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Validation of the Hazard and Vulnerability Analysis of Coastal Erosion in the Caribbean and Pacific Coast of Colombia

Oswaldo Coca-Domínguez * and Constanza Ricaurte-Villota

Marine and Coastal Geosciences Program, Marine and Coastal Research Institute "José Benito Vives de Andréis" (INVEMAR), Calle 25 #2-55, Salguero Beach, Rodadero, Santa Marta 470001, Colombia
* Correspondence: oswaldo.coca@invemar.org.co

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Abstract: A hazard and vulnerability assessment of coastal erosion is an essential first step for planning and decision-making, because it is part of risk management and its results are in the form of easily interpreted traffic-light maps. For the analysis of the assessment in this work, a methodology is proposed which considers three components for both hazard (magnitude, occurrence, and susceptibility) and vulnerability (exposure, fragility, and lack of resilience), through a semi-quantitative approximation, by applying relative indices to different variables. This methodology has been adapted to analyze hazards and vulnerability caused by coastal erosion combining physical and social aspects. For the validation of this methodology, Spratt Bight Beach (Colombian Caribbean) and La Bocana beach (Colombian Pacific) were selected in order to have contrasting regions and to validate the application of the method over a geographical range. One of the most significant outcomes of the assessment of the degree of hazard and vulnerability is that the rating may represent different combinations of factors. It is therefore important to study and interpret the components separately, allowing us to propose corrective and/or prospective focused interventions at local and regional levels. In terms of vulnerability, the assessment highlighted the importance of cultural ecology as a factor of resilience to coastal hazards.

Keywords: coastal processes; risk management; geohazards; cultural ecology; coastal vulnerability index

1. Introduction

There are different types of dangerous events that affect the coastline, which can include climate, oceanographic factors, and geological, as well as those arising from changes in weather conditions, including tropical cyclones, generated by such things as seismic events causing tsunamis, El Niño–Southern Oscillation (ENSO), coastal erosion, and sea-level rise by climate change. All these phenomena cause multiple human, economic, and environmental losses. Coastal erosion, which is defined as the invasion of land by the sea, or as the tendency of the coastline to retreat, generating significant loss of beaches and ecosystems that are used for human activities [1], is one of the natural coastal hazards affecting Colombian territory [2–4]. This is a natural process by which the coastline adapts to variations in sea level, energy levels, sediment addition, and existing topography [5]. The coastline of the continents has gradually reached its current configuration because it has suffered considerable erosion and deposition during most of the Holocene, a period characterized by a general rise in global sea level. Some areas continue to evolve through the redistribution of sediments resulting from the same phenomena, erosion and deposition [5]. In addition to the natural effect there is human interference, which includes: changes in fluvial sediment flows, channeling and flood control works, land reclamation schemes, channel dredging, and more recently, coastal protection structures [6].

Coastal erosion affects a large part of the Colombian coastline, including island areas. On the Caribbean Coast, of the 2564 km of coastline, 569 km has a high degree of erosion, which corresponds to 22.2% of the total coastline [7,8]. On the other hand, of the 1790 km of coastline in the Colombian Pacific, 356 km has some degree of erosion, corresponding to 20% of the total coastline [9]. Despite the large scale, until recently, little was known about the hazard posed by this phenomenon and the degree of vulnerability of the exposed elements (ecosystems, physical infrastructure, the communities settled in this area, and the local and national cultural heritage).

Over the years, different definitions for hazard and vulnerability have been developed [10–14]. González [12] defines hazard as the probability of a phenomenon of a certain magnitude occurring, which can cause damage without saying that such a phenomenon exists or does not exist. On the other hand, vulnerability is defined as a characteristic of an individual or group, based on its ability to anticipate, survive, resist, and recover from the effect of a natural hazard [14,15].

Coastal erosion hazard and vulnerability studies have been developed by researchers around the world, such as Contreras and Kienberger [16], who carried out a study along the European coast, based on the morphological, geological, hydrological, and lithological context of each coastal segment. Although Merlotto and Piccolo [17] used a quantitative hazard and vulnerability index to assess erosion hazard on the Argentine coastline, they are not discriminated by components. Boruff et al. [18] examined vulnerability to erosion on the coasts of the United States by combining a socio-economic vulnerability index with a physical vulnerability index, made by the U.S. Geological Survey (Coastal Vulnerability Index, CVI). Gornitz [19] analyzed vulnerability and considered the physical susceptibility of the coastline, using an index to categorize areas of the United States that are subject to flooding/erosion due to sea-level rise and included 6 physical variables: relief, lithology, morphology, vertical–horizontal movements, and tidal range. Finally, McLaughlin et al. [20] introduced an index to be used on a national, provincial, and local scale, and 3 sub-indices: erosion resistance, wave energy, and socio-economic activities, the last being used for the first time in this type of study. These same studies have developed and presented similar results, but with different methods and ways of presenting the results, and all with the aim of contributing to the planning and management of risk due to coastal hazards.

Several studies have emphasized the physical and morphological aspects that influence coastal erosion on sandy and rocky coasts [21–25], and others have delved into social, economic, cultural, ecological, and institutional factors [24–36]. Similarly, the combination of economic and environmental factors [25], and the use of different indices [26,28] as the Beach Vulnerability Index (BVI) [26]. This study presents a specific methodological adaptation of the hazard and vulnerability of beaches to coastal erosion, combining the intrinsic physical and socio-economic aspects of this phenomenon, under a GIS environment.

The objective of this study was to validate a methodology to evaluate hazard and vulnerability due to coastal erosion in two contrasting zones, Spratt Bight Beach on San Andrés Island (Colombian Caribbean coast) and La Bocana (Colombian Pacific coast). This allows the identification of the coastline areas that are most susceptible to this phenomenon, but it also serves as a tool for risk management, decision-making, and planning policy for Colombia's coastal areas.

Finally, this study was based on a local scale assessment, because, according to Gaillard [37], this explains how communities face risks depending on their cultural vagueness, social structure, economic status, and resilience. That is why this research focused on the local culture of the communities of the Caribbean and Pacific coasts, which is fundamental to addressing coastal erosion.

1.1. Study Area: Spratt Bight Beach, San Andrés Island, Caribbean Coast

The archipelago of San Andrés, Providencia and Santa Catalina is located to the west of the Caribbean Sea, approximately 700 km northwest of the continental zone of Colombia, being the most northern territory of the country. The island of San Andrés is located between 12°28′55″ N, 81°40′49″ W and 12°35′37″ N, 81°43′23″ W. This study was conducted specifically at Spratt Bight Beach (Figure 1A), a 1590 m long sandy beach located at the north tip of the island [38]. According to Decree 323 of 18 November 2003, urban and rural soils are defined through the Urban or Rural Insular Planning

Units (UPI-U or UPI-R); the area adjacent to the beach of interest in this study corresponds to UPI-U17, whose name is Spratt Bight hotel renovation and commercial area. In this beach, the amplitude can be up to 60 m in some sectors, and the slope is variable between 6 and 15°, this zone has a micro-tidal range (amplitude < 2 m) [38].

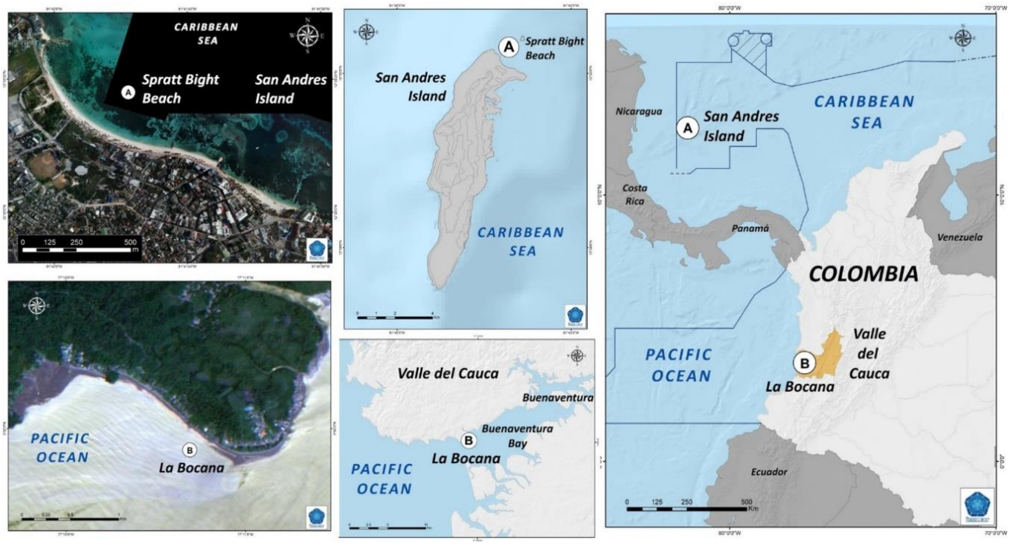

Figure 1. Study area. (**A**) Spratt Bight, San Andrés Island, Caribbean coast. (**B**) La Bocana, Buenaventura bay, Pacific coast.

Raizales (Afro-Caribbean ethnic group) represent between 30% and 35% of the approximate total 75,167 inhabitants of the archipelago projected for 2013 [39,40]. The importance and relevance of this ethnic group lies in the maintenance of customs and cultural roots. Tourism and trade are the most important economic activities and employ the largest number of people on the island [40].

