vulnerability is generally medium to high when considering a 10-year return period, except for profiles 7 (low, MA 3, I_i 4), 8 (very high; MA 4, I_i 8), 10 (very high, MA 5, I_i 8), 11 (low, MA 6, I_i 3) and 13 (very high, MA 7, I_i 9). The vulnerability for the 25-year return period is high to very high, except for profiles 3 (medium, MA 3, I_i 5), 7 (low, MA 3, I_i 4) and 11 (low, MA 6, I_i 4). Furthermore, profiles 8

(MA 4), 10 (MA 5) and 13 (MA 7) have a high or very high vulnerability for each return period, while profile 11 (MA 6) has a low vulnerability for all the return periods.

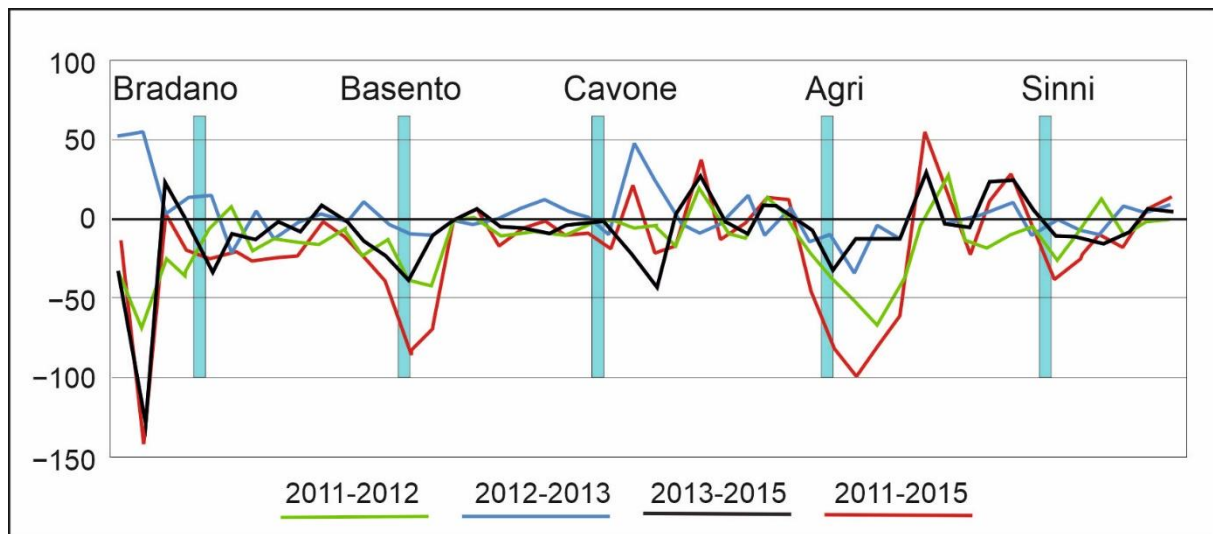


Figure 3. Recent shoreline evolution (river names are reported and their positions are outlined in blue).

The socio-economical vulnerability analysis (Table 8) indicates that the Coastal Index Damage (IDC) ranges from 4 to 8, corresponding to medium to severe damage. The macro-areas 4, 5 and 6 have the lowest value (IDC = 4), while highest values characterize the macro-areas 2, 3 and 7. The highest value of the macro-area 2 is due to the population, urbanization state and ecological interest. The situation of the macro-area 3 is due to the ecological importance and the increase in urbanization and only to the urbanization (U_M and $U_{10 km}$) for macro-area 7.

Table 8. Socio-economical vulnerability of the Ionian Basilicata coast. D = potential damage, E = exposure and S = socio-economical vulnerability.

