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A Climate Change Vulnerability Index and Case Study in a Brazilian Coastal City

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Abstract: Coastal areas are highly susceptible to the effects of climate change, particularly to sea-level rise and extreme rainfall events, resulting in increased social and environmental vulnerabilities. In this context, the need for predictive planning instruments, especially in densely populated coastal areas, is a critical management priority. A number of indexes has been developed to assess coastal vulnerability. However, coastal vulnerability indexes are yet to simultaneously consider inland (e.g., landslides and flooding) and ocean (sea-level rise and coastal erosion) hazards in conjunction. To help fill this gap, we developed the Socio-Environmental Vulnerability Index for Coastal Areas. The proposed index is a diagnostic tool to assess the socio-environmental vulnerability of coastal regions in the context of climate change. Applied to the city of Santos, a coastal municipality in São Paulo state, Brazil, the index revealed that most of the city are in areas highly vulnerable to sea-level rise and floods related to extreme rainfall events. Findings show that, in fact, approximately 70% of the area of Santos (27.5 km^2) consists of high vulnerability areas mostly located close to urban drainage channels, residential, and other built-in areas. Another 0.12% (0.05 km^2) were classified as very high vulnerability areas compromising port and industrial infrastructure. These results highlights the susceptibility of the urban insular area of Santos to climatic change hazards. This study might prove relevant to support local decision-makers in preparing adaptation plans and responding to climate-related risks in vulnerable coastal cities.

Keywords: coastal areas; climate change; multiple climate hazards; extreme events; Brazil

1. Introduction

With the growth of human cities, especially the coastal ones, and the increase of the climate hazards due to climate changes, the vulnerability and risk levels are also increasing. The increase of the hazards, and the complexity of the new cities, asks for more potent tools for assessing the risk and vulnerability of urban areas. Additionally, these tools now must provide a broader view on the vulnerability to help the construction of adaptive measures to cope with the future changes.

Since the first assessment report of the International Panel on Climate Change (IPCC) in 1990 [1], vulnerability and risk assessments have been used as important approaches to examine climate change-related risks and impacts, such as variations in temperature, rainfall, and sea-level rise (e.g., [1–3]). These assessments have mostly focused on coastal areas, where climate-related stressors are predicted to significantly affect urban populations and infrastructure.

From the risk perspective, some studies, such as [4], can cope with multiple hazards, extending the framework of vulnerability, or using a vulnerability approach access the social aspect of the risk.

However, the focus on risk represents a step-forward and requires a large amount of local data that is, most of the time, unavailable for extended areas.

Noteworthy is the number of indexes that have been developed to assess coastal vulnerability (e.g., [2,5–7]). This is also true for Brazil (see e.g., [8–11]); however, coastal vulnerability indexes are yet to simultaneously consider inland (e.g., landslides and flooding) and ocean (sea-level rise and coastal erosion) hazards in conjunction, which can be relevant especially in areas where the relief makes an important role on the landscape. To help fill this gap, we developed the Socio-Environmental Vulnerability Index for Coastal Areas (SEVICA) using the city of Santos, on the central coast of São Paulo, as a case study. The proposed index is a diagnostic tool to assess the socio-environmental vulnerability of coastal regions in the context of climate change and is particularly focused on impacts on critical infrastructure. It supports decision-making in preparing adaptation strategies in response to environmental change, particularly climate-related change.

2. Vulnerability Indexes and Variables

There are many definitions of vulnerability; one of the most accepted is the IPCC's, which defines it as "(. . .) the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" [12] (p. 5). In this paper, we adopt the concept of social-environmental vulnerability, which encompasses both biophysical and social factors. Furthermore, we also consider "place vulnerability", weighting the dependency of a population on local infrastructure, as suggested by [13]. An index that applies these concepts takes into account both physical and social impacts on human populations. Ultimately, it provides an integrated perspective to vulnerability studies.