1.2. Study Area: La Bocana, Buenaventura Bay, Pacific Coast

La Bocana is located on the Pacific coast, in Buenaventura bay, Valle del Cauca. This village is located between 77°12′0.64″ W, 3°50′22.80″ N and 77°10′41.91″ W, 3°50′14.87″ N (Figure 1B). La Bocana is village #4 of the district of Buenaventura and includes 4 sectors: Pianguita, Vistahermosa, Centro or Lomadentro, and Shangay, which are controlled by the Community Council Comunidad Negra de Bazán—La Bocana, which is an afro-descendant community. The beach of the study area has a length of 4034 m, a slope between 4 and 8°, and shows a total amplitude that varies between 2 m during high tide and 300 m during low tide. It has a semi-diurnal and semi-monthly tidal system, and the range is mesomareal (amplitude from 2 to 4 m) during minimum tides, and meso to macro-tidal (amplitude > 4 m) during maximum tides. La Bocana has a population of approximately 3258 inhabitants [41], of which 90% are black, 5% are indigenous, and 5% are mestizos [42]. Its economy is based on artisanal fishing and eco-tourism activities throughout the year, especially in the holiday season.

2. Materials and Methods

The methodology of coastal erosion hazard and vulnerability assessment includes 3 components for each factor: hazard— (1) magnitude, (2) occurrence, and (3) susceptibility; vulnerability— (1) exposure, (2) fragility, and (3) resilience (Figure 2). The hazard assessment was done on a scale between 1:2500 and 1:10,000, and the vulnerability was assessed at the community level. The hazard data were obtained through field work or in situ, using secondary information, and through a laboratory process (changes in coastline); for vulnerability, workshops with the community and secondary information were acquired. The final product is in the form of easy-to-interpret traffic-light maps for decision-makers, where the lowest values are dark green, low values are light green, medium are yellow, high are orange, and very high are red.

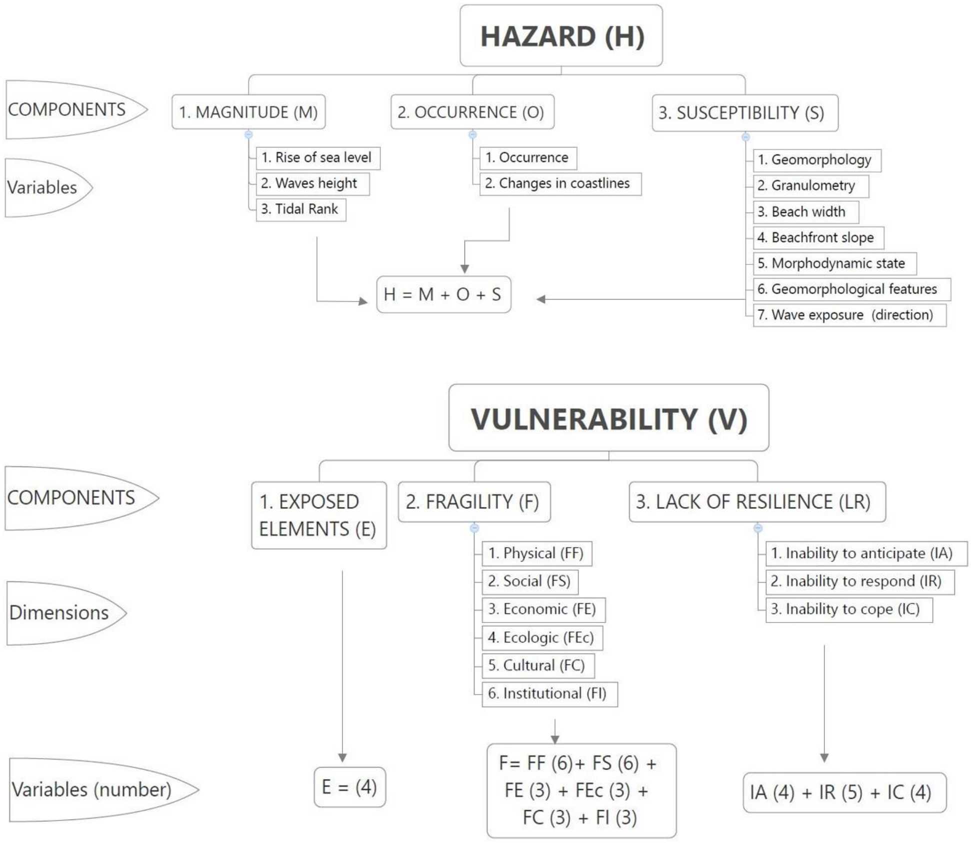

Figure 2. General methodological framework of hazard and vulnerability assessment for coastal erosion. Hazard is shown with its 3 components (1. Magnitude, 2. Occurrence, and 3. Susceptibility), the variables for each component, and the equation. Vulnerability is shown with its 3 components (1. Exposure, 2. Fragility, and 3. Lack of Resilience). Exposure is shown along with its variable; Fragility has 6 dimensions and a number of variables; and Lack of Resilience is shown with its 3 dimensions and variables.

2.1. Hazard

Hazard (H) is defined as the probability that a phenomenon of a certain magnitude will occur in a specific area. The hazard level depends on 3 components: magnitude (M), frequency of occurrence (O) [43], and susceptibility of the land (S) [44]. In this way, M is given by the energy level of the different phenomena that affect the coastal area; thus, the greater the energy of the phenomenon, the greater the negative effects and, therefore, the greater the danger. Three variables were used to measure magnitude. These were adapted from Gortniz [19], Gortniz et al. [45], and Merlotto and Bértola [46]; data were extracted from INVEMAR-GEO [47], INVEMAR-GEO [38], and Thomas et al. [48,49]. Then, O corresponds to the frequency of the phenomenon, and was classified as follows: future (event that has never occurred but the available information does not allow one to discard its occurrence), past (event already occurred previously in the place or in similar conditions), and present (event detectable or evident at present). This variable is resolved qualitatively and with secondary information. To define the occurrence, we used the variation in the coastline and/or presence of the phenomenon in a certain period of time, adapted from what was proposed by Gotniz [19], Gortniz et al., [45], and Merlotto and Bértola [46], which represent the rates of erosion or accretion (m/year) of the historical evolution of the coastline (Table 1. Finally, S is defined as the degree of propensity of a segment of the coastline to develop a process of attrition [44]. Susceptibility depends on the geological and geomorphological characteristics of the study area. To assess it, seven variables were taken into account: geomorphology, features, granulometry, width, slope, morphodynamic state of the beaches, and finally wave exposure, adapted from Gortniz et al. [45], Merlotto and Bértola [46], and Rangel and Posada [50].

Table 1. List of variables per component considered in the hazard assessment and ranking description.

Component	Variables	Hazard Ranking					
		Very Low (1)	Low (2)	Medium (3)	High (4)	Very High (5)	Reference
Magnitude (M)	Tide amplitude (m)	0–1	1.1–2	2.1–3	3.1–4	>4.1	[19,45,46]
	Average height of breaking waves (m)	0–0.4	0.41–0.8	0.81–1.2	1.21–1.6	>1.6	[19,45,46]
	Sea-level rise (mm/year)	Decline 1	Relative stability (0)	Increase of up to 0.5	Increase between 0.5 to 1	Increase >1	[19,45]
Occurrence (O)	Coastline variation (m/year)	Accumulation (> 0.5)	Stability (0.5 to 0)	Rate of change (0 to −0.5)	Rate of change (−0.51 to −1)	Rate of change (>−1)	[19,45,46]
	Occurrence	Future	-	Past	-	Present	This research
Susceptibility (S)	Geomorphology	Low cliffs of rock with a minimal beach	High cliffs of rock without beach	Beaches with high cliffs River and marine terraces	Sandy beaches with low river and sea terraces	Beach Mangrove swamp	[19,45,46]
	Granulometry (millimeters)	>1 Very thick sand to gravels	0.51–1 Thick sands	0.26–0.5 Medium sands	0.126–0.25 Fine sands	Less than 0.125 Very thin and sludge	[34]
	Beach width (m)	More than 80	50–80	25–50	10–25	0–10	[46]
	Beachfront slope	More than 8.1°	8°–6.1°	6°–4.1°	4°–2.1°	2°–0°	[46]
	Morphodynamic state	Dissipative	-	Intermediate	-	Reflective	[47]
	Geomorphological features	No features	-	1–2 features	-	More than 2 features	[50]
	Wave exposure (direction)	With obstacles 0°	-	Indirect waves 45°	-	Direct waves 90°	[50]

2.2. Vulnerability

The vulnerability assessment (V) took three components into account (Table 2): the first corresponded to exposure (E); the second to the fragility (F) of the different dimensions [51] (physical, social, economic, ecological, institutional and cultural); and the third to the lack of resilience (R), understood as the inability to respond, anticipate, and face). Global vulnerability is the result of the crossing of these three components [16,45,52,53].

All the variables used (Table 2) were evaluated and classified using two sources: (i) the information contained in the existing literature and cartography on the study area, and (ii) the verification of the information and collection of new data through field trips and interviews with the community. These variables and ranges were adapted mainly from Contreras and Kienberger [16], McLaughlin et al. [20], Merlotto and Bértola [46], Ojeda et al. [52], and Cardona [53].

The variables of the different dimensions of fragility were adapted, taking into account the general conditions but emphasizing the relationship with the phenomenon of coastal erosion. For example, for physical fragility, the characteristics of the dwellings were taken into account. Regarding cultural fragility, Alexandrakis et al. [35] mention that they explored the global importance of cultural heritage (physical or immaterial); in our case, the size or level of heritage was not taken into account, but simply the presence or absence of these. In this way, the classification of the different variables was developed.

