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Vulnerability assessment of Massaguaçú Beach (SE Brazil)

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ABSTRACT

With the aim of summarizing several coastal indicators in one index, this paper proposes a vulnerability index to coastal erosion. This index synthesizes coastal and inland indicators quantitatively, becoming a useful tool for coastal planning and better management of coastal resources. The index is composed of coastal variables: beach morphology, shoreline position, dune field configuration, wave exposure and presence of rivers and/or inlets; and inland variables: terrain elevation, vegetation, coastal engineering structures, occupation percentile and soil permeability. In order to validate the proposed method, it was applied to Massaguaçú Beach (SP) in the Southeast of Brazil. According to its characteristics, the beach was divided into three sectors from south to north. Sectors 1 and 3 are classified as being of moderate vulnerability, both with index 5, while sector 2 is classified as high vulnerability, with index 7.5.

1. Introduction

The intense pressure on coastal environments makes them vulnerable to changes, being coastal erosion one fundamental aspect in reshaping the coast. In the last decades coastal zones have been intensely occupied, and with the increased value of real estate, infrastructure and buildings (Pilkey and Cooper, 2004), these regions are more populated than continental interiors (Small et al., 2000). If sea-level rise projections for the next decades are confirmed (e.g. IPCC, 2007; Rahmstorf, 2007), coastal flooding and erosion will cause unprecedented socioeconomic damages. Sea-level rise will certainly exacerbate the already intense coastal erosion experienced by many beaches worldwide.

The concept of vulnerability approaches susceptibility to harm, exposure, coping capacity (Birkmann, 2007) and physical and social systems (Mahendra et al., 2011). Due to differences in approach, it is always a challenge to integrate physical and socioeconomic sciences (McFadden, 2007). Nevertheless, it is still an interesting method for coastal zone management, urban planning and sustainable decision-making. Analyzing the vulnerability of coasts to erosive processes is paramount to the urban planning of coastal cities and a valuable method to minimize socioeconomic impacts caused by natural disasters (Sousa et al., 2008).

Several methods to evaluate the vulnerability of coastal zones to different hazards such as sea-level rise (Gornitz et al., 1994; Pendleton et al., 2010), cliff erosion (Nunes et al., 2009; Del Río and Gracia, 2009), coastal erosion (Bush et al., 1999) and storms (Bosom and Jiménez, 2011) have been developed for different regions and scales.

This work proposes an index that encompasses ten indicators divided in coastal and inland variables. The definition and selection of indicators is not a trivial task. Data acquisition is expensive and limited both in spatial and time scales. In addition, coasts present innumerous physical processes with complex interactions at different scales, varying from micro (e.g.: swash processes) to macro (sea-level variations) agents. However, previous studies highlight several reliable indicators and proxies that can likely promote coastal erosion, such as those proposed by Bush et al. (1999). The proposed method is applied at a study case in which we assess the vulnerability to coastal erosion at Massagaçú beach, Brazil. There are only a few and recent studies on the site and there is no long-term information on waves, beach morphology, etc. Therefore, the general indicators used in the present evaluation are based on Bush et al. (1999).

Massaguaçú Beach (Caraguatatuba) lies in the northern coast of the São Paulo State, Southeast of Brazil (Fig. 1). The region is close to the Tropic of Capricorn, the climate is tropical-humid, without dry seasons (Köppen, 1948) and average rainfall between 1500 and 2000 mm yr^{-1}. The vegetation is high and dense, characterized by Mata Atlântica biome. The municipal area of Caraguatatuba is of 484 km^2. In 1991, the population was of 52,878 in 2010 it was of 99,540 inhabitants, almost doubling in 19 years (IBGE, 2010).