There are many vulnerability indexes in the literature (Table 1), but most of them have been initially created to meet local needs, and adapted later for other contexts. These indexes differ in the variables used and reflect the purpose of the vulnerability assessment. However, these somewhat reductionist approaches to vulnerability assessment have been criticized due to their inability to inform systemic considerations. Further, [14] highlights the need for the convergence of many existent interpretations to better understand the real advantages of multiple perspectives of a problem.

Table 1. Examples of different approaches to measuring vulnerability.

Vulnerability Concept	Index Name	Variables/Parameters/Factors	Reference
Geophysical	CVI	Relief, geomorphology, rock type, vertical sea level movement, shoreline displacement, tidal range, wave height	[2]
	SI	Relief, rock type, geomorphology, sea level tendency, shoreline displacement rate, mean tidal range, mean annual maximum significant wave height	[3]
	CVI	Geomorphology, coastal slope, relative sea-level rise rate, shoreline erosion/accretion rate, mean tide range, mean wave height	[15]
	CSI	CVI (Thieler e Hammar-Klose,1999)	[16]
Social	SoVI	Personal Wealth, age, density of the built environment, single-sector economic dependence, housing stock and tenancy, race—African American, race—Native American, race—Asian, occupation, infrastructure dependence	[6]
	CsoVI	Poverty, age, development density, Asian and immigrants, rural/urban dichotomy, race and gender, population decline, ethnicity (Indian) and farming, infrastructure employment reliance, income	[15]

Table 1. *Cont.*

Vulnerability Concept	Index Name	Variables/Parameters/Factors	Reference
Socio-Environmental	PVI	CVI (Thieler e Hammar-Klose,1999) + CsoVI	[17]
	N.D	Flood-risk zones, population, housing units, females, ethnic population, young (under 18), elderly (age over 60), single mother households, renter-occupied housing units	[18]
	N.D	Flooding risk, population and structure, differential access to resources, population with special evacuation needs	[19]
	N.D	Socioeconomic index, land use index, eco-environmental index, coastal construction index, disaster-bearing capability index	[20]
	N.D	Sea level rise, storm surge, number of cyclones in the last 5 years, river discharge, foreshore slope, soil subsidence, km of coastline, population close to coastline, percentile of disabled persons, shelters, cultural heritage, awareness and preparedness, km of drainage, growing coastal population, recovery time, uncontrolled planning zones, flood hazard maps, institutional organizations, flood protection	[7]

Note: N.D = Not defined.

The variety of existing indexes underscores a number of possible approaches to thematic vulnerability [21]. Füssel and Klein [22] argue that such approaches vary from a more physical context reflecting the main focus of the studies (e.g., [2]) to a more social-based approach that incorporates social variables and factors better representing the adaptation capacity of local populations (e.g., [7]). The latter is more aligned with the concept of place vulnerability proposed by [13], and the concept of contextual vulnerability adopted by [23].

Despite the differing focus of the indexes, their formulation has not changed much since the early vulnerability studies. It is still based on metrics, mainly arithmetic or weighted mean of factors [2]. The core metrics have not changed because of the simplicity of their application and the variety of weighting techniques that provide the indexes the capability to better analyze a given problem. Critical constraints of traditional approaches to the formulation of indexes using quantitative means include limited contextual richness that could otherwise be obtained through qualitative approaches, and a bias towards easily collected and measureable data.

Studies by [10,24] are examples of vulnerability analyses applied to the Brazilian coast. They use a socio-environmental vulnerability approach to point out that the urban expansion on the Brazilian coast occurs often in vulnerable areas, which usually exposes the population to major risks. These regions have been targeted as a result of increased economic interest relating to oil and gas mega projects. In this context, it is important to develop a rapid and robust index that considers the biophysical and social dimensions of vulnerability, and, by doing so, enables the production local level vulnerability maps that can assist decision-makers to develop better adaptation strategies.

3. Materials and Methods

Multiple Hazards Index

The SEVICA consists of seven factors; four of them are geophysical and three are socio-economic factors (Figure 1). Each of these factors features independent parameters and formulation, as shown in Table 2. Each parameter features, in turn, a quantitative vulnerability scale ranging from 1–5. The vulnerability level of a factor is defined by the parameters' mean.

