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Application of a Coastal Vulnerability Index. A Case Study along the Apulian Coastline, Italy

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Abstract: The coastal vulnerability index (CVI) is a popular index in literature to assess the coastal vulnerability of climate change. The present paper proposes a CVI formulation to make it suitable for the Mediterranean coasts; the formulation considers ten variables divided into three typological groups: geological; physical process and vegetation. In particular, the geological variables are: geomorphology; shoreline erosion/accretion rates; coastal slope; emerged beach width and dune width. The physical process variables are relative sea-level change; mean significant wave height and mean tide range. The vegetation variables are width of vegetation behind the beach and posidonia oceanica. The first application of the proposed index was carried out for a stretch of the Apulia region coast, in the south of Italy; this application allowed to (i) identify the transects most vulnerable to sea level rise, storm surges and waves action and (ii) consider the usefulness of the index as a tool for orientation in planning strategies. For the case study presented in this work, the most influential variables in determining CVI are dune width and geomorphology. The transects that present a very high vulnerability are characterized by sandy and narrow beaches (without dunes and vegetation) and by the absence of Posidonia oceanica.

Keywords: coastal vulnerability index; climate change; sea level rise; storm surges; waves action; Mediterranean coasts

1. Introduction

The potentially massive impact of climate change on the world's coastal zones is globally recognized. The projections given by the Intergovernmental Panel on Climate Change (IPCC) indicate a globally averaged sea level rise (SLR) [1–3]; future storms are expected to become more intense with larger peak wind speeds; average wave conditions (wave height and direction) are also expected to be modified by climate change with frequent flooding events induced by severe overtopping and overwash. These climate change-driven variations in environmental forcing are likely to result in significant physical impact along the coasts [4]. The assessment of the vulnerability of coastal areas to climate change is therefore a topic of growing interest worldwide. There is an increasing need for a detailed knowledge of the wave conditions in order to design the coastal interventions [5–8]. In literature, there are different approaches and methodologies for the assessment of vulnerability and risk due to different types of hazard such as those related to climate change. A review of a multi-risk assessment for climate change impacts is discussed by [9] while in [10] are described the most commonly used methods to assess coastal vulnerability. According to [10] the methods to assess coastal vulnerability can be grouped into four main categories: index-based methods, indicator-based approach, GIS-based decision support systems, methods based on dynamic computer models.

Among the index-based methods, the coastal vulnerability index (CVI), originally presented by [11,12] is the first synthetic index to assess coastal vulnerability to climate change, in particular to SLR. The method uses a number of variables that affect coastal vulnerability and allows assessment of the relative coastal vulnerability of the different stretches of an investigated coastal area.

The CVI formulation proposed by [13], that modified the initial index proposed by [11,12], has been widely used for other applications and studies at different territorial scales [14–18]. In literature there are various applications of the CVI with modifications and integrations of physical parameters to adapt the index to the particular coastal area [19–26].

In this context, the present paper proposes a methodology and presents a case study for assessment of the physical vulnerability to coastal hazards; in particular, the paper proposes a CVI suitable for Mediterranean areas which considers 10 variables. Six variables replicate those proposed by [13], while the others 4 variables have been chosen to better characterize the Mediterranean coasts, especially the low-lying coastal areas.

Regarding the Mediterranean Sea, in literature there are several studies in relation to climate change. A review of climate change projections over the Mediterranean region based on global and regional climate change simulations is described in [27]. Storm surges and wind-waves constitute a further element of vulnerability and hazard for coastal areas in relation to erosion and dune breaching. Various studies have been carried out on this topic [28–32]. Projections of extreme storm surge levels along Europe have been investigated by [33]; the results obtained for the Mediterranean Sea predict changes mostly in the ±5% band, either positive or negative. As described by [33] these results are in line with the historical trends and there is consensus among different studies (e.g., [28,30,31]) for no changes, or even a decrease in the frequency and intensity of extreme events. Furthermore, as reported by [31] the increase of mean sea level and land subsidence, might significantly increase the hazard posed by coastal floods. Due to the concentration of economic activities in coastal areas, the European Environmental Agency [34] also consider the Mediterranean Sea region as one of the main climate change hotspots (i.e., one of the areas most responsive to climate change).