Tides in the region are micro-tidal with maximum range of 1.2 m. Massaguaçú is a reflective beach with narrow/inexistent surf-zone, strongly dynamic with continuously evolving beach

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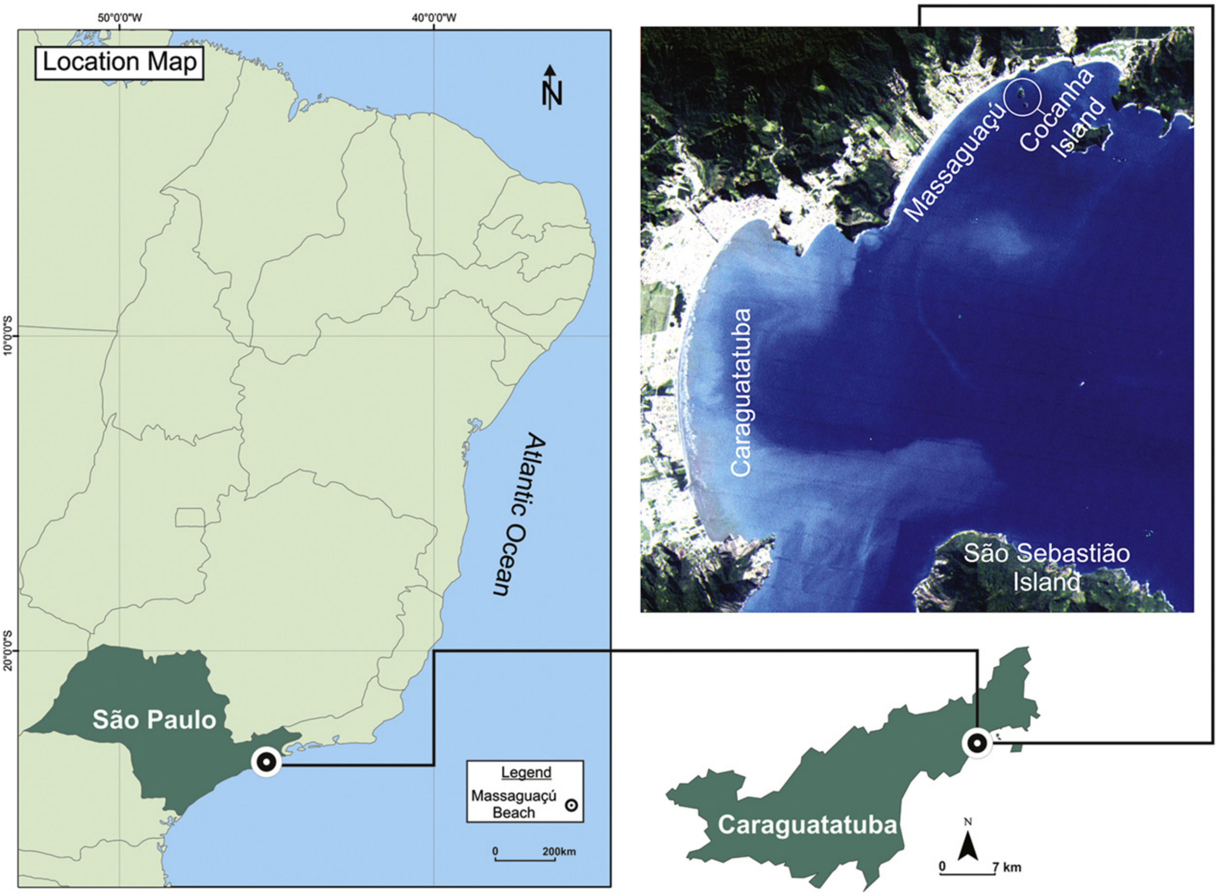


Fig. 1. Location of the study site. In the image, Caraguatatuba Bay in the southwest and São Sebastião Island in the south (Landsat 7).

cusps. The main wave incidence direction is from E-SE in spring and summer and from S and SW during winter and fall, conditioned by stormy conditions (Pianca et al., 2010). Strong winds associated to the cold fronts advancing northwards are associated to the most energetic waves from south. In winter conditions, waves with heights between 2 and 3 m are predominant, but offshore wave heights of up to 6 m can also be observed.

The Massaguaçú bay is 7.5 km long with average profile extension of about 60 m in the southern and northern part and 50 m in its central area. Based on some local characteristics, the beach has been divided in three sectors. Sector 1 (south) is an area with only recent occupation. Sector 2 (central) concentrates the urban settlement and presents a road (Rio-Santos road) running parallel to the shoreline and close to the beach along this entire sector. Sector 3 (north), confined by a narrow coastal plain, presents parts of the Serra do Mar Mountain causing the road to be diverged inland and limiting the occupation.