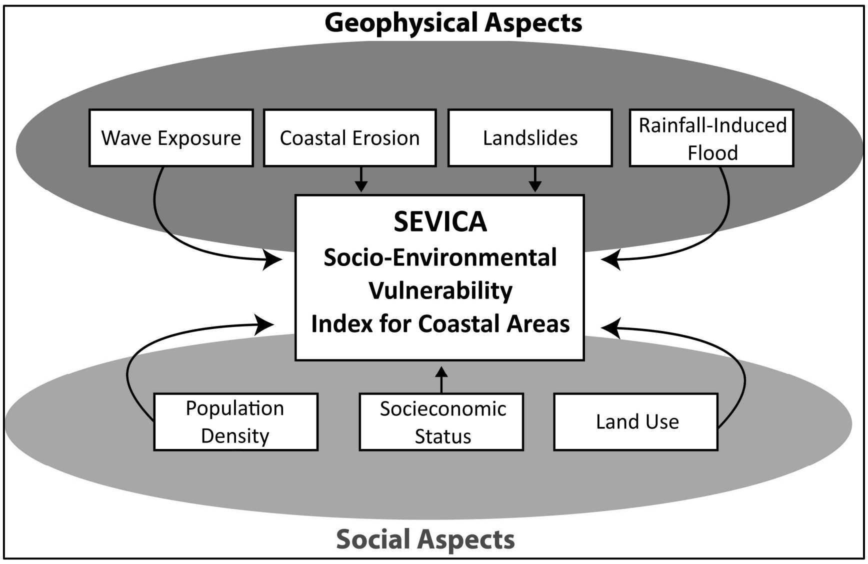

Figure 1. Structure of the Socio-environmental Vulnerability Index for Coastal Areas (SEVICA).

Table 2. Factors, parameters, and data sources for the Socio-environmental Vulnerability Index for Coastal Areas (SEVICA).

Factor	Parameters	Source of Data
Flooding (F)	Slope (S) Number of Extreme Events (NEE) Water Body Proximity (WBP)	DEM Climatic Models, Meteorological Data Hydrography Maps
Landslides (L)	Slope (S) Number of Extreme Events (NEE) Geotechnical Classification of Soil(GCS)	DEM Climatic Models, Meteorological Data Geology institutes, Mineralogy institutes, or Engineering Institutes
Coastal Erosion (CE)	Geomorphology (G) SLR (SLR) Tide Height (TH)	Geology institutes, Mineralogy institutes, or Engineering Institutes IPCC, Sea Level Rise Models Oceanography institutes, Navy
Wave Exposition (WE)	SLR (SLR) Relief (R) Distance of the coast (DC)	IPCC, Sea Level Rise Models DEM Geopolitical Maps
Socioeconomic Status (SS)	Education Level (EL) Income (I)	Nacional or Regional Census Nacional or Regional Census
Population Density (PD)	Population Density (DENS) Age (A)	Nacional or Regional Census Nacional or Regional Census
Land Use (LU)	Land Use (USE)	Local Government

The variables for each parameter were selected based on literature review (see Table 1), and expert elicitation. It also took into account data availability and the possibility to aggregate variables. The classification scales for each parameter are presented in Table 3.

The expert elicitation was used to determine the variables to be considered on the landslide factor of the index, and involved eight specialists on landslides. This elicitation was made by an open interview (unstructured) that was conducted by the authors, one by one, starting with the introduction to the objectives of the index. After that the experts were asked to provide their opinion about what the variables should be, and those that should not be, included in the factor. Based on the literature review and the expert elicitation, we selected three variables which were presented back for two of the experts, in order to confirm the choice. Later, these two last specialists were consulted during the design of the soils geotechnical classification into five categories used by the index. The specialists concluded that the proposed classification was enough to represent the susceptibility of landslides based on soil characteristics, and the combination with the other variables of the factor.

Table 3. Parameters' classification scale.