Regarding the application of CVI in the Mediterranean area, Doukakis [35] carried out a study to map the relative vulnerability of the western Pelleponese in Greece for a coastal length of about 50 km, while a recent application of the CVI index utilizing GIS technology is due to [36]. Another study carried out in Greece is that described by [37]; in this study, the classification of the southern coast of the Gulf of Corinth according to the sensitivity to the future sea level rise is attempted by applying the Coastal Sensitivity Index (CSI), with variable ranges specifically modified for the coastal environment of Greece, utilizing GIS technology. The results of the CVI application with an adaptation to the coast of Andalusia, Spain, are described in [38], a modified version of the CVI approach with an application to peninsular coastline of Spain is described in [4], while the Egyptian Mediterranean coast was examined for vulnerability to sea-level rise using the CVI by [39].

The study described in this paper, as mentioned above, presents an application of the CVI with the integration of four physical variables. The choice of these variables is due to the consideration that for low-lying coastal areas of the Mediterranean, which represent 46% of the Mediterranean coastline [40], coastal flooding generated by storm surge and wave-breaking represents one of the main destructive natural disasters in the Mediterranean [41].

In this direction, the four integrated variables, emerged beach width, dune width, width of vegetation behind the beach and Posidonia oceanica, are representative of the Mediterranean areas, and allow an evaluation of the ability of “natural systems” to dissipate the wave energy.

According to the CVI formulation proposed by [13], a relative vulnerability score is assigned to each variable based on the potential magnitude of its contribution to physical changes on the coast.

Variables are ranked on a linear scale from 1–5 in order of increasing vulnerability and CVI values are classified in four different groups using percentiles as limits.

2. Methods and Data

2.1. Methods

The proposed CVI considers the following 10 variables:

1. Geomorphology
2. Coastal slope
3. Shoreline erosion/accretion rates
4. Emerged beach width
5. Dune width
6. Relative sea-level change
7. Mean significant wave height
8. Mean tide range
9. Width of vegetation behind the beach
10. Posidonia oceanica

In addition to the six variables described by [13], four new variables have been proposed: Emerged beach width; dune width; width of vegetation behind the beach and Posidonia oceanica. The new proposed variables, representative of the Mediterranean coast, allow us to evaluate the ability of "natural systems" to dissipate the wave energy. In particular, sandy beach-dune systems constitute the natural barrier protecting coastal areas against flooding due to storm surge and wave impacts. Furthermore, the effects of a well vegetated beach and seagrass Posidonia oceanica on wave energy have significant implications for coastal protection.

All variables have been divided into three typological groups: Geological, Physical process and Vegetation.

The Geological variables are:

- Geomorphology that expresses the relative erodibility of different landform types (e.g., rocky cliffs, sandy beaches) along the coast and requires information on the spatial distribution of landform types and their stability;
- Coastal slope that is an indicator of the relative vulnerability to inundation and of the potential rapidity of shoreline retreat;
- Shoreline erosion/accretion rates that allows to make assessments on the state of erosion or accretion;
- Emerged beach width is a variable related to the ability to dissipate wave energy; a wider beach has greater ability to dissipate the wave energy and therefore to reduce the impact of extreme events (e.g., storm surges).
- Dune width that represents an important variable for the conservation of the coastal zone, increasing its resilience [42–46]; in fact, dune can reduce the risk of erosion, as they constitute a reserve of sediment, and can counteract the risk of flooding of the hinterland.

The Physical process variables are:

- Relative sea level change that is derived from the time series of sea level records at each tide gauge stations along the coast; this variable includes both eustatic sea-level rise as well as regional sea-level rise due to isostatic and tectonic adjustments of the land surface;
- Mean significant wave height represents the potential for storm erosion. It is well known that storm erosion is directly related to the energy contained in storm waves and that the wave height has to be above a certain threshold (which depends on local conditions) to cause beach/dune erosion.

- Mean tide range that is linked to both permanent and episodic inundation hazards.