Nuber (2008) describes sediments in Massaguaçú as being composed by medium to coarse sands, moderately selected without biodetritic carbonate content. It is possible to observe slight longshore variations in sediment size, decreasing in size gradually from south to north.

The synthesis of coastal and inland indicators into an index provides subsidies for coastal planning as an important tool to better manage coastal natural and socioeconomic resources. The proposed index is also a way to quantify coastal changes in different periods, e.g.: before and after any intervention like beach enlargement and nourishment, implantation of coastal protection constructions or even the development of urban structures near the beach.

2. Material and methods

Details about the indicators and the proposed index calculation will be given in this section. The indicators are introduced with special attention to the occupation percentile, which was calculated with the use of ArcGIS 9.3 software. Although having the same importance as the other indicators, its formulation is explained in more details, followed by the description of the index calculation.

2.1. Indicators

In order to avoid or minimize the impacts of coastal erosion on the beach, Bush et al. (1999) presented a simple and rapid assessment method based on environmental indicators or geoindicators. Table 1 presents in three main columns the Index, the two variables and the ten indicators. This paper uses the indicators presented in Sousa et al. (2011) to assess the coastal vulnerability to erosive processes. This method approaches a considerable number of natural and anthropic indicators organized in order to encompass the most significant agents that act on the coast. Such indicators include coastal (beach morphology, shoreline position, dune field configuration, wave exposure and presence of rivers and/or inlets) and inland (terrain elevation, vegetation, coastal engineering structures, occupation percentile and soil permeability) variables, used to build the index. A brief description of each indicator is presented below:

Beach morphology is of prime importance for the acting coastal dynamic processes of a coastline (Krause, 2004). However, in case of absence of long-term morphological data, GIS tools can be used to evaluate the coastline evolution or the shoreline position. In

Table 1
Indicators used to vulnerability assessment of Massaguaçú. Adapted from Sousa et al. (2011).

	Variables	Indicators	Low	Moderate	High
Index	Coastal	Beach morphology	Good sand supply and robust beach morphology	Potential interruption of sediment supply and moderate to narrow beach profile	Narrow beach with sediment supply interrupted or compromised
		Shoreline position	Advance	Stable	Retreat
		Dune field configuration	Presence of extensive and high dune field	Presence of sparse and short dunes	Absence of dunes
		Wave exposure	Presence of natural barriers (islands, reefs or beachrocks)	Presence of offshore sandbars reducing the wave energy	Wide fetch with no natural obstacles minimizing wave energy
		Presence of rivers and/or inlets	>100 m	Between 50 and 100 m	<50 m
	Inland	Terrain elevation	>6 m	3–6 m	<3 m
		Vegetation	Dense with mature forest and no erosive evidences	Well established with grass and bushes	Little or no vegetation
		Coastal engineering structures	Absence of coastal structures	Small or few significant structures	Presence of seawalls, groins, breakwaters, jetties, etc.
		Occupation percentile	<30%	Between 30 and 70%	>70%
		Soil permeability	Permeable with little or no occupation	Moderate permeability due to occupation/urbanization	Permeability seriously affected with presence of urban settlement well developed

wave-dominated beaches, changes on coastal processes (incident waves), climatic characteristics (storms or hurricanes) and anthropic activities (e.g.: occupation) may cause alterations on sediment budget and consequently on beach morphology and shoreline position.

Dune fields act as natural barriers that protect the coastal zone from waves and storm surges. They are also important for the sediment budget, being a sediment source to the adjacent beaches.

The ***wave exposure*** parameter is defined by the degree of exposure or protection of the coastline to the incident waves, related mainly to the presence/absence of obstacles that provide shelter to the coastline (e.g.: islands, beachrocks or sandbanks).

Rivers or inlets are very dynamic features and their impact on the coast is related to the interaction of stabilizing and destabilizing factors. Unstable inlets can migrate several meters during the year or present an intermittent opening, causing abrupt coastline changes and be the cause of flooding in the adjacent hinterland. Both situations can cause socioeconomic damages to the adjacent communities. The small drainage basin rivers that reach the ocean in Massaguaçú present very unstable inlets