Factor	Parameter/Classification	1	2	3	4	5	Reference
Landslide	Number of Extreme Events in the last 10 years (NEE)	≤3 events	≤10 events	≤20 events	≤36 events	>36 events	Adapted from [7]
	Geotechnical Classification of Soil (GCS)	Bedrock	Tertiary non-expansive soil, fractured rock with rugous surface	Laterite soils, sandy soil	Alluvial (quaternary), fractured rock with clean ruptures filled with clays	Colluvium and talus body, expansive Soils	Expert elicitation
	Slope (S)	≤20%	≤40%	≤60%	≤80%	>80%	Adapted from [25]
Flooding	Number of Extreme Events in the last 10 years (NEE)	≤3 events	≤10 events	≤20 events	≤36 events	>36 events	Adapted from [7]
	Slope (S)	≥80%	≥60%	≥40%	≥20%	<20%	Adapted from [25]
	Water Body Proximity (WBP)	>150 m	>100 m	>50 m	>20 m	≤10 m	Adapted from [26]
Wave Exposure	Sea Level Rise (SLR)	≤0 m	≤0.3 m	≤0.5 m	≤0.7 m	≤0.9 m	Adapted from [25]
	Relief (R)	> 50 m	>20 m	>10 m	>5 m	≤1 m	Adapted from [24]
	Distance of the coast (DC)	>150 m	>100 m	>50 m	>20 m	≤10 m	Adapted from [26]
Coastal Erosion	Sea Level Rise (SLR)	≤0 m	≤0.3 m	≤0.5 m	≤0.7 m	≤0.9 m	Adapted from [25]
	Geomorphology (G)	Rocky, high cliffs, seawalls	Medium cliffs and indented coast, bulkhead	Low cliffs, alluvial plain	Cobble beach, estuary, lagoon	Sand beach, mud flat, delta	Adapted from [25]
	Tide Height (TH)	≤0.5 m	≤1 m	≤1.5 m	≤2.0 m	≤2.5 m	Adapted from [15]
Population Density	Population Density (DENS)	≤5000	≤10,000	≤50,000	≤100,000	>100,000	Elaborated by authors
	Age (A)	25–30 years old	35–40 years old	15–20 years old and 40–50 years old	5–15 years old and 50–60 years old	0–5 years old and more than 60 years old	Adapted from [6]
Socio-economic level	Income (I)	>20 LMW	up to 20 LMW	up to 10 LMW	up to 5 LMW	up to 2 LMW	Adapted from [8]
	Education Level (EL)	Graduated or higher	Undergraduated	College	High School	Elementary school or less.	Adapted from [8]
Land Use	Land Use (USE)	Environmental protection area or natural habitat	Rural Area	Residential Area	Commercial Area	Industrial Area	Elaborated by authors.

Note: LMW = local minimum wage.

The factors' vulnerabilities were obtained from the average value of the considered parameters, according to Equation (1):

$$\text{Factor}_v = (P_1 + P_2 + P_3 + \ldots + P_n) \times n^{-1} \quad (1)$$

in which,
Factor_v = Factor's vulnerability;
P_{1-n} = Parameter;
n = number of parameters considered.

Once the values for all factors were calculated using the arithmetic mean, according to Equation (1), the SEVICA itself can be calculated as a weighted mean of the factors, as given by Equation (2):

$$\text{SEVICA} = (\text{F.p}_1 + \text{L.p}_2 + \text{CE.p}_3 + \text{WE.p}_4 + \text{SS.p}_5 + \text{PD.p}_6 + \text{LU.p}_7) \times \left(\sum_{i=1}^{7} p_i\right)^{-1} \quad (2)$$

in which,
F = Flooding factor index;
L = Landslides factor index;
CE = Coastal Erosion factor index;
WE = Wave Exposition factor index;
PD = Population Density factor index;
SS = Socioeconomic Status factor index;
LU = Land Use factor index;
p = weights to each factor.