The CVI used in this study is adapted to coastal erosion from that used by Gornitz et al. [45] for the effects of sea-level rise. The index allows variables to be related in a quantifiable way and generates numerical data.

For the hazard and vulnerability assessment, each of the variables in Tables 1 and 2 was divided into 5 classes of influence on coastal erosion, with each of the classes scoring from 1 to 5. Therefore, 1 corresponds to very low, 2 to low, 3 to medium, 4 to high, and 5 to very high.

Once the segments for the hazard and the areas of the community sectors for vulnerability were obtained, where each of them was the minimum unit of analysis in which the physical and social attributes were established on the coastline, through simple statistical equations. A similar approach was taken by Alexandrakis and Poulos [26]. The first step was to calculate the absolute values (*Vabs*) of the weighted variables (*fn*) for each segment through a sum:

$$Vabs = \sum f_n \tag{1}$$

Next, the results were normalized with respect to the theoretical maximum and minimum values of the index, in order to obtain a hazard index (*H*). This index was calculated using the following equation (*n* is the number of variables per element):

$$H = \left[\frac{(Vabs - n)}{n * 2} \right] * 100. \tag{2}$$

After achieving these results, and to obtain the global hazard (*HG*), the sum of its three components was multiplied by the number (*n*) of the dimensions of each one. Then, it was divided by the sum of the number (*n*) of dimensions:

$$HG = \frac{(H_R M * n) + (H_R O * n) + (H_R S * n)}{n + n + \ldots n} \tag{3}$$

where $H_R M$ is magnitude of the hazard, $H_R O$ is occurrence of the hazard, and $H_R S$ is susceptibility of the hazard. The value of n defines the weighting of each dimension. Once the maximum and minimum theoretical values of the index were obtained, equivalent ranges were defined; the minimum value is 0 and the maximum is 200; the equivalent ranges were defined as follows: very low <40, low 40–80, medium 80–120, high 120–160, and very high >160 (Table 3).

Table 2. List of variables per component considered in the vulnerability assessment and ranking description.

Component	Variable	Ranking					
		Very Low (1)	Low (2)	Medium (3)	High (4)	Very High (5)	Reference
Exposure (E)	Distance to vegetation covers (m)	More than 80	Between 80 and 50	Between 50 and 30	Between 30 and 10	Less than 10	[16]
	Population density (inhabitants/Ha)	0–27	28–44	43–59	60–77	More than 77	[16,46,53]
	Housing density (houses/ha)	0–10	11–20	21–30	31–40	More than 41	[16,46]
	Number of infrastructure services	Less than 10	11–15	16–20	21–25	More than 26	[16,46]

Component	Dimension	Variable	Vulnerability Ranking					
			Very Low (1)	Low (2)	Medium (3)	High (4)	Very High (5)	Reference
Fragility (F)	Physical Fragility (FP)	Material	Rustic (wood)	-	Masonry	-	Concrete	This research
		Ceilings	Lightweight	-	Roof tile	-	Heavy (concrete)	This research
		Housing status	Good conditions		Regular state	-	Disrepair	This research
		Index K. Coastal Structure	Extreme (K > 1)	Maximum (K = 0.51–1)	Mean (K = 0.11–0.5)	Minimum (K = 0.0001–0.1)	No structures (K = 0)	[50]
		Service Infrastructure	More than 10	8–9	5–7	3–4	Less than 2	[53]
		Communication-Roads	Main roads	Re-labeled road	Track, trail, path	Waterway	Wooden bridges	[20]
	Social Fragility (FS)	Age of the population	From 18 to 55 years old	-	>55 years old	-	<18 years old	[16,46,53]
		Employment, sector and time of dedication	More than 80% tourism sector	-	More than 80% farming sector	-	More than 80% fishing sector	[34,53]
		Work intensity	Full time	-	Half time	-	Unemployed	[53]
		Education of the population	More than 80% professional	-	More than 80% high school	-	More than 80% primary school/without education	[53]
		Educational facilities	University/high school	-	High school/primary school	Primary school	Without schools	[53]
		Health services	Level III (hospital)	-	Level II (hospital)	Level I (health center)	Without health services	[53]
	Ecological Fragility (FEc)	Percentage of vegetation cover	More than 80% coverage	Between 60% and 80% coverage	Between 30 and 50% coverage	Between 10% and 30% coverage	Less than 10% coverage	[16]
		Species conservation	Permanent presence of birds and sea turtles	-	Occasional presence of birds and sea turtles	-	No presence of birds or sea turtles	[16]
		Contamination	No trash	-	Occasional presence of garbage	-	Continuous accumulation of garbage	This research

Table 2. *Cont.*

Component	Dimension	Variable	Vulnerability Ranking					
			Very Low (1)	**Low (2)**	**Medium (3)**	**High (4)**	**Very High (5)**	**Reference**
	Economic Fragility (FE)	Tourism vocation	Full time	-	Tourist season	-	No tourism	This research
		Economic activities	Tourism, fishing, and other activities (commerce, services)	-	Tourism and fishing	-	Only fishing	This research
		Ecosystem services	Foods/materials/tourism	-	2 services	-	0–1 service	This research
	Cultural Fragility (FC)	Forest practices	Presence	-	-	-	No presence	[16]
		Cultural beach practices	Presence	-	-	-	No presence	[16]
		Ethnic communities	Presence	-	-	-	No presence	[16,20]
	Institutional Fragility (FI)	Presence of relief agencies	Permanent	For seasons	Remote control	Critical moments	No presence	[16,53]
		Community organization	Permanent	For seasons	Remote control	Critical moments	No presence	[16,53]
		Presence of the State	Permanent	For seasons	Remote control	Critical moments	No presence	[16,53]
Component	**Dimension**	**Variable**	**Ranking**					
			Very Low (1)	**Low (2)**	**Medium (3)**	**High (4)**	**Very High (5)**	**Reference**
Lack of Resilience (R)	Inability to anticipate (IA)	Mitigation works	More than 80%	Between 60% and 80%	Between 30% and 50%	Between 10% and 30%	Less than 10%	[16]
		Type of housing constructions	Rustic (wood) more than 80%	Rustic (wood) between 60% and 80%	Rustic (wood) 50% and concrete 50%	Concrete between 60% and 80%	Concrete more than 80%	[53]
		Knowledge of coastal erosion	More than 80%	Between 60% and 80%	Between 30% and 50%	Between 10% and 30%	Less than 10%	[16]
		Emergency plan	Coastal erosion emergency plan	-	-	-	No emergency plan	[16]
	Inability to cope (IC)	Distance to relief agencies	In the town	-	Within 5 km	-	More than 5 km	[16]
		Access (Roads)	Land rout	-	Airway	-	Seaway	[20]
		Evacuation routes	Have evacuation routes	-	-	-	No evacuation routes	[16]
		Distance to capital city	Less than 5 km (any type of road)	-	10–20 km (route with limited access)	-	More than 20 km (route only air or water)	[16]
	Inability to respond (IR)	Ceilings	Lightweight	-	Roof tile	-	Heavy (concrete)	This research
		Housing	Rustic (wood) more than 80%	Rustic (wood) between 60% and 80%	Rustic (wood) 50% and concrete 50%	Concrete between 60% and 80%	Concrete More than 80%	This research
		House insurance	They have home insurance	-	-	-	They do not have home insurance	This research
		Vegetation response	Vegetation present	-	-	-	Without presence of vegetal cover	[16]
		Community organization	Community social organization present	-	-	-	No community social organization present	[53]

Table 3. Equivalence ranges, reference colors, and their descriptions. Adapted from [54], with permission from publisher Ricaurte-Villota et al., 2019.

Scale		Hazard	Vulnerability
Very High	160–200	Physical systems currently present coastal erosion processes, with high erosion rates. External conditions can present high incidences of oceanographic factors, whereas geological and geomorphological conditions present highest values of weakness or susceptibility to coastal erosion.	Exposure levels have the highest values; housing, ecosystems, and populations are located on the coastline. The systems or dimensions show the greatest weakness in each element, which have the lowest capacity to respond, cope, and recover.
High	120–159	The systems present or have presented some process of coastal erosion. Oceanographic conditions are strong and can have a greater incidence on the coastline, with high values of magnitude. Most of the intrinsic variables of the continental area have the conditions for coastal erosion processes to be generated.	Elements that present a high level of exposure to a hazard, and high fragility conditions, characterized by rigid structural elements, construction systems that do not allow a response and are in a state of advanced deterioration. Elements or systems are incapable of recovering from the effects caused by a phenomenon.
Moderate	80–119	Possibly coastal erosion occurs or be presented, with intermediate rates. The magnitude of incidence in terms of external variables has intermediate values or ranges between high and low values, for example, it can have a high wave and a micro-tidal regime. The physical conditions of the coastline present intermediate values, meaning that the natural conditions are moderately strong to respond to coastal erosion.	Elements that present a moderate level of exposure to the hazard, with intermediate levels of fragility, characterized by structural elements (socio-economic, institutional, etc.) whose state and resilience are acceptable. A population or ecosystems with limitations to respond and adapt to changes generated by an event.
Low	40–79	Accretion or stability values on the coastline. Some incidence variables are not strong, and the coastal area has strengths to resist coastal erosion in most of the variables.	Elements that can present a relatively low level of exposure to a given phenomenon, with fragility characterized by structural typology resistant and in good condition. Socioeconomic population capable of recovering from a drastic change in its environment. Building systems are not rigid and have the capacity to mobilize.
Very low	0–39	It presents accretion values, weak conditions of attack to the coast. The intrinsic systems of the coastline remain strong and resistant to the different processes that can weaken them and generate coastal erosion.	They are systems that have very low exposure or are far away from the coastline. Most of the systems have very low fragility, i.e., they have been strengthened, and have high capacity to adapt, respond, and cope with coastal erosion.