	Profile	P_M	U_M	E_M	U_{10km}	IDC	D	E	S
MA 2	Profile 1—RH Bradano	2	2	3	1	8	D3	E4	S3
	Profile 2—Metaponto L. Hermitage	2	2	3	1	8	D3	E4	S3
	Profile 3—Metaponto L. Rotonda	2	2	3	1	8	D3	E4	S3
	Profile 4—Metaponto L. Katy	2	2	3	1	8	D3	E4	S3
	Profile 5—LH Basento	2	2	3	1	8	D3	E4	S3
MA 3	Profile 6—RH Basento	1	0	3	3	7	D3	E4	S3
	Profile 7—LH Cavone	1	0	3	3	7	D3	E4	S3
MA 4	Profile 8—RH Cavone	1	0	3	0	4	D2	E4	S2
	Profile 9—LH Agri	1	0	3	0	4	D2	E4	S2
MA 5	Profile 10—RH Agri	1	0	3	0	4	D2	E4	S2
MA 6	Profile 11—Lido Policoro	1	0	3	0	4	D2	E4	S2
	Profile 12—LH Sinni	1	0	3	0	4	D2	E4	S2
MA 7	Profile 13—RH Sinni	1	2	1	3	7	D3	E4	S3

Because it has not been possible to measure the exposure (people and economic/environmental assets) due to the lack of reliable data, the study has considered a high value (E4) of the “exposures” to calculate the socio-economical vulnerability of the different macro-areas. The macro-areas 2, 3 and 7 present a high vulnerability (S3), while the macro-areas 4, 5 and 6 present a medium vulnerability (S2) (Table 8).

The coastal flooding index has been calculated considering the four return periods. The results (Figure 4, Supl.mat. Table S4) clearly indicate that, in the 1-year return period, the flooding vulnerability is moderate or medium (ZPI 3–4), except for the southern macro-area (7), which presents a very high flooding vulnerability. The flooding vulnerability increases with longer return periods: medium to high flooding vulnerabilities are observed for return period of 10 or 25 yr, while high to very high vulnerabilities are related to a 100-year return period. However, profiles 7 (MA 3) and 11 (MA 6) present a lower vulnerability compared to the other profiles, and profile 11 is characterized by a low vulnerability (ZPI 4) for all return periods.

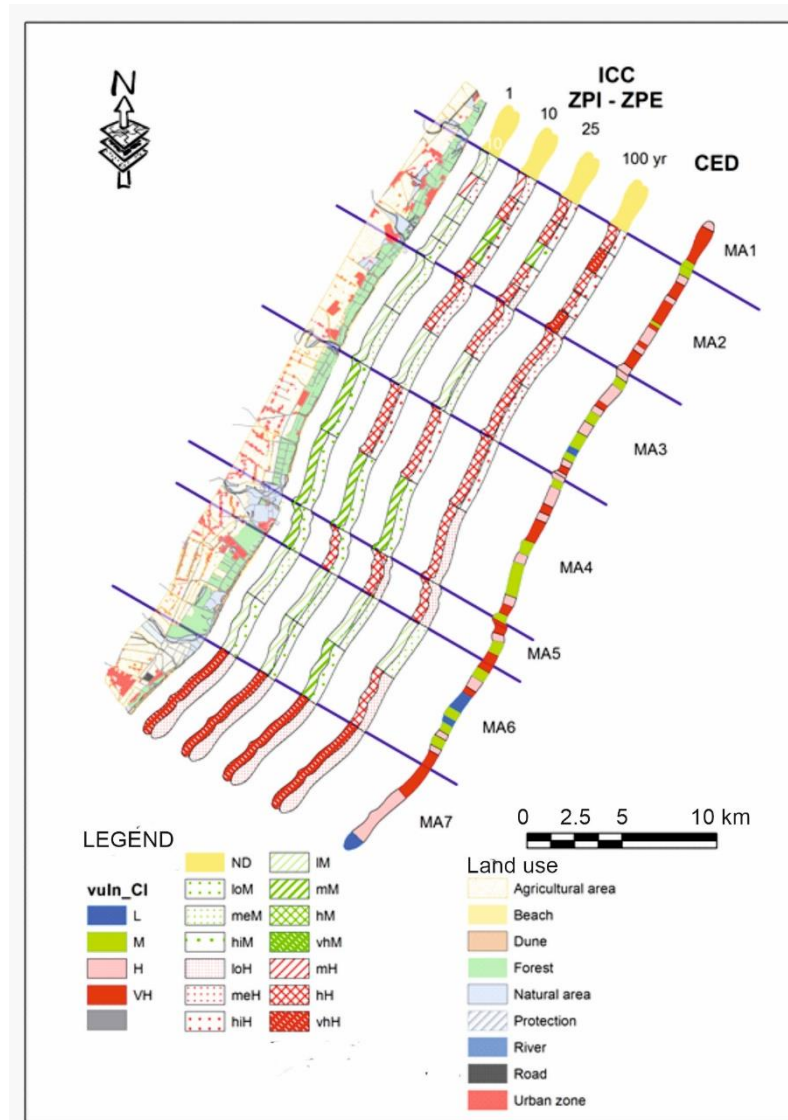


Figure 4. Synthesis of the results.