4. Case Study

Santos is the location of the largest port of Latin America. The city has a population of 419,400 people [27]. Ninety-nine percent of the population lives in Santos insular area, which is 39.4 km^2 (Figure 2). The insular area also houses all of the government buildings, most of the port infrastructure, and all of the city's public health and safety facilities, including hospitals, public schools, fire stations, police stations, public gymnasiums, armed forces, and public transport stations.

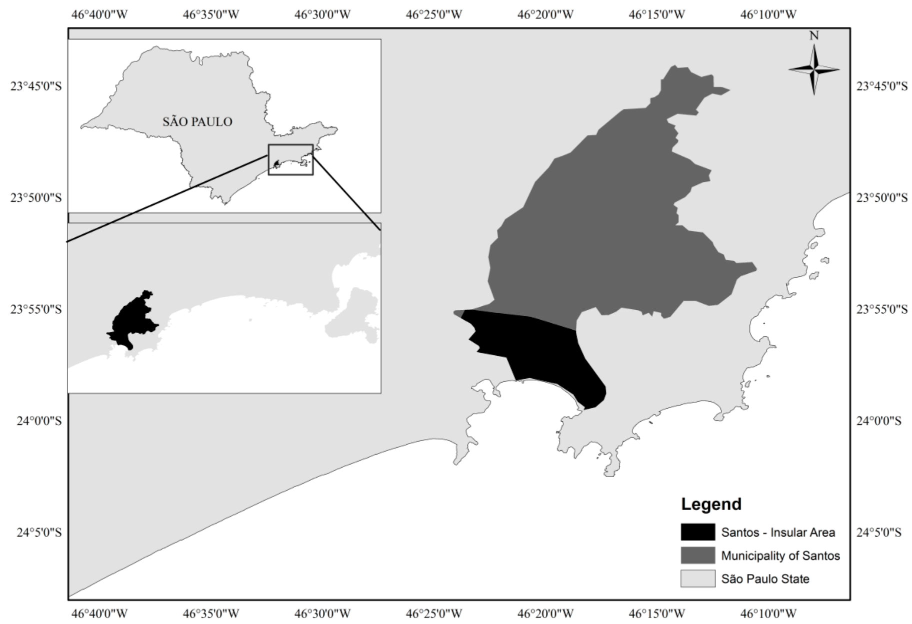

Figure 2. Santos, central coast of Sao Paulo, Brazil, highlighting the study area.

This insular area is also the main target for the investments relating to Pre-Salt Layer Oil and Gas projects, and associated real estate development. It is a flat and lowland area (average elevation less than 10 m in most of the area) and, therefore, potentially vulnerable to sea-level rise. Flooding caused by extreme precipitation is also a problem, which is likely to be intensified by climate change. Santos is, therefore, an adequate case to develop and test our socio-environmental vulnerability index. Further, this study may prove timely as local authorities are currently discussing a new urban master plan for Santos.

Index Operationalization

This study considered climate change under two [28] scenarios in analyzing the vulnerability of the infrastructure: (1) RCP 4.5, that is a medium impact scenario, with projected temperature increase ranging from 0.9–2 degrees Celsius, and sea-level rise of approximately 0.33 m in 2040; and (2) RCP 8.5, the most extreme scenario, with temperature increase ranging from 1.4–2.6 degrees Celsius, and sea-level rise of approximately 0.38 m. Two variables from the climatic projections were analyzed under these scenarios: sea-level rise and precipitation. Precipitation was estimated for the year 2040 using data from HadGem3 and Miroc5 models, obtained from ETA-CPTEC/INPE, Brazil [29,30]. The sea-level rise was estimated, also for 2040, at 0.33 m for scenario 4.5, and 0.38 m for scenario 8.5 based on data from the IPCC AR5 report [28]. These variables were incorporated in the index together with variables from other sources, in factors that included landslide, flooding, wave, coastal erosion, population density, socio-economic characteristics, and land use (Table 4). For both scenarios the 2040 climatic variables, were projected over the actual land use to provide a snapshot of the vulnerability.

Table 4. Factors, parameters and data sources for index operationalization.