The Relative Value Index (VR) of the vulnerability, where (n) is the number of variables, is obtained in the same way as in the hazard, using the following equation:

$$VR = \left[\frac{(Vabs - n)}{n * 2} \right] * 100 \quad (4)$$

Similarly, for global vulnerability (VG), the sum of its three components is made from the number (n) of dimensions of each, where $V_R E$ is exposure of the vulnerability, $V_R F$ is fragility of the vulnerability, and $V_R LR$ is lack of resilience of vulnerability:

$$VG = \frac{(V_R E * n) + (V_R F * n) + (V_R LR * n)}{n + n + \dots n} \quad (5)$$

where E corresponds to the exposed elements and F corresponds to Fragility and its Physical (FP), Social (FS), Economic (FE), Ecological (FEc), Institutional (FI), and Cultural (FC) dimensions, calculated as:

$$F = \frac{(FP) + (FS) + (FE) + (FEc) + (FC) + (FI)}{n} \tag{6}$$

In Equation (7), LR corresponds to the lack of resilience comprising inability to respond (IR), inability to anticipate (IA) and inability to cope (IC), calculated as:

$$LR = \frac{(IR) + (IA) + (IC)}{n} \tag{7}$$

3. Results

In this section, two case studies of coastal zones with different characteristics are presented, and the proposed methodology was used to validate them.

3.1. Case Study: Spratt Bight Beach, San Andrés Island, Caribbean Coast

3.1.1. Hazard

The hazard assessment at Spratt Bight Beach showed a medium level magnitude (Figure 3A) but high levels of occurrence and susceptibility (Figure 3B,C). The result of crossing these 3 components was that 69.2% of the Spratt Bight coastline had a high hazard to coastal erosion (Figure 3D), located at the northwestern and southeastern ends of the beach. The magnitude showed a medium level because the area is protected by a barrier reef, reducing the height of the wave, in addition to a micro-tidal regime. With respect to occurrence, the general evaluation of the changes in the coastline showed a retrocession trend with values ranging from −0.1 to −1.8 m/year, analysis between 1990 and 2014 [26], being the sectors to the northwestern and the central areas, the most affected. Finally, susceptibility was high because this is a narrow beach (low adaptation to change) with fine, easy-to-transport sand.

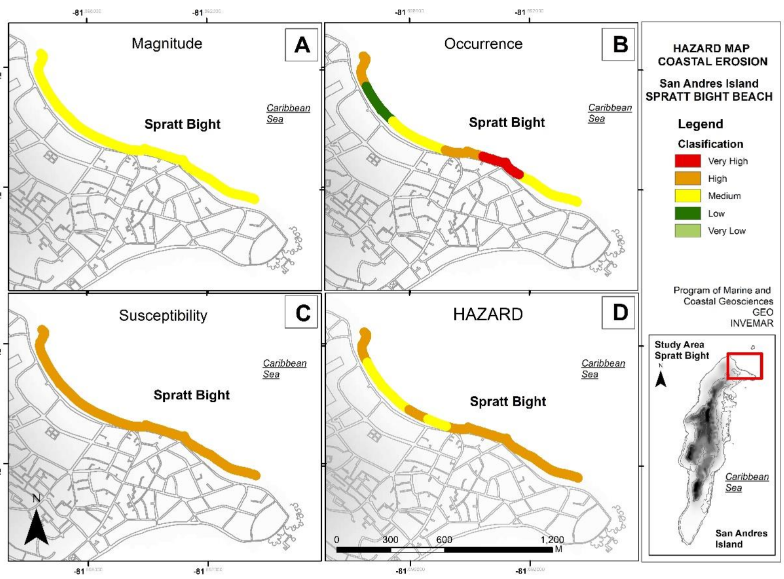

Figure 3. Hazard of coastal erosion in Spratt Bight, San Andrés Island, Caribbean coast. (**A**) Magnitude, (**B**) Occurrence, (**C**) Susceptibility, and (**D**) Hazard.

3.1.2. Vulnerability

The Spratt Bight vulnerability analysis showed a medium level exposure for the whole area (Figure 4A). This value derives from greater exposure of the physical (amount of service infrastructure and density of houses) and population variables (population density), but low exposure to natural variables (little vegetation at the site). Fragility was low; almost all dimensions were very low except for ecological and cultural, showing high fragility (Figure 4B). The lack of resilience was high (Figure 4C), because the inability to anticipate was high, as a result of the rigidity of the structures (made of concrete), which does not allow easy adaptation to the phenomenon, whereas the inability to respond was classified as medium and the inability to cope was low; this is due to the proximity and presence of relief institutions. The sum of these components (exposure, fragility, and lack of resilience) showed a medium vulnerability in the area (Figure 4D).

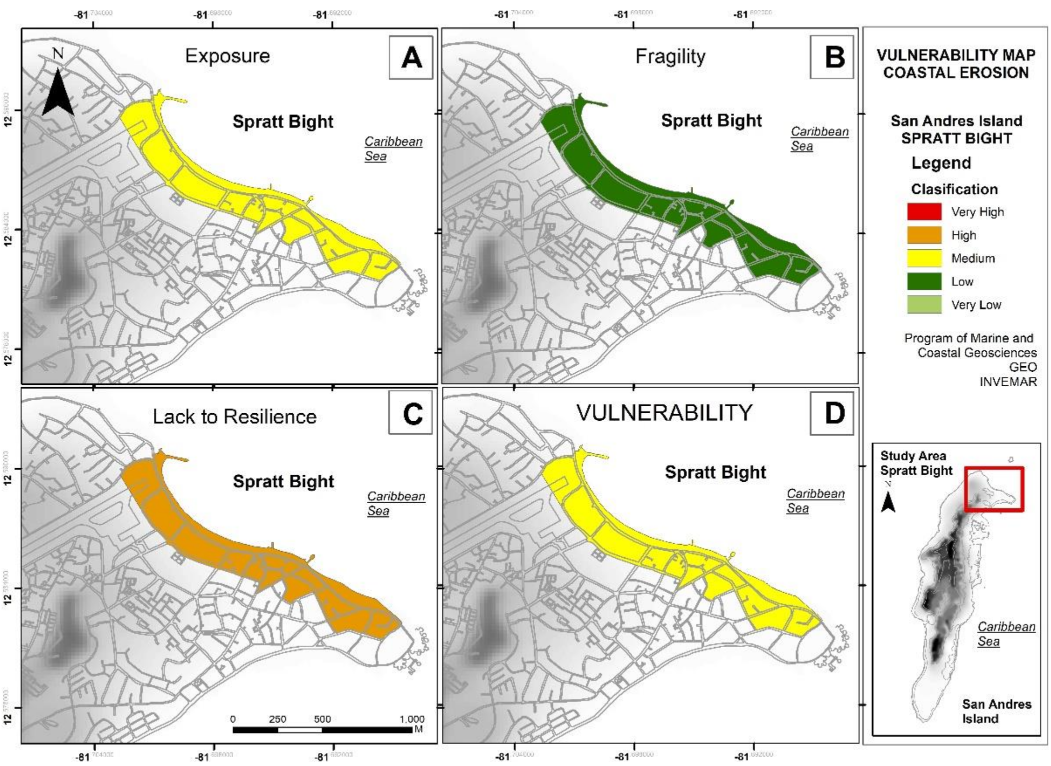

Figure 4. Vulnerability to coastal erosion in Spratt Bight, San Andrés Island, Caribbean coast. (**A**) Exposure, (**B**) Fragility, (**C**) Lack of Resilience, and (**D**) Vulnerability.

3.2. Case Study: La Bocana, Bay of Buenaventura, Pacific Coast

3.2.1. Hazard

The La Bocana hazard assessment showed that 87.88% of the coastline is at high and very high hazard levels, and 12.12% is at a medium level (Figure 5D). The high hazard percentage, 60.61%, occurred in the sectors of Shangay, Centro, the east side of Pianguita, and the west side of Vistahermosa. The very high hazard range was only found in the Vistahermosa sector and corresponds to 27.27%, whereas the medium hazard (12.12%) was found in the western end of the Pianguita sector.

The magnitude (Figure 5A) showed mean values in almost the entire area except Vistahermosa, where it was high, determined by a higher wave height, according to the wave model performed by MADS-INVEMAR [55]. Very high occurrence was observed in Vista Hermosa and Centro (near the pier), where shoreline changes have been most intense in recent years and erosion rates exceed 1 m/year, whereas the rest of the area had low and very low values, as shoreline changes were accretion or stability (Figure 5B). Susceptibility was high in almost the entire area, except in Vistahermosa and the western part of Pianguita, where it is very high (Figure 5C), because in these sectors the beach is narrower, with a high slope, and the waves hit directly.