The Vegetation variables are:

- Width of vegetation behind the beach that is a variable related to vulnerability to storm events. In fact, the presence of vegetation is useful to dissipate wave energy and to reduce erosion in case of extreme events;
- Posidonia oceanica that is a marine phanerogam endemic to the Mediterranean basin which forms extended meadows along its coasts in a bathymetric surface to 0–40 m depth in clear waters [47]; several studies have shown the influence of these marine phanerogam on the nature and dynamics of coastal sediments [48–51]. The Posidonia oceanica colonize sandy beaches, [52] rocky substrates [53,54] and is generally absent in the depositional area of fine sediments such as the mouth of coastal rivers [55,56] in relation to the high rate of turbidity which causes a reduction of light penetration [57]. Recent papers [58,59] have confirmed that Posidonia oceanica forms a key coastal habitat, which plays a crucial role in the physical equilibrium of a large portion of the Mediterranean coasts. Therefore, the Posidonia oceanica is considered the resistance/resilience slime of the extreme weather events and SLR.

A stretch of coast is divided into a number of transects (or cross-sectional profiles of the beach) in order to assess its vulnerability. Each transect is characterized by a control area 0.5 km wide. Variables are ranked on a linear scale from 1–5 in order of increasing vulnerability.

The CVI is obtained by the square root of the product of the vulnerability scores assigned to each variable divided by the total number of variables:

$$\text{CVI} = \sqrt{(\text{a}\cdot\text{b}\cdot\text{c}\cdot\text{d}\cdot\text{e}\cdot\text{f}\cdot\text{g}\cdot\text{h}\cdot\text{i}\cdot\text{l})/10} \quad (1)$$

where a = Geomorphology, b = Coastal slope, c = Shoreline erosion/accretion rates, d = Emerged beach width, e = Dune width, f = Relative sea-level change, g = Mean significant wave height, h = Mean tide range, i = Width of vegetation behind the beach, l = Posidonia oceanica.

CVI values are classified in four different categories (low vulnerability, moderate vulnerability, high vulnerability and very-high vulnerability) using percentiles as limits.

2.2. Data

In the following, the data sources used to define the 10 variables are listed.

- Geomorphology has been derived from the map data (DTM) combined with the lithological map available on the Territorial Information System of Apulia Region, Sit-Apulia [60], for a 0.5 km grid cell;
- Coastal slope (%), has been estimated in accordance with [61]; it has been determined from a topographic and bathymetric grid extending 5 km landward and seaward of the shoreline. Elevation data have been obtained from the digital model available on the Sit-Apulia as gridded topographic and bathymetric elevation at 1 m vertical resolution for 8 m grid cells.
- Shoreline erosion/accretion rates (m/year), have been estimated as average values at the considered transect. The shorelines used were derived from the orthophotos available for years from 1992 to 2012, available on the Sit-Apulia [60];
- Emerged beach width (m), has been measured from the point where evidence of usual wave/tide impact ends to the point where vegetation or infrastructures begin. It has been evaluated considering the regional orthophotos, available on the Sit-Apulia [60];
- Dune width (m), has been evaluated considering the regional orthophotos, available on the Sit-Apulia [60]. Relative sea-level change (mm/year), has been derived considering the data reported for Mediterranean by National Oceanic and Atmospheric Administration, NOAA [62].

- Mean significant wave height (m), has been obtained with reference to the data of the Monopoli wave buoy belonging to the National Wave Metric Network (ISPRA—Institute for Environmental Protection and Research);
- Mean tide range (m), has been obtained from the European Environmental Agency- EEA data-base [63];
- Width of vegetation behind the beach (m), has been evaluated by considering the regional orthophotos, available on the Sit-Apulia [60]. The width of vegetation has been determined by clear and obvious signs of flora, indicated by the green area behind the beach; the measure was interrupted in the case of intersection with infrastructures such as roads, houses, etc.
- Posidonia oceanica (Boolean: presence/absence), has been evaluated on the basis of a research study carried out by Apulia Region [64].