Factor	Parameter	Data Source
Landslide (L)	Number of Extreme Events in the last 10 years (NEE) Geotechnical Classification of Soil (GCS) Slope (S)	ETA-CPTEC/INPE, Brazil [29,30] IPT [31] Topodata [32,33]
Flooding (F)	Number of Extreme Events in the last 10 years (NEE) Slope (S) Water Body Proximity (WBP)	ETA-CPTEC/INPE, Brazil [29,30] Topodata [32,33] IPT [31]
Wave Exp (WE)	Sea Level Rise (SLR) Relief (R) Distance of the Coast (DC)	IPCC AR5 [28] Topodata [32,33] Elaborated by authors.
Coastal Erosion (CE)	Sea Level Rise (SLR) Geomorphology (G) Tide Height (TH)	IPCC AR5 [28] IPT [31] Elaborated by authors.
Populaton Density (PD)	Population Density (DENS) Age (A)	Brazilian Census [27] Brazilian Census [27]
Socioeconomic Status (SS)	Income (I) Education Level (EL)	Brazilian Census [27] Brazilian Census [27]
Land Use (LU)	Land Use (USE)	Santos master plan *

* The Land Use map was elaborated by the Santos City council, in 2013; it is the city's current master plan.

In this study, with the exception of "land use", which was weighted higher to emphasize its role as a determinant of infrastructure location, all parameters have the same weight. The sum of the scored weights was equal to one unit.

The factors were weighted based on expert elicitation involving academics and decision-makers. The formulation of the index, for this case, is described in Equation (3):

$$\text{SEVICA} = (0.13 \times (\text{F} + \text{L} + \text{CE} + \text{WE} + \text{PD} + \text{SS}) + 0.22 \times \text{LU}) \quad (3)$$

in which,
F = Flooding;

L = Landslides;
CE = Coastal Erosion;
WE = Wave Exposition;
PD = Population Density;
SS = Socioeconomic Status;
LU = Land Use.

5. Results and Discussion

Our findings indicate that, under both IPCC scenarios, approximately 70% of the area of Santos (27.5 km^2) consist of level 4 (high vulnerability) areas. The assessment of vulnerability of Santos under IPCC scenarios RCP 4.5 and RCP 8.5 [28] is presented in the form of thematic maps (Figures 3 and 4). These highly vulnerable areas include major roads and streets, and some residential areas. They are located in low areas and/or close to urban drainage channels. Some of those residential areas, in particular, have been built over alluvial soils, which are naturally more susceptible to erosion. These areas are also associated with high levels of vulnerability based on the wave exposition factor. These are low land areas with elevation less than 1m above current sea level, and therefore subject to high sea-level rise risk.

"Very high" vulnerable areas comprise, especially under IPCC scenario RCP 8.5, approximately 0.12% of the area of Santos (0.05 km^2). These areas are associated with port and industrial (particularly oil) activities. They are nearly at sea level; located at the end of inland water drainage channels. In combination, land use, sea level, inundation and landslides) are critical factors rendering these areas maximum level of vulnerability. Considering that the results of the index are sensible to the predictions of the RCP scenarios, more critical scenarios, or realities, could lead to an increase on the vulnerability of the region. In fact, there are a lot of other scenarios that can be taken into account to evaluate the vulnerability, and that were not considered here, for the case study.