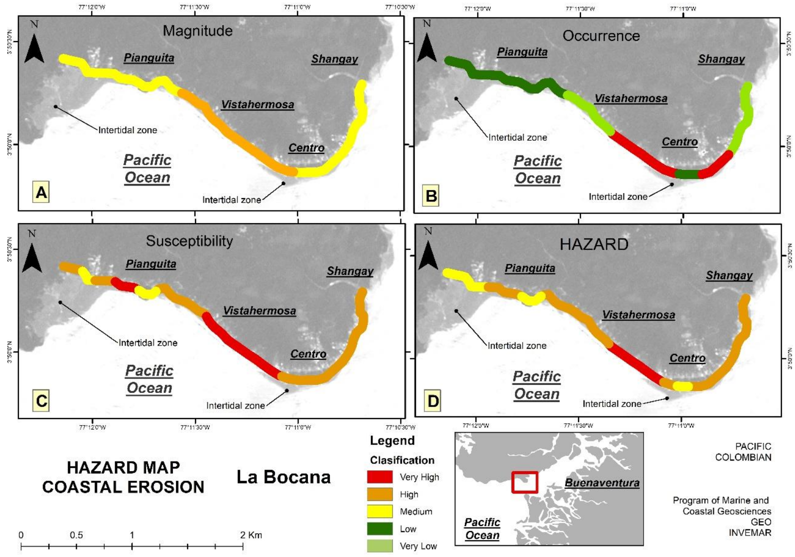

Figure 5. Hazard of coastal erosion in La Bocana, Pacific Coast. (**A**) Magnitude, (**B**) Occurrence, (**C**) Susceptibility, and (**D**) Hazard.

3.2.2. Vulnerability

The vulnerability assessment of La Bocana showed that the exposure had differential behaviors across the area, showing 3 levels (Figure 6A): medium level in Vistahermosa and Pianguita, high in Centro, and very high in Shangay. The last two sectors have the highest population and housing densities, whereas the Pianguita sector has the highest hotel infrastructure. Fragility was also divided into 3 levels (Figure 6B): very low in Centro, medium in Vistahermosa and Pianguita, and high in Shangay. This is due to the fact that little service infrastructure (health, education, etc.) is located in the Centre sector. Pianguita and Vistahermosa have low economic fragility (higher employment due to tourist activity). The lack of resilience for La Bocana (all 4 sectors) was medium (Figure 6C); this means that this is a population that is moderately prepared to respond to coastal erosion, because its inhabitants are adapted to environmental changes and the material of their houses allows flexibility. Finally, total vulnerability was medium in Centro, Vistahermosa, and Pianguita, whereas in Shangay it was high (Figure 6D).

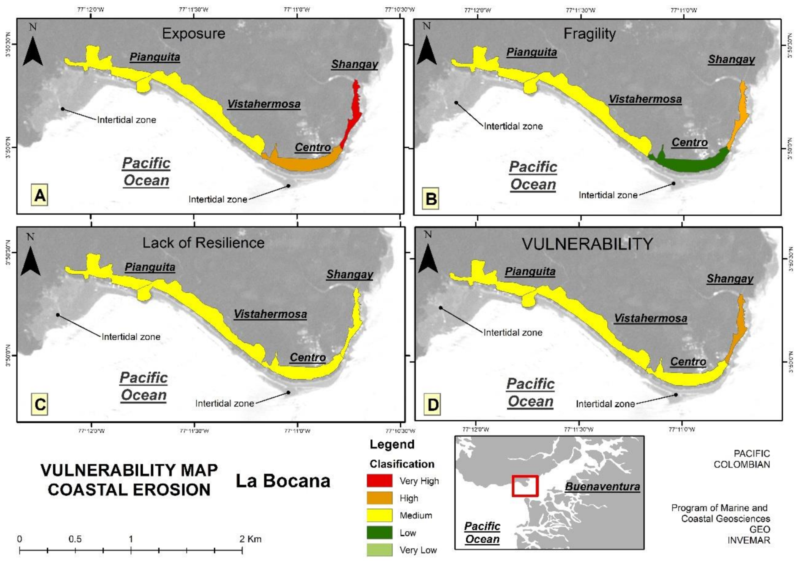

Figure 6. Vulnerability to coastal erosion in La Bocana settlement, Pacific Coast. (**A**) Exposure, (**B**) Fragility, (**C**) Lack of Resilience, and (**D**) Vulnerability.

3.3. Spratt Bight, San Andrés Island, Caribbean Coast vs. La Bocana, Buenaventura Bay, Pacific Coast

3.3.1. Hazard

The comparison of the results obtained from the hazard assessment between the two coasts shows that the variables that influence magnitude with high scores were tidal amplitude in the Pacific and the height of waves and rise in average sea level in the Caribbean (Table 4). As for occurrence, the variation in the coastline responds differently along the beaches, passing through values of accretion, stability, and high rates of erosion, regardless of the region. On the other hand, these beaches showed a higher percentage of past occurrence and a lower present occurrence value. This could mean that, at some point in the evolution in the medium-term, erosion processes have occurred, despite which the predominant values were of average classification (Table 5). The simple fact of being a beach geoform makes them more susceptible to changes, due to the unconsolidated material. Another high-ranking factor in susceptibility was granulometry, which presented a grain from fine to very fine, allowing greater transport; the susceptibility results marked a higher percentage in the high classification (Table 6). The results showed a higher percentage for the two beaches at hazard of high coastal erosion, with scores between 120 and 130 being the most predominant, barely surpassing the average classification (Table 7).

Table 4. Results of the magnitude component of the hazard by coastal erosion, study area, ranking, and final score obtained. The percentage represents the number of segments on each ranking over the total number of segments.

Variables	Location	Ranking				
		1	2	3	4	5
Tide amplitude	Spratt Bight	100%	-	-	-	-
	La Bocana	-	-	-	-	100%
Average height of breaking waves	Spratt Bight	-	-	-	100%	-
	La Bocana	-	70.59%	29.41%	-	-
Sea-level rise	Spratt Bight	-	-	-	-	100%
	La Bocana	-	-	100%	-	-
Magnitude (M) (score and percentage)	Spratt Bight	-	-	116.67 100%	-	-
	La Bocana	-	-	116.67 69.70%	133.33 30.30%	-

Table 5. Results of the occurrence component of the coastal erosion hazard, by study area, ranking, and final score obtained. The percentage represents the number of segments on each ranking over the total number of segments.

Variables	Location	Ranking				
		1	2	3	4	5
Coastline variation	Spratt Bight	14.29%	-	42.86%	28.57%	14.29%
	La Bocana	21%	21%	32%	-	26%
Occurrence	Spratt Bight	-	-	57%	-	43%
	La Bocana	-	-	74%	-	26%
Occurrence (O) (score and percentage)	Spratt Bight	-	50.00 14.28%	100.00 42.87%	150.00 28.57%	200.00 14.28%
	La Bocana	-	50.00 18.18%	100.00 54.55%	-	200.00 27.27%

Table 6. Results of the susceptibility component of the coastal erosion hazard, by study area, ranking, and final score obtained. The percentage represents the number of segments on each ranking over the total number of segments.

Variables	Location	Ranking				
		1	2	3	4	5
Geomorphology	Spratt Bight	-	-	-	-	100%
	La Bocana	5.88%	2.94%	-	-	91.18%
Granulometry	Spratt Bight	-	-	-	100%	-
	La Bocana	5.88%	-	-	-	94.12%
Beach width	Spratt Bight			64.29%		35.71%
	La Bocana	20.59%	8.82%	38.24%	26.47%	5.88%
Beachfront slope	Spratt Bight	71.43%	-	-	-	28.57%
	La Bocana	-	-	-	-	100%
Morphodynamic state	Spratt Bight	-	-	100%	-	-
	La Bocana	-	-	100%	-	-
Geomorphological features	Spratt Bight	100%	-	-	-	-
	La Bocana	-	-	70.59%	-	29.41%
Wave exposure (direction)	Spratt Bight	-	-	28.57%	-	71.43%
	La Bocana	29.41%	-	50.00%	-	20.59%
Susceptibility (S) (score and percentage)	Spratt Bight	-	-	-	121.43 (61.54%) 135.71 (7.69%) 150.00 (30.77%) 100.00%	-
	La Bocana	-	-	114.29 12.12%	142.86 60.61%	178.57 27.27%

Table 7. Coastal erosion hazard results, by study area, ranking, final score obtained, and percentage. The percentage represents the number of segments on each ranking over the total number of segments.

Dimension	Location	Ranking				
		1	2	3	4	5
Hazard (H) (score and percentage)	Spratt Bight	-	-	116.66 30.77%	150.00 69.23%	-
	La Bocana	-	-	116.67 18.18%	154.16 66.67%	170.83 15.15%

3.3.2. Vulnerability

The results of the exposure in the two study areas show that housing density and service infrastructure are the most exposed elements, whereas the elements of low exposure are vegetation coverage in Spratt Bight and low local population density in the two regions. For the two areas, there was predominance of a medium classification score; in the Pacific, the area closest to the pier was the one with a score equivalent to high and very high class (Figure 7).