Table 1 shows the range of vulnerability for the 10 variables. Regarding the variable geomorphology, the ranges of vulnerability considered are those proposed by [65]. The ranges of vulnerability for the variables of relative sea-level change, mean significant wave height and shoreline accretion/erosion rate have been chosen in agreement with those proposed by [37]. Regarding the variable coastal slope, the values have been chosen considering previous studies carried out for the Mediterranean coast [4,36,37]. In particular, the range chosen are those proposed by [4]. Regarding the variables emerged beach width, dune width and width of vegetation behind the beach, the ranges of vulnerability have been defined in consideration of the characteristics of the Italian and Mediterranean area [66]. Furthermore, the available data (regional orthophotos) made it possible to verify the similarity of these considered values with those typical of the Mediterranean environment. Finally, for the variable mean tide range, the ranges of vulnerability have been chosen in accordance with those proposed by [37] but the scores (linear scale from 1–5) are different. This assumption, in agreement with [13], is based on the concept that, in general, microtidal (tide range < 2.0 m) and macrotidal (tide range > 4.0 m) are characterized by high and low risk, respectively. The reasoning is based primarily on the potential influence of storms on coastal evolution, and their impact relative to the tide range. For example, on a tidal coast-line, there is only a 50 percent chance of a storm occurring at high tide. Thus, for a region with a 4.0 m tide range, a storm having a 3 m surge height is still up to 1 m below the elevation of high tide for half a tidal cycle. A microtidal coastline, on the other hand, is essentially always "near" high tide and therefore always at the greatest risk of inundation from storms [13]. Mediterranean area is a microtidal environment and the coast of Apulia has a tide range < 1 m. As such, the range of vulnerability, as mentioned above, are those proposed by [37] but the assigned scores are the inverse.

Other researchers (e.g., [12,67]) claimed the opposite; the large tidal range coast-lines were assigned a high-risk classification, and microtidal coasts received a low risk rating. The reasoning for this is that although a large tidal range dissipates wave energy, limiting beach or cliff erosion to a brief period of high tide, it also delineates a broad zone of intertidal area that will be most susceptible to inundation following long-term sea-level rise. Furthermore, the velocity of tidal currents depends partially on the tidal range. High tidal range is associated with stronger tidal currents that are capable of eroding and transporting sediment [67].

Table 1. Ranges of vulnerability for the considered variables.

Type Variables	Variables	Score				
		Very Low 1	**Low 2**	**Moderate 3**	**High 4**	**Very High 5**
Geologic	Geomorphology	Rocky, cliffed coasts	Medium cliffs, indented coasts	Low cliffs, alluvial plains	Cobble beaches, estuary, lagoon	Barrier beaches, sand beaches, salt marsh, mud flats, deltas, coral reefs
	Coastal slope (%)	>12	8–12	4–8	2–4	<2
	Shoreline Erosion/accretion (m/year)	>(+ 1.5)	(+1.5)–(+0.5)	(−0.5)–(+0.5)	(−0.5)–(−1.5)	<(−1.5)
	Emerged beach width (m)	>100	50–100	25–50	10–25	<10
	Dune width (m)	>100	75–100	50–75	25–50	<25
Physical process	Relative sea-level change (mm/year)	<1.8	1.8–2.5	2.5–3.0	3.0–3.4	>3.4
	Mean significant wave height (m)	<0.3	0.3–0.6	0.6–0.9	0.9–1.2	>1.2
	Mean tide range (m)	>0.8	0.6–0.8	0.4–0.6	0.2–0.4	<0.2
Vegetation	Width of vegetation behind the beach (m)	>400	200–400	100–200	50–100	<50
	Posidonia oceanica (Boolean: presence/absence)	Present				Absent

3. The Study Area

The proposed CVI index has been applied to a stretch of the coast of the Apulia Region, Southern Italy, between the marinas of Torre Canne and Villanova (Figure 1).

Figure 1. Case study area—Marinas of Torre Canne and Villanova, Apulia Region, Southern Italy.

Starting from the north, Torre Canne (Figure 2), the first stretch of about 7 km (up to Torre San Leonardo), which corresponds to the first 15 to 24 investigated transects, is characterized by beautiful beaches, which the Apulia Region has intended to protect by establishing with Regional Law No 31/2006, the Coastal Dunes Park. The park covers about 1.000 hectares. In the protected area there are many priority habitats, strongly threatened for their intrinsic fragility and for being located in areas at risk, but also habitats of the Community interest representative of the biogeographical reality of the Community territory. In the area there are beaches, consolidated dunes, retrodunal ponds and fossil dunes. The remaining 5 km of coastline, ranging from Torre San Leonardo to the port of Ostuni marina (Villanova) which make up the remaining nine transects of the study area, are jagged cliffs and consist of a series of coves with small beaches surrounded by Mediterranean vegetation.