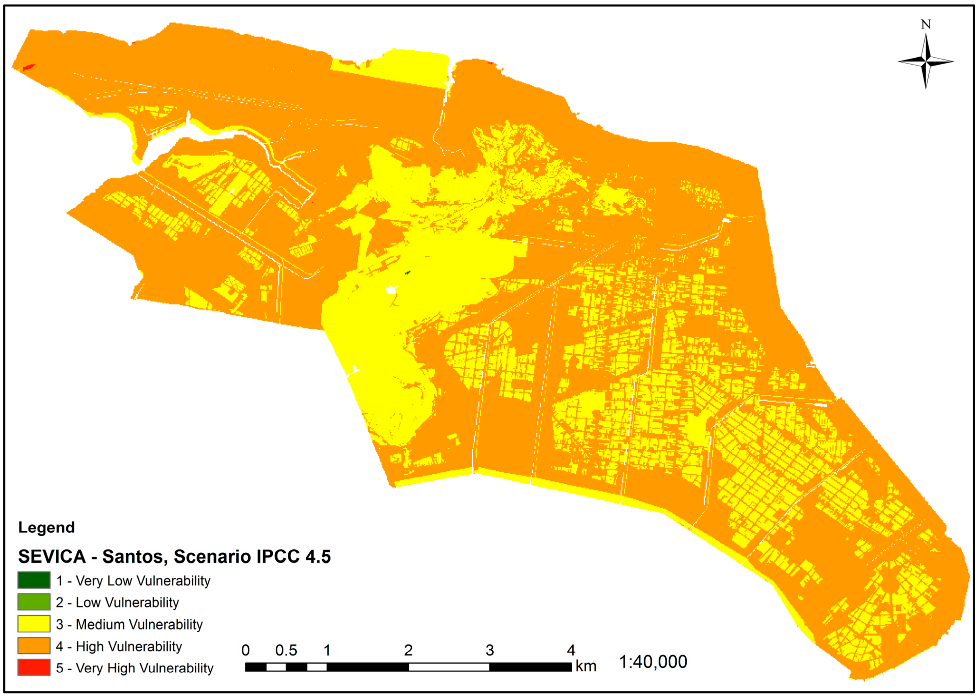

Figure 3. Vulnerability of Santos under scenario IPCC 4.5 (0.33 m sea-level rise projection) based on the SEVICA index.

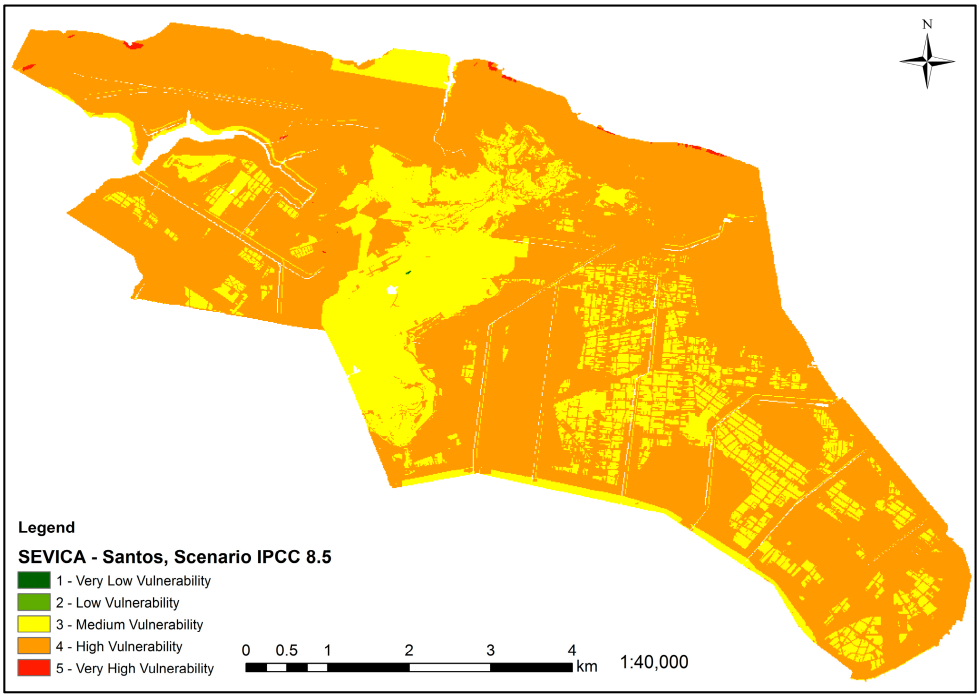

Figure 4. Vulnerability of Santos under scenario IPCC 8.5 (0.38 m sea-level rise projection) based on the SEVICA index.