Physical fragility (Figure 8) presented a high score for Spratt Bight, observed in the variables of type of material and roofs. Unlike La Bocana, where these represent low values; this is an essential point in coastal erosion studies, because this phenomenon is not a shock but a chronic hazard that allows light constructions to be easier to handle than hard constructions. Social fragility (Figure 9) showed the deficiencies in La Bocana, due to the weakness in the working conditions, education, and health of the population, obtaining medium (Pianguita and Centro), high (Vistahermosa), and very high (Shangay) results. On the other hand, Spratt Bight presented very low values. The highest-ranking ecological fragility (Figure 10) variable in both the Caribbean and the Pacific is beach pollution. The results showed that Spratt Bight has a high ecological fragility and La Bocana has medium (Pianguita and Vistahermosa) and high (Centro and Shangay) ecological fragility. There was a marked difference in economic fragility (Figure 11) between the Caribbean and Pacific coasts. In the Caribbean, there is massive tourism that generates income to the population, whereas in the Pacific, tourism is at a medium to low level. As a result, Spratt Bight showed very low economic fragility, and in the Pacific, despite having sectors with low fragility, the maximum values of economic fragility were observed in Shangay. The results of cultural fragility (Figure 12) reflect the cultural differences between the two regions. The Caribbean region had the highest fragility value (very high—5 score) and the Pacific region (Vistahermosa and Centro) had the lowest fragility value (1 score), and only Shangay and Pianguita have ceased to preserve cultural heritage and therefore obtained high values of fragility (133 score). Finally, institutional fragility (Figure 13) shows greater state abandonment in the Pacific region, which obtained an average rating (3 score); in the Caribbean region the presence of the state is greater, represented by low fragility (1 score).

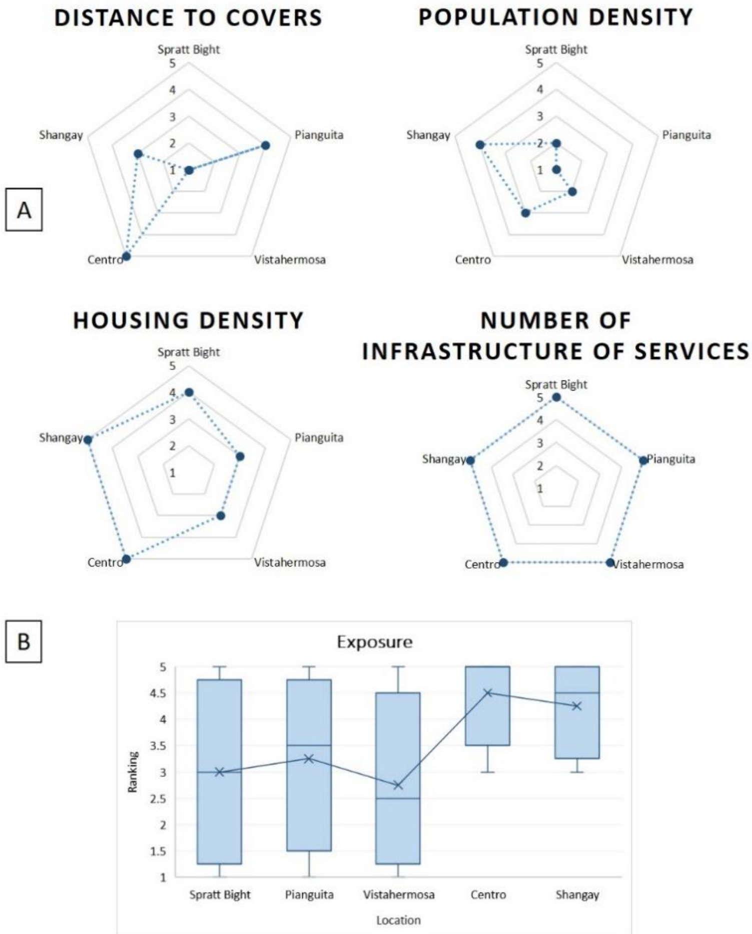

Figure 7. (**A**) Ranking of four variables representing exposure for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of exposure on each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments as it was in hazard.

Lack of resilience in Spratt Bight was classified as very high due to its inability to anticipate (5 score) where there are very few mitigations works; however, the values in La Bocana were high (4 score in Centro), because the houses did not have *"palafitos"* (stilt house). A moderate score (3) was observed in Pianguita and low scores (2) were observed in Vistahermosa and Shangay (Figure 14). It was observed that the inability to cope has a big difference between regions. In the Caribbean, this inability is low

(2 score), whereas in the 4 sectors of the Pacific the score was 5; in all variables Spratt Bight beach was ranking 1, whereas the beaches of La Bocana had 3 and 5 ranking (Figure 15). Concerning the inability to respond, Spratt Bight again presented high values (4 score). This was determined by the predominance of rigid structures (concrete constructions and hard roofs) which do not allow for their easy transfer, making it less resilient; in La Bocana, medium and low values were obtained, because houses made of wood, with light roofs, allow a better response to the intrinsic nature of the hazard by coastal erosion (Figure 16). The overall results showed that there is greater exposure and greater fragility in the Pacific than in the Caribbean and a greater lack of resilience in the Caribbean, leading to moderate vulnerability in both regions, with the exception of Shangay, which was classified as having high vulnerability.

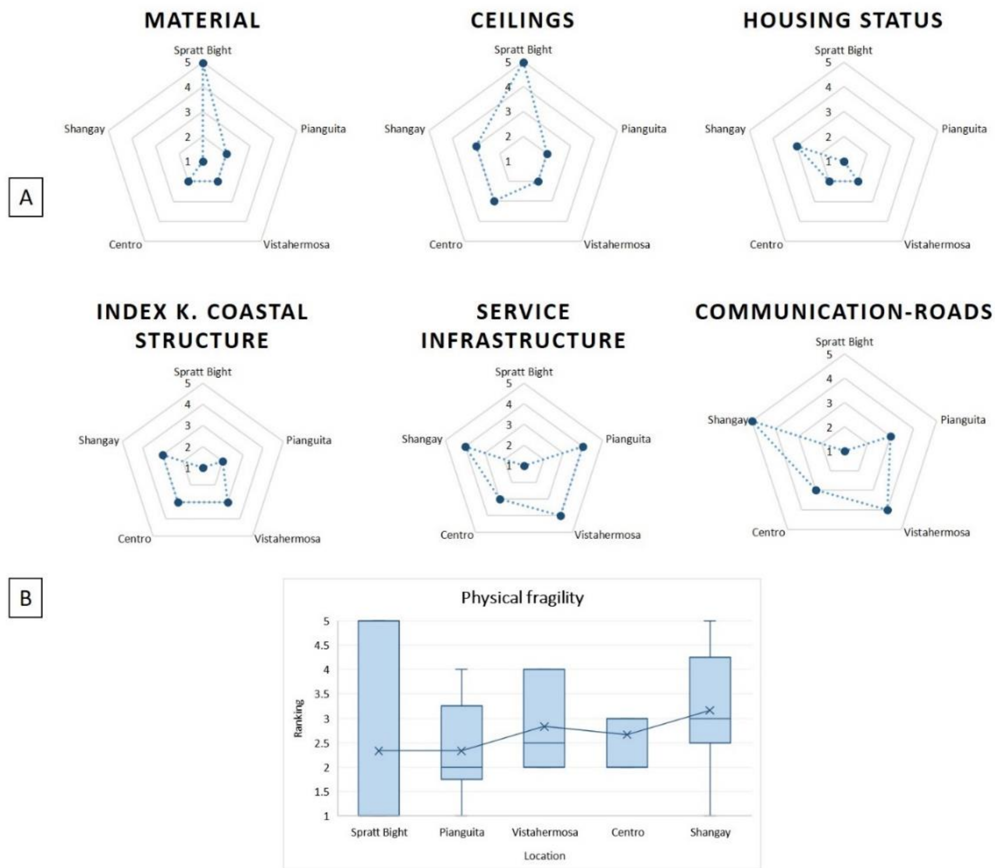

Figure 8. (**A**) Ranking of four variables representing physical fragility for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of physical fragility for each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments, as was the case for hazard.

Figure 9. (**A**) Ranking of four variables representing social fragility for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of social fragility for each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments, as was the case for hazard.

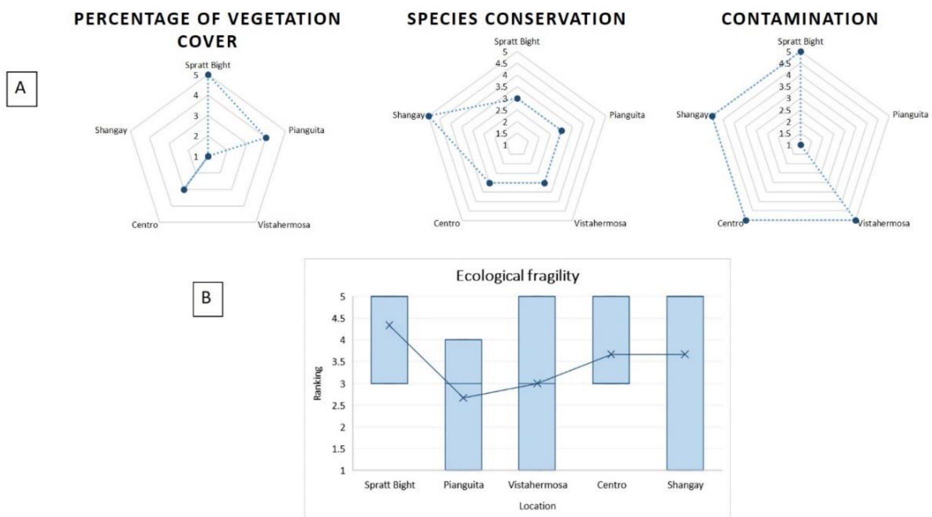

Figure 10. (**A**) Ranking of four variables representing ecological fragility for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of ecological fragility for each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments, as was the case for hazard.