Figure 2. Case study area and related transects.

The study area is mainly devoted to seaside tourism, and there are indeed many tourist accommodation facilities (hotels, resorts, etc.).

4. Results

A Geography Information System (GIS) platform has been used to better process the data. The stretch of coast has been divided into 24 transects; geomorphology includes very-high vulnerability and moderate vulnerability;coastal slope values are <2% varying between 0.75% (min) and 1.52% (max), while shoreline erosion/accretion rates is classified as very-low to very-high vulnerability. The value of the relative sea-level change is constant at low vulnerability and mean tide range is constant at very-high vulnerability. Mean significant wave height is constant at high vulnerability. Emerged beach width includes high vulnerability and moderate vulnerability, while dune width includes very-high vulnerability, high vulnerability and moderate vulnerability. Width of vegetation is classified as very-low to very-high vulnerability. Finally, Posidonia oceanica predominantly shows a low vulnerability since it is present in many transects.

The estimated minimum CVI value calculated for the case study is 30, while the maximum value is 300. The CVI mean is 123.40, the median is 84.85. The classes of CVI values have been divided into "low vulnerability" (green), "moderate vulnerability" (yellow), "high vulnerability" (orange) and "very-high vulnerability" (red) categories, respectively, on the basis of 25th, 50th, and 75th percentiles [13] as summarized in Table 2.

Table 2. Vulnerability categories.

Category	CVI Values
Low	<72.43
Moderate	72.43–84.85
High	84.85–163.62
Very-high	>163.62

Table 2 shows the vulnerability categories, while Table 3 shows the vulnerability value associated to each variable and the estimated CVI values for each transect (a = Geomorphology, b = Coastal slope, c = Shoreline erosion/accretion rates, d = Emerged beach width, e = Dune width, f = Relative sea-level change, g = Mean significant wave height, h = Mean tide range, i = Width of vegetation behind the beach, l = Posidonia oceanica).

Table 3. Vulnerability value associated to each variable and CVI values for each transect.

Transect	a	b	c	d	e	f	g	h	i	l	CVI Value	CVI Category
1	5	5	1	3	5	2	4	5	5	1	86.60	High
2	5	5	1	4	5	2	4	5	5	5	223.60	Very High
3	5	5	2	4	5	2	4	5	5	1	141.42	High
4	5	5	1	4	5	2	4	5	3	1	77.46	Moderate
5	5	5	1	3	4	2	4	5	5	1	77.46	Moderate
6	5	5	5	4	3	2	4	5	3	5	300.00	Very High
7	5	5	1	4	4	2	4	5	3	5	154.91	High
8	5	5	1	4	4	2	4	5	3	1	69.28	Moderate
9	5	5	4	4	5	2	4	5	2	1	126.49	High
10	5	5	2	4	4	2	4	5	3	1	97.98	High
11	5	5	2	4	4	2	4	5	2	1	80.00	Moderate
12	5	5	2	3	4	2	4	5	2	1	69.28	Moderate
13	5	5	3	3	3	2	4	5	2	1	73.48	Moderate
14	5	5	2	3	3	2	4	5	4	5	189.73	Very High
15	5	5	2	3	5	2	4	5	5	5	273.86	Very High
16	3	5	2	4	5	2	4	5	5	5	244.94	Very High
17	3	5	2	4	5	2	4	5	4	5	219.08	Very High
18	3	5	1	4	5	2	4	5	4	1	69.28	Moderate
19	3	5	2	3	5	2	4	5	4	1	84.85	Moderate
20	3	5	1	3	5	2	4	5	1	1	30.00	Low
21	3	5	2	3	5	2	4	5	4	1	84.85	Moderate
22	3	5	2	3	5	2	4	5	1	1	42.42	Low
23	3	5	1	3	5	2	4	5	5	1	67.08	Low
24	3	5	2	2	5	2	4	5	5	1	77.46	Moderate

Figure 3 shows a screenshot of the GIS page with the CVI values for the case study area.

Figure 3. CVI value for each transect.