These results represent the propensity of the urban area of Santos to the hazards provided by climatic changes. As a vulnerability index, the great value and originality of the SEVICA is the fact that it comprises in it the two major risks of climatic changes, extreme rainfall, and sea level rises. The proposed index is also applied to an area, not only a coastal line, and put it together in one simple map for the decision-maker to evaluate. Other indexes used worldwide, such as the ones of [2,6,7], are very effective in studying vulnerability of one hazard and many other socioeconomic and biophysical factors, but not in overlapping more than one hazard in the same place.

One of the disadvantages of SEVICA lies in the need for various input data to evaluate the vulnerability, which can limit its application to more developed countries that have a better history of collecting data. In Brazil, for example, the lack of data impacts severely on the application of the index in many other cities that could benefit from it. On the other hand, the results of the SEVICA have a great value when prioritizing actions towards a better understanding and adaptation to the climatic threat due its capability of showing which areas are more affected from these threats and, in a retro-analysis, show which hazards are more relevant to each area. For example, the landslide factor in Santos is not a major threat for the city since it is located on a mostly flat area. Meanwhile the flooding factor is a great threat, because the city is crisscrossed by fluvial channels that were projected in the 1950s and are not prepared for the augmented frequency expected from the extreme rain events in the event of the climatic changes.

Altogether, the index application is relatively easy, and its interpretation is simple, which contributes enormously to the communication of the vulnerability. SEVICA has also a great potential to improve awareness about climatic hazards on coastal areas, which makes the index a relevant contribution to the vulnerability discussion, and a viable tool of study and diagnosis for adaptation research and policy-making.

6. Conclusions

The "snapshot" provided by the SEVICA is an important step towards developing more adequate response strategies, including identifying and producing additional data and analyses. By studying vulnerabilities of urban coastal areas, at a range of sizes, local decision-makers can better plan for adaptation and, consequently, increase adaptive capacity to climate-related extreme events. In that context, this study proposed a social-environmental vulnerability index that considers multiple climate-related inland and coastal hazards. The index was tested in the city of Santos, Brazil, and revealed that most of the city's area and critical infrastructure are highly vulnerable to climate change events (e.g., flooding and sea-level rise). Our index provides a useful tool to assessing the socio-environmental vulnerability of coastal regions to climate change. Unlike other indexes, the index proposed here considers four hazards simultaneously, which allows evaluation of vulnerability to each hazard individually and/or in combination. Though the proposed SEVICA was designed with a focus on city planning, it also allows the analysis of other aspects of vulnerability.

Our findings demonstrate that Santos, like other coastal cities in the world, is highly vulnerable to climate change, particularly sea-level rise and flooding. The proposed index revealed major vulnerabilities to climatic change of critical infrastructure. This suggest that responding to a disaster would prove challenging since the emergency response facilities and services would also be affected. In addition, the growth of the city has been driven mostly by economic interests, without proper consideration of natural hazards. Such information is very timely considering that the city of Santos is currently discussing a new urban master plan and it has yet to incorporate climate change vulnerability in the local agenda.

Vulnerability assessment is a diagnose step of adaptation planning and studies, so indexes like SEVICA are highly recommended to be developed and tested worldwide in similar regions and results and appointments compared to generate a more robust collection of data on how vulnerability studies can help prioritize actions toward an adapted coastal settlement, and adapted communities to climate changes challenges.

It is in our team's objective to study the application of SEVICA to other major Brazilian cities, such as Rio de Janeiro, Salvador, Recife, and Fortaleza, and future studies will be developed in similar coastal areas in other regions of the world. Although our index produced useful information for city planning, other specialized studies would allow for better planning decisions. Further research would benefit, for example, from a risk analysis that could complement our study by demonstrating probabilistic climate-related risks. Additional studies that include stakeholders in the process of weighting the indicators, and evaluation of the results are also suggested. For example, a dissemination workshop held with Santos city council staff as part of this research proved insightful and demonstrated the applied nature of the index.

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