The results of the coastal erosion index (Figure 4, Supl.mat. Table S4) indicate that:

1. A low-medium coastal erosion vulnerability is observed along the entirety of the Basilicata Ionian coast, except for profile 8 (right side of the Cavone), which presents a high vulnerability;
2. Similar results are observed for the 10-year return period, indicating a general low-medium vulnerability, except for profiles 2, 3 and 4 at Metaponto and profile 8 at the right side of Cavone;

3. The coastal erosion vulnerability associated with the 25- and 100-year return periods is generally low to medium along the Basilicata Ionian coast, except for profile 1 at the Bradano mouth, profiles 2, 3 and 4 at Metaponto and profile 8 at Cavone, which indicate a high vulnerability.

The integrated coastal risk of the Ionian Basilicata coast is generally medium to high (Figure 4, Supl.mat. Table S4). In particular, the risk is medium for a return period of 1 year for nearly the entire littoral, except at the Metaponto River (high) and at the right side of the Sinni River (high). The vulnerability increases with a longer return period ($Tr = 10, 25$ e 100): the risk is high for a 100-year return period, except at Policoro Lido, which is characterized by a medium vulnerability.

4.3. Physical Vulnerability Index (CeD)

The application of the second method is based on two parameters: the beach width and the shoreline evolution. In 2010 and 2020, the beach width ranged from 5 to 150 m, with a mean value of about 39 m, and the beach width slowly increased from north to south (Figure 5). The macro-area 2 presented the narrower beach, with a mean value of 28 m, while the macro-areas 6 and 7 were characterized by a continuous wide beach (more than 40 m). The widest beach (153 m) was observed locally in the macro-area 3 due to the levelling of the coastal dunes.

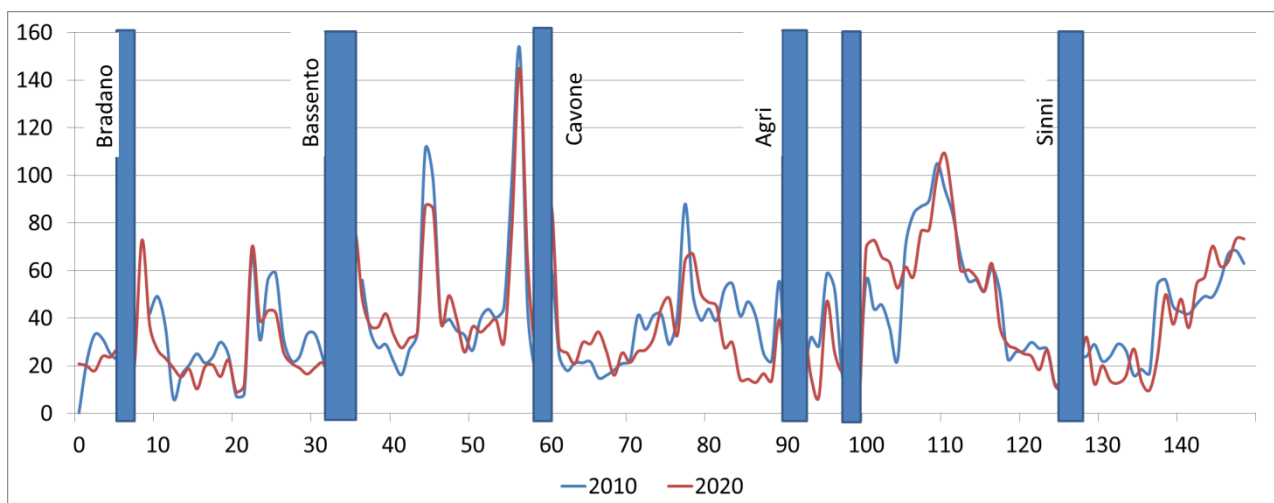


Figure 5. Beach width (in m) in 2010 and 2020. The numbers indicate the transects from north to south. The blue lines represent the limits of the macro-area.