5. Discussion

For the case study area, the most important variables are geomorphology, shoreline erosion and accretion rates, beach width, dune width, width of vegetation behind the beach and Posidonia oceanica, since the other variables are constant. As described above, the variable geomorphology mainly includes sandy beaches (very-high vulnerability) and low cliffs (moderate vulnerability), while shoreline erosion and accretion rates attain values between low vulnerability and moderate vulnerability.

The variable emerged beach width attains values between moderate vulnerability and very high vulnerability, as the beaches are not very large but rather narrow, while for the variable dune width in the area, the dune is present only in some transects characterized by no significant widths. Width of vegetation behind the beach is classified as very-low to very-high vulnerability while Posidonia oceanica is present in many transects.

In particular, transects from 1 to 3 are characterized by a sandy beach, with a low coastal slope and moderate emerged beach width; it should be noted that there is the absence of dune and vegetation, with constructions built close to the shoreline; for transect 1 and 3 the vulnerability is partly mitigated by the presence of Posidonia oceanica.

Transects 4 and 5 present a moderate vulnerability due to the presence of a modest dune, vegetation and Posidonia oceanica.

In transect 6 and 7, the value of vulnerability increases in relation to the absence of Posidonia oceanica, and for transect 6 a greater erosion is observed.

The transects from 8 to 13 present vulnerability that is predominantly moderate in relation, especially due to the presence of vegetation and Posidonia oceanica.

The transects from 14 to 17 (Torre San Leonardo), are characterized by the transition from sandy beach with dunes to low cliffs; in this stretch of coast there is an increase in vulnerability due to the absence of Posidonia oceanica and to the considerable reduction of the dune and the vegetation; this stretch is characterized also by an intensive land use with important population centers.

The transects from 18 to 24 are characterized by low and moderate vulnerability for the presence of Posidonia oceanica and vegetation.

It is important to highlight that in index-based methodologies, such as CVI, the availability of reliable and up-to-date databases is crucial. Variables like geomorphology and coastal slope can be considered stable since present negligible changes in time, while for the relative sea level change, mean tide range, and mean significant wave height, consolidated, international databases exist. For the variable shoreline erosion/accretion rates, reliable and up-to-date databases may not always be available [68]. For this variable, as well as for emerged beach width, dune width and width of vegetation behind the beach, it may be necessary to consider field measurements or the use of aerofotogrammetry. The field measurements are more precise but require significant investment and are limited in time and space. While the use of aerofotogrammetry is less accurate, it can be extended to larger areas. A more recent and useful tool for creating databases on these variables is the multispectral processing of images from satellites; these images present higher resolution with pixel processing and gradation based on photographic interpretation procedures (multispectral processing). This allows activating procedures for semi-automatic and/or automatic recognition of spatial elements. In fact, the increasing availability, resolution and spatial coverage of satellite imagery in recent years now provides a powerful alternative to derive reliable, global scale shoreline data. In this direction, in many recent studies the satellite images coupled with image processing techniques have been used [69–73].

6. Comparison between Two Index-Base Methods

In the present paper, the proposed CVI has been compared with the index-based method proposed by [37], postponing its verification to a later study by more complex process-based models (e.g., [74,75]).

The objective of the comparison is to evaluate, compared to an index similar in structure and range of vulnerability for each variable, the effects of further variables not yet taken into account. Specifically, it should be noted that the use of additional variables such as emerged beach width, dune width, width of vegetation behind the beach and posidonia oceanica, is based on the consideration that these variables can be useful to better characterize the Mediterranean coasts, especially the low-lying coastal areas.

Regarding the Coastal Sensitivity Index (CSI) proposed by [37], it uses the following physical variables: geomorphology, coastal slope, relative sea-level rise rate, shoreline erosion or accretion rate, mean tidal range and mean wave. This index was applied to the southern coast of the Gulf of Corinth, Greece. The obtained results are summarized in Table 4 and shown in Figure 4.

Table 4. Comparison between the proposed CVI and the CSI.

Transect	Proposed CVI	CSI Karymbalis et al. [37]
1	High	Moderate
2	Very high	Moderate
3	High	Very high
4	Moderate	Moderate
5	Moderate	Moderate
6	Very high	Very high
7	High	Moderate
8	Moderate	Moderate
9	High	Very high
10	High	Very high
11	Moderate	Very high
12	Moderate	Very high
13	Moderate	Very high
14	Very high	Very high
15	Very high	Very high
16	Very high	High
17	Very high	High
18	Moderate	Low
19	Moderate	High
20	Low	Low
21	Moderate	High
22	Low	High
23	Low	Low
24	Moderate	High

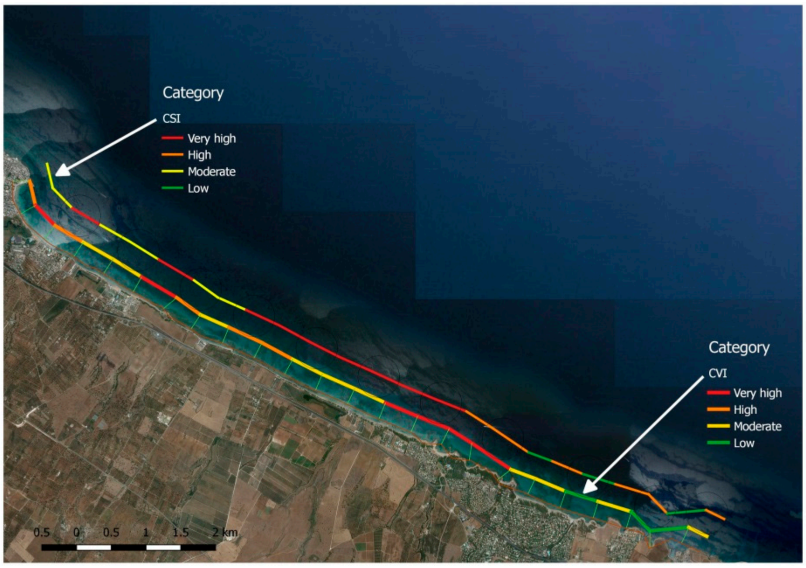

Figure 4. Proposed CVI and CSI values.

Generally, the two investigated methods show similar results. Some differences have been found likely due to the four variables proposed in the CVI to evaluate the ability of "natural systems" to dissipate the wave energy: emerged beach width; dune width; width of vegetation behind the beach and Posidonia oceanica.

In particular, for the cases of transects 9–13, the presence of Posidonia oceanica and the width of the vegetation determine a reduction of vulnerability in relation to the values obtained with the CSI. However, in the case of transects 16 and 17, the absence of Posidonia oceanica and dunes, the narrow beaches and the small width of the vegetation, determine an increase in vulnerability.

7. Conclusions

The CVI is a useful method for the assessment of the relative physical vulnerability of a stretch of coastline to the effects of climate change. The present paper proposes a CVI formulation, suitable for the Mediterranean coasts, that considers 10 variables and allows us to evaluate the vulnerability with respect to SLR, storm surges and waves action. In the following, the main conclusions of the study are as follows.

The tailored index CVI indicates that the dune width and the geomorphology are the most important drivers in building a regional index in terms of increasing the risk of flooding in this region. Regarding dune width, different transects are characterized by the absence of dunes or small-width dunes. Therefore, the relative vulnerability scores are mostly 5 (very-high vulnerability) and 4 (high vulnerability). For the geomorphology variable, most of the case study area consists of sandy beaches with a relative vulnerability score of 5 (very-high vulnerability).

On the contrary, width of vegetation behind the beach, shoreline erosion/accretion rates and Posidonia oceanica variables show a negligible influence. Width of vegetation behind the beach and shoreline erosion/accretion rates are classified as very-low to very-high vulnerability, while Posidonia oceanica is present in many transects.

The application of the proposed index shows the feasibility of the index and the possibility of using the CVI to make assessments on coastal vulnerability with respect to climate change.

The aim of the future research is to validate the proposed index by comparing it with the more complex numerical models in order to make the index a useful tool for coastal planning and management.

Author Contributions: D.P. Data curation, Formal analysis, Methodology, Validation, Writing-original draft, Writing-review & editing; F.D. Writing-review & editing; L.R. Validation (collaboration in the CVI application), Writing-original draft (collaboration in paper writing); F.P. Validation (collaboration in the CVI application); G.R.T. Conceptualization, Supervision, Writing-review & editing.

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