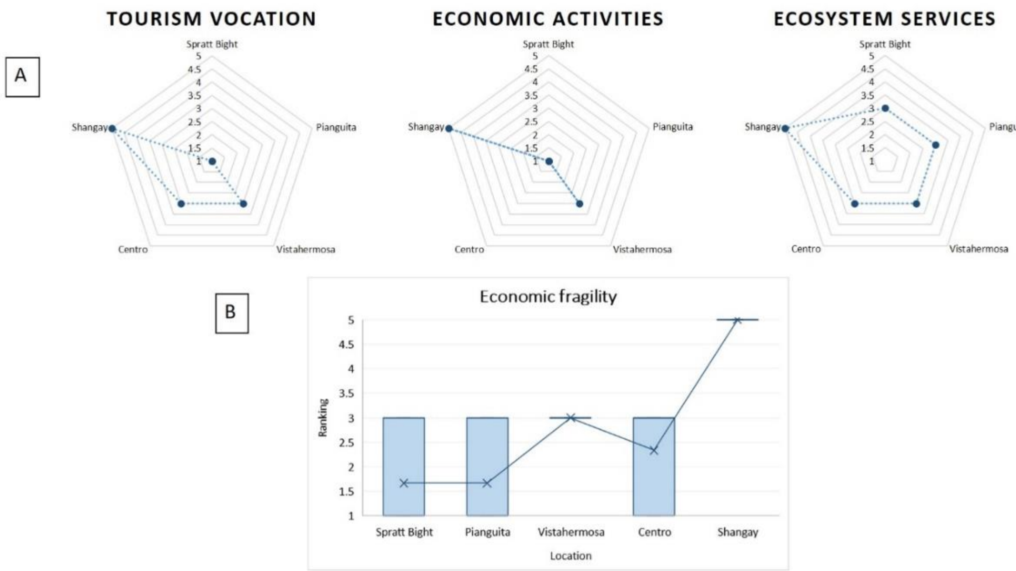

Figure 11. (**A**) Ranking of four variables representing economic fragility for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of economic fragility for each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments, as was the case for hazard.

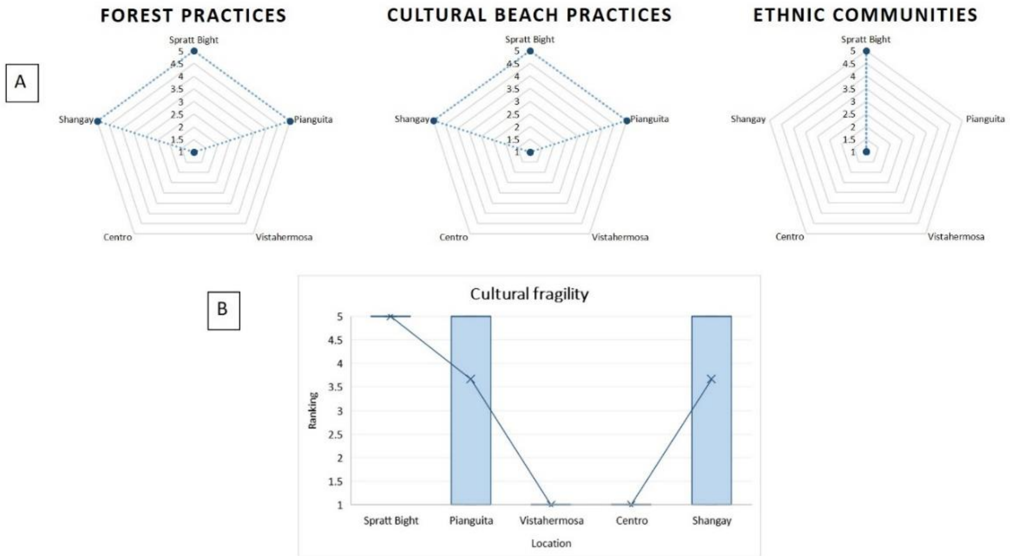

Figure 12. (**A**) Ranking of four variables representing cultural fragility for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of cultural fragility for each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments, as was the case for hazard.

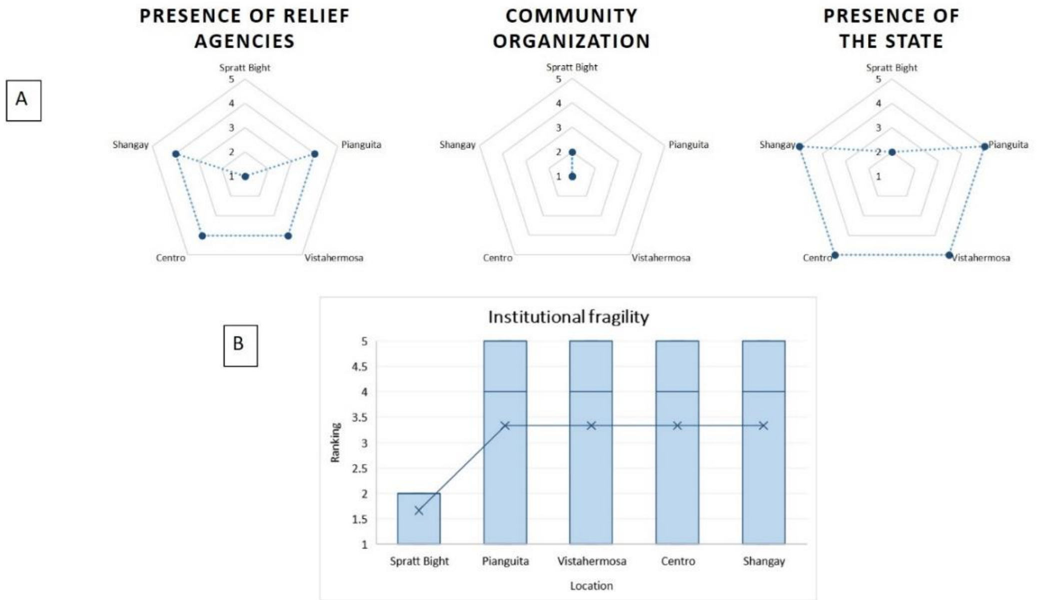

Figure 13. (**A**) Ranking of four variables representing institutional fragility for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of institutional fragility for each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments, as was the case for hazard.

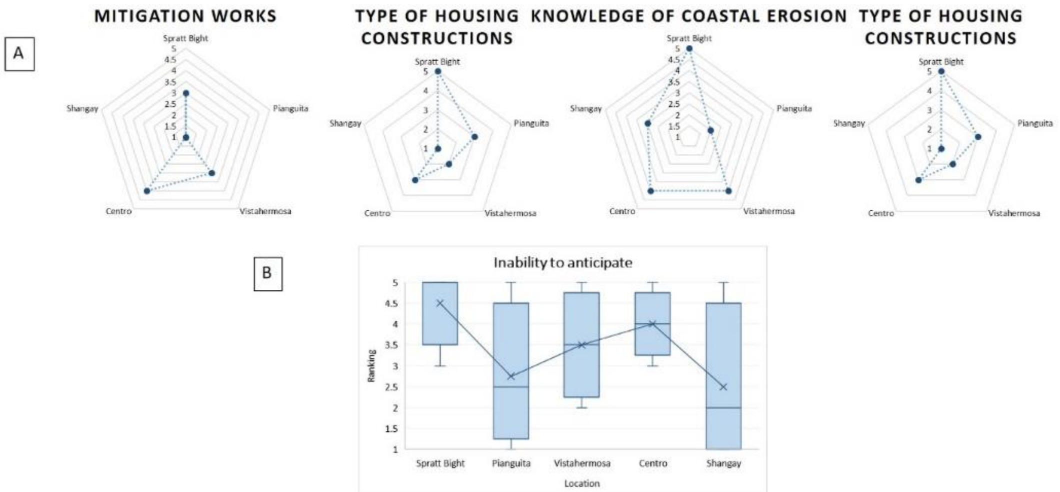

Figure 14. (**A**) Ranking of four variables representing inability to anticipate for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of inability to anticipate for each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments, as was the case for hazard.

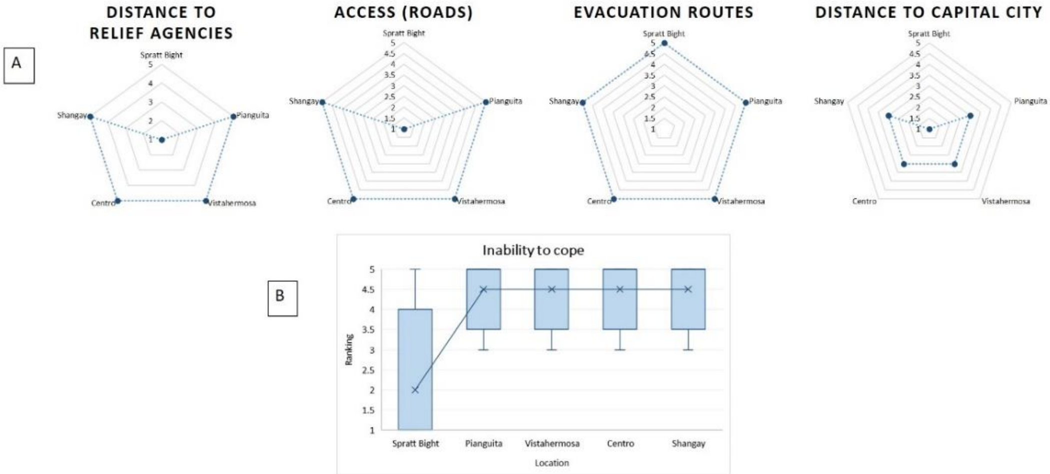

Figure 15. (**A**) Ranking of four variables representing inability to cope for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of inability to cope for each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments, as was the case for hazard.