The rates of the long-term shoreline evolution (Figure 6) range from -8 m/yr to $+4$ m/yr (corresponding to a beach width change of -340 m to $+160$ m), while the rates of the short-term evolution vary from -6 m/yr to $+1.7$ m/yr (corresponding to a net change of -77 m to $+22$ m). The results also indicate that the most intense erosion or shoreline retreat generally occurs in the river mouth areas and especially on the southern side (left bank).

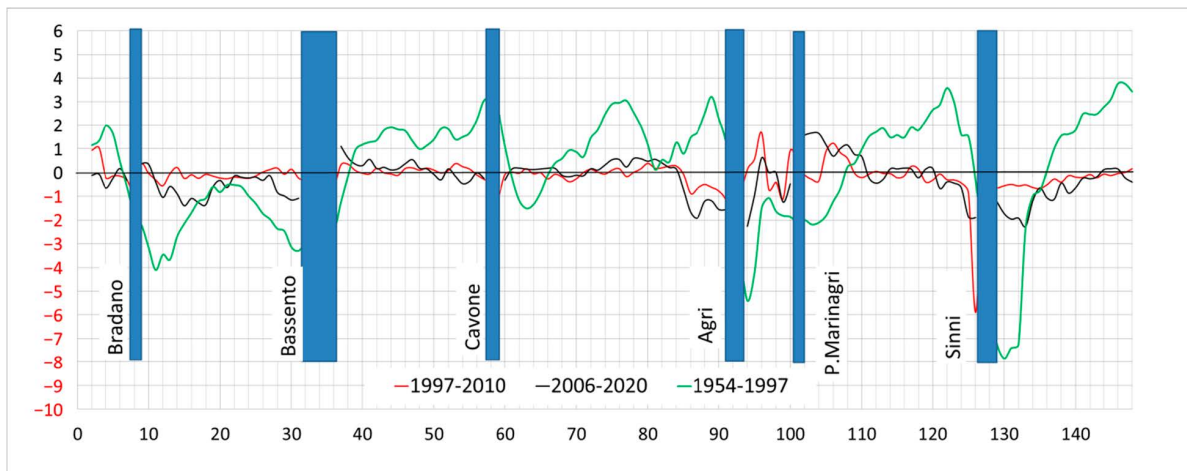


Figure 6. Shoreline evolution (in m/yr) at three different periods: from 1954 to 1997, from 1997 to 2010 and from 2006 to 2020. The blue polygons represent the fluvial areas (no data). The numbers indicate the transects from North to South.

The long-term evolution (1954–1997) shows a “clear pattern”. In fact, shoreline retreat is observed for the macro-areas 2 and 5, while shoreline advance is observed for the macro-areas 3 and 4 (except locally near the river mouth). The macro-areas 6 and 7 can be subdivided in two zones: shoreline retreat on the left bank of the river, and shoreline advance southward. By contrast, the short-term shoreline pattern is irregular, with an alternation of shoreline retreat and advance. The macro-area 7, however, is characterized by a general shoreline retreat, especially at the Sinni River mouth.

The “physical erosion vulnerability” (CeD) is reported in Figure 7. The results highlight a great variability of the CeD along the coast, which is generally greater than 2.5 (high to very high). The macro-areas 2 and 5 present a very high to high vulnerability. The macro-areas 3 and 4 mainly have a high to medium vulnerability but locally present a very high or low vulnerability. A medium to low vulnerability is obtained for the macro-area 6, but the vulnerability is locally high to very high at the two edges. The vulnerability of the macro-area 7 ranges from very high in the northern edge to low in the southern one. Finally, the worst situations are observed in the river mouth areas and at the Marinagri harbor.

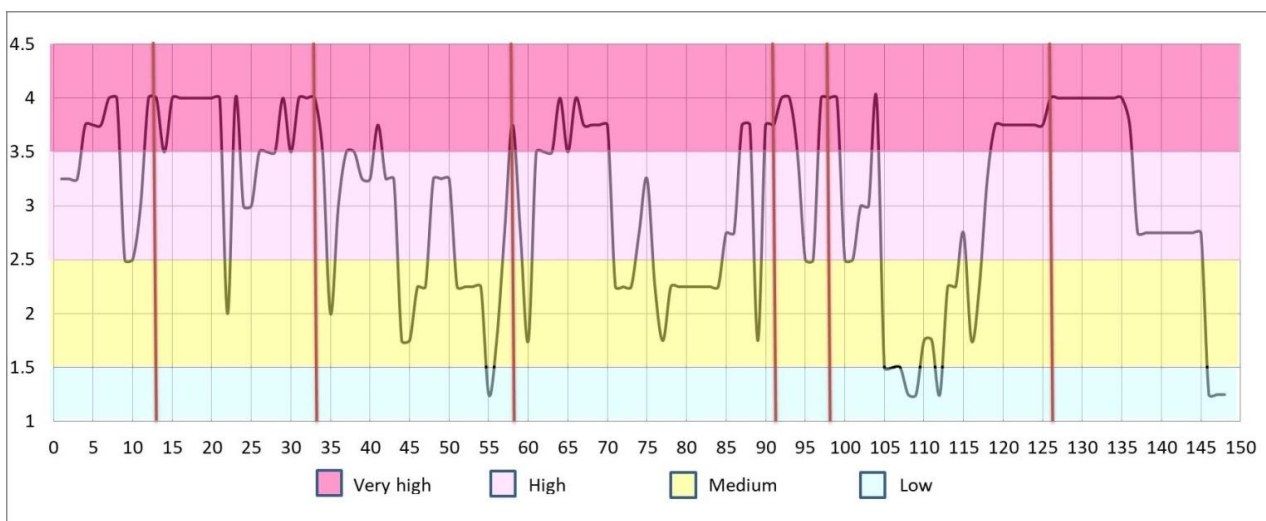


Figure 7. Physical erosion vulnerability of the Basilicata territory. The vertical lines represent the limit of the macro-areas. (CeD values: <1.5: low, 1.50–2.50: medium, 2.50–3.50: high and >4: very high).

5. Discussion

The starting point of this study was the subdivision of the coastline into seven cells corresponding to geomorphological units. A correct approach to define the limits of the coastal stretches should be based on the identification of physical, geographical and socio-economical discontinuities and on the hydro-sedimentary processes. In the literature, different parameters are used to divide the coastal system such as harbors' jetties, perpendicular structures, fluvial mouths, headlands, coastal morpho-types and morpho-evolutive characteristics [51–54]. Ref. [55] used the concept of the discontinuity of longshore sediment transport to define littoral cells. Ref. [56] also used tidal inlets and estuaries to divide the coast of England and Wales. The subdivision should also consider that the available data are sufficiently representative of all the variables used.

The EuroSION project proposes a subdivision of the coast in the sedimentary cells characterized by a complete sedimentary cycle, which includes the source, the transport and the deposit [57]. For EuroSION, the definition of coastal sedimentary cells allows for the definition of the sediment budget. The importance of dividing shorelines into cells, based on geomorphic features or anthropic interruption, is often used for management, since they can be considered as coastal spatial unities that comprise the sediment budget concept [52,58]. Such concept has been used to implement sediment management plans in Emilia-Romagna (Italy [59]). Similarly, in Tuscany (Italy), the coastal zone has been divided in 56 sectors, for which detailed information was collected, including the sediment budget, and successively used to define a management plan [59]. In India, 26 primary cells, sub divided into 58 sub cells, were identified and used for the preparation of a Shoreline Management Plan [58]. In the present study, the limits of the macro-cell correspond to the river mouth and harbor jetties since the movement of sand along the beaches within the cell does not significantly affect the beaches in the adjacent cell. These cells, used to assess the vulnerability and risk against flooding and erosion events, represent key features for the definition of integrated coastal management plans.

The recent evolution of the Basilicata shoreline is relatively preserved from human interventions, except in macro-areas 3 and 5, where the harbors' jetties have modified the hydro-sedimentary processes. The construction of the harbors' jetties is responsible for the accretion and erosion on the upstream and downstream sides of the ports: the harbors' jetties interrupt the alongshore sediment transport, causing downdrift erosion. The sand-accumulated upstream of the harbors' jetties could potentially be used for sediment bypass to provide a local solution to the downstream erosion. Furthermore, the erosion was so intense that the local beach disappeared, requiring the construction of different groins and breakwaters to protect the coastal area. However, several studies have demonstrated that hard structures do not solve erosion problems and may shift erosion downdrift [60–62]. In addition, the results are in line with other studies [52,63], highlighting that the construction of hard structures is not in agreement with the strategic management plan. Indeed, to ensure effective and efficient solutions for the Basilicata coast, management options should be broadened, and a range of different strategies and solutions are probably required, including ecosystem-based solutions. Currently, four options can be adopted, as described by [64], which are: (1) protection, (2) accommodation, (3) planned retreat and (4) sacrifices. Accommodation strategies, for instance, could be proposed for MA7, while protection solutions using hard structures and/or soft protection measures could be defined to preserve population centers, economic activities and natural resources. Furthermore, the proposed methodologies are a first attempt to consider coastal erosion in flood-prone areas. The results obtained with the two methods are in agreement with the recent shoreline evolution and are fairly similar, indicating a medium to high vulnerability to flooding and erosion. The results obtained with the CeD method are comparable to the results obtained with the Integrated Coastal Risk method related to the 10- or 25-year return period. The risk obtained with the CeD method is instead generally higher, with a greater spatial variability. Our methods are also further conceived as a decision support tool, since the results can be easily displayed on maps to highlight regions or areas where the factors that contribute to

shoreline changes may have the greatest potential to contribute to changes in the shoreline retreat [65]. The resulting maps of risk to flooding and erosion were used by the Basilicata authority to develop the Regional Coastal Plan and to identify eventual protective measures [2]. A similar approach has been used by the Apulia Regional Coastal Plan, which defines the “state of the conditions” of the coastal zone, highlighting its “critical nature” and “potential” in relation to multiple factors, both endogenous and exogenous [24,66]. Such approach, with the creation of maps, represents a simplified way of characterizing a very complex system and, as noted by [18,67], is a useful element in coastal management among local authorities.

As suggested by [67], every vulnerability/risk assessment is unique, and the selection of factors to apply for a given vulnerability assessment depend on many aspects—particularly the purpose and scale of the vulnerability assessment and the data availability. In the present study, the first method is based on sets of indicators for different vulnerability factors, focusing on flooding and coastal erosion, and defines three indices (ZPI, ZPE and ICC) ranging between 0 and 1. The data used concern the marine-weather conditions, the physical conditions, the coastline evolution, the protection and the socio-economic conditions. Such method (with the definitions of Coastal Vulnerability Index and risk) is one of the most commonly used and simple methods to assess coastal vulnerability to sea level rise, particularly due to erosion and/or flooding [4,24,68–71]. For instance, [72] classified the Emilia-Romagna coast in terms of flooding and erosion vulnerability using the Gornitz method. Di Paola et al. [73] applied the Gornitz method to assess the vulnerability of Gran Canaria Island (Spain). Moreover, because the Basilicata Ionian area has a high naturalness value, we assume that the exposure value is very high without necessarily inducing a very high risk. As a consequence, vulnerability and risk are similar, and the results can be compared with the second method that does not include the socio-economical component.

The second method is a simple vision of the level of the “combined” risk of all the coastal areas subjected to erosion and floods due to common or extreme storm surges. In other words, the CeD index outlines the ability of self-protection played by the coast, where the erosion process can be emphasized by the inability of defense from storms, consequently generating a high degree of vulnerability and risk of the coastal system and the back hinterland. Ref. [74] argued that this is of fundamental importance to the development of good coastal management since it defines boundaries that mark the extent of impingement by coastal hazards. The same authors used a simple procedure to define the 50-year setback line. Contrary to the first method, the second method is performed along cross-shore profiles, and the distance between two successive profiles is chosen arbitrary, inducing a greater variability in the assessment.

Our results further indicate that the complexity of the method and the numerous variables used are not determinant of the vulnerability and risk assessment. In the first case, a better knowledge of the coastal system will be obtained, and, as suggested by [75,76], all available data will be used to create an index. Earlier, [76] claimed that using numerous variables gave more correct results. However, according to [75] the selection of the variable to develop the vulnerability index is strongly related to the scale at which the hazard is to be assessed and is imposed by the data availability. Our results further suggest the method should also be as simple as possible, which is often a function of data availability. The results of the second method, using an index based on quantitative information regarding the shoreline evolution, confirm that the simple method can be developed, as reported by [77]. Two methods were used by [73] to assess the coastal vulnerability, exposure and risk along Gran Canaria Island (Spain). Their results suggest that one method can be used for the entire island, while the second one, which is more detailed, is to focus on coastal risk along a specific stretch. Similarly, we suggest that the CeD method, based on fewer parameters, can be used at a regional scale, while the second one, the Integrated Coastal Risk method, could be used at a local scale or when critical situations have been assessed with the first method.

Finally, the methodologies used could be improved by integrating data and information related to other hazards and land uses considering that the final goal is to assess the threats affecting low coastal areas in view of climate change. In fact, the two methods adopted in this paper are therefore useful for the preliminary assessment of risks to flooding and erosion. Furthermore, if we further analyze and compare the results obtained from both methods, it appears that only the first method allows for the distinction between flooding and erosion. Flooding and erosion risks associated with a 1-year return period are generally low to moderate when considered separately, but the integrated risk is medium and locally high. The risk is generally higher for a longer return period (high for a 10-year return period). The results also indicate a spatial variability of the vulnerability, which is probably due to the morphology of the beach. It also appears that the Basilicata Ionian coast is more subjected to flooding than erosion; however, our method cannot tell the extension of the flooding event. This result is important in flood and coastal erosion risk management because there is a fundamental difference between alleviating flooding and alleviating erosion. In fact, flood losses are often recurrent, and floods of different magnitudes may occur in any combination of years; otherwise, erosion is an on-going process that can normally only be delayed. As a consequence, flooding vulnerability or risk should be higher if we consider a combination of successive events. According to our results, repeated flooding events will certainly occur in the macro-area 7 and eventually in the macro-areas 2, 3 and 5, likely causing a change in the land use. On the other hand, erosion processes, mainly due to the reduction of sediment supply, will require protection measures in order to preserve the local economy based on tourism activities.

6. Conclusions

The analysis of the coastal evolution is fundamental to identifying the trend of historical variations and also to elaborating on forecasted scenarios. The main challenges are related to the availability of reliable historical data, to their validity, to the methodologies applied and, finally, to the timescales between the various surveys. The information obtained from satellite images and aerial photos are related to the scales, which define the tolerance of the measurements performed.

In the present study, two methods were applied to define the vulnerability of the Basilicata Ionian coast to erosion and marine flooding. The results obtained are similar, but the multi-risk approach provides a greater level of coastal risk. This method, only based on two factors chosen from the morphological setting components, is easier to be used by the manager and allows for the identification of a “critical situation” at the medium term. It should also be stated that such approach based on the shoreline evolution trend, without appropriate corrections linked to other fundamental variables, can provide only qualitative and general information on the future evolution of a qualitative and wide maximum. However, the Sentinel-2 satellite images allow for a frequent analysis of the shoreline that could improve the results obtained by providing more features on satellite images.

The second method is a multi-hazard risk assessment and indicates that the Basilicata Ionian coastal area is more subject to marine flooding than erosion. Therefore, different solutions could be proposed to reduce this hazard. Moreover, the maps and data presented here can be viewed in two ways:

1. as an example of where physical changes are most likely to occur in relation to erosion or marine flooding; and
2. as a planning tool for the Ionian Basilicata region.

The two-level analysis approach used in this study has proven its efficiency, suggesting that the CeD method can be used to continuously monitor the regional coastal situation, using, for instance, Sentinel satellite images. Successively, the Integrated Coastal Risk method could be applied when vulnerable coastal stretches identified with the CeD method deserve further analysis. An appropriate Integrated Coastal Zone Management perspective should focus on the preservation of beaches and protected areas (including river mouths and wetlands), in compliance with environmental restrictions. In this context, the method

proposed highlights hotspots for future coastal planning (e.g., priority areas for flooding, for beach erosion). This information could also help the authorities or stakeholders to implement mitigation measures.

According to the results, different actions could be designed and implemented to reduce the potential flooding and erosion vulnerability and increase the resilience of the coastal system.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse10070888/s1>. Table S1: Determination of the weights for the morphological vulnerability indicators “V” and “H”. Table S2: Determination of the “weight” for the socio-economical vulnerability “E”. Table S3: Values of the different indicators and morphological vulnerability defined for each profile for the different return periods. Table S4: Flooding index, erosion Index, combine coastal risk index along the Basilicata Ionian coast.

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