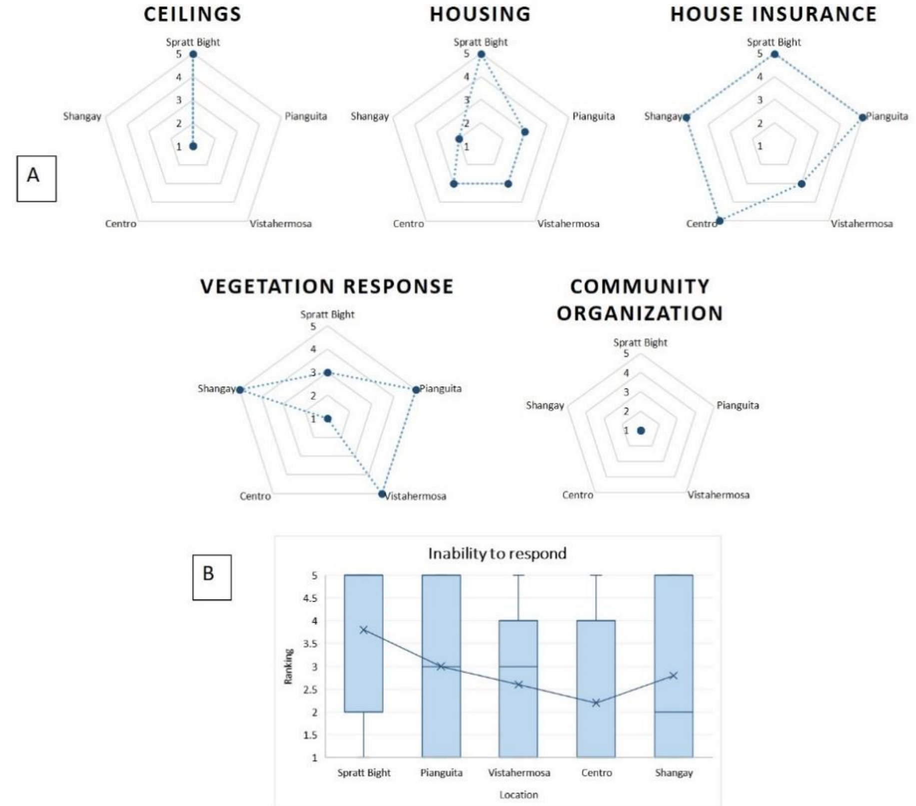

Figure 16. (**A**) Ranking of four variables representing inability to respond for two study areas (and five villages): San Andrés, Caribbean Coast (Spratt Bight) and La Bocana, Pacific Coast (Pianguita, Vistahermosa, Centro, Shangay) of Colombia. (**B**) Minimum and maximum values of inability to respond for each village and average rank. Results are shown by ranking, given that units of analysis are rank levels and not segments, as was the case for hazard.

4. Discussion

The different methodologies related to coastal erosion risks have implemented different models, indices, or methods, emphasizing the physical susceptibility factors of the coastal area, but few have stopped to evaluate the human aspects in direct relation to the nature of the phenomenon. However, some related studies have been implemented in the Caribbean [36] and Colombia [50,56]. The differences between some authors [22,24,56] lie not only in the use of different indices, GIS methods (e.g., Fuzzy), and models, but also in the minimum spatial units of analysis, some using homogeneous lines or areas. This study combines areas with a grid. Previous studies assigned different weights to assessed variables, whereas this study avoided bias.

This work presents in an integral way the hazard and the vulnerability, unlike other indices in the world that have been proposed specifically as physical phenomena [28,30,32,57] or the vulnerability of their systems [25,33,34]. For example, the BVI index [26] specifically develops the physical vulnerability of the beaches, addressing it in a very detailed way, and other studies have proposed within same analysis physical and human variables, examining risk values [31,35,50].

This study was done on the beaches of the Caribbean and the Colombian Pacific (Spratt Bight and La Bocana), each one being an example of different environmental conditions (morphological, oceanographic, climatic, and human intervention). Although the results show that the hazard was high in Spratt Bight and in a large percentage of the La Bocana coastline, the spatial differences in the latter are related to the sectors exposed to the waves, with morphological variations and natural structures (i.e., in the area of the La Bocana coastline). This is in agreement with the proposal by Stive et al. [58] and Galgano [59] that the evolution of the coastline can be variable in a wide range of spatial scales.

Coastal erosion is caused by many factors [60,61], although the result is the same: loss of the coastline. Therefore, the hazard level represents different combinations of factors, which must be taken into account for decision-making, prevention, and mitigation.

The vulnerability analysis also found that different combinations of factors could produce the same level of vulnerability, so it is important to study the components separately. For example, the two regions showed an average level of vulnerability, with the exception of the Shangay area in La Bocana, but each region responds differently in terms of the components and shows a contrast between them. On the Pacific coast, for example, given their lightweight construction systems (timber) and houses on piles, these building systems are adapted for meso-tidal conditions and allow high levels of resilience, although institutional presence and living conditions are deficient (high and medium fragility, respectively). On the other hand, in the Caribbean region, constructions are rigid and do not allow adaptability (low resilience), but institutional presence and living conditions are better in this area (low fragility). Similar results, that is, those broken down into their variables or components, have been presented in a spatial way [62] or in tables, but presenting things in this way means that it is possible to identify the variable or component with the highest score and which requires intervention.

Similarly, vulnerability is not homogeneous along the coast, varying on a spatial scale, such as the differences observed between Shangay and the other sectors of La Bocana. This is linked to the fact that each sector has different exposed elements with particular characteristics.

Our results agree with INVEMAR-CORALINA [40], a study of vulnerability to sea-level rise for the island of San Andrés which, using a different methodology, also found a low socio-economic fragility for the Spratt Bight region. The strength of this study's methodology is that each component was constructed from the conceptual basis of hazard and vulnerability, considering all the elements that affect the phenomenon, including the different dimensions of fragility. Taking into account several dimensions is important because vulnerability can be conceptualized as a synthesis of different dimensions (cultural characteristics, age, organization and political, economic, and institutional conditions of the environment in which the community develops), which are analyzed from different scales, and allow a better understanding of the conditions of a community [63,64].

On the other hand, the resilience of coastal communities, in this case those of the Colombian Pacific, can be facilitated by their ancestral knowledge of the environment, as proposed by Meza [65], communities use their cultural heritage to adapt to environmental conditions with particular characteristics, a theory of social anthropology known as cultural ecology. In contrast, in the Caribbean, modernization, the process of structural change that a society undergoes in its economic, political, and socio-cultural spheres, caused many ancestral practices to be lost [66]. Modernization creates imbalances between technology, ecology, economy, and population [65,67,68], assuming that dangers and disasters are the result of inadequate relations of coexistence between a community and its environment [69,70]. However, Rempis et al. and Luís et al. [67,68] propose citizen participation as a strategy, adopting a holistic approach, to reduce negative processes in interventions on the coastal zone.

Finally, the results of this study and its presentation as a traffic-light map are a good tool for decision-makers, and contribute to an adequate risk management, because they help to identify the most affected sectors, allowing the planning and prioritizing of prevention or mitigation measures. In addition, we can understand that there are regional differences in the whole context of human groups (local weaknesses and strengths), for example, between the Caribbean and the Colombian Pacific, as shown in this study, and this allows us to attack weaknesses and consolidate strengths, making programs more effective.

5. Conclusions

The methodology based on a theoretical and conceptual construction allows it to adapt to the physical and human heterogeneity of the different regions, in addition to obtaining closer, more realistic, and accurate results with respect to the intrinsic nature of coastal erosion. This methodology is exhaustive with respect to the classification of the variables that are part of the phenomenon of coastal erosion.

The analysis of hazard focused on the beach area, and the methodological approach allows for adapting it to include other types of coasts, such as cliffs. The use of data measured in situ or of numerical models of different coastal processes and other oceanographic variables can improve the accuracy of the results.

For vulnerability, a complete methodology was presented, thanks to the combination and integration of components, dimensions, and variables. On the other hand, the inclusion of data on land values, gross domestic product, capital, income, and so on would facilitate risk analysis.

The level of hazard and vulnerability from coastal erosion shows spatial differences related to the diversity of morphological elements exposed along the coast. Similarly, the results represent different combinations of factors, so it is important to identify the components separately, on a regional scale, and they must be taken into account for decision-making, prevention, and mitigation.

Considering several dimensions is important, because vulnerability is the sum of multiple aspects in which the community develops, such as the cultural, social, political, economic, and institutional spheres. This study shows the importance of cultural ecology as a resilience factor for coastal hazards, in this case marine erosion.

Finally, hazard and vulnerability to coastal erosion maps allow for a probabilistic vision of the phenomenon, extending the range of options, the time, and the determining variables of the phenomenon, contrary to diagnostic maps, which generate static maps or photographs of the current situation, not allowing for long-term decision-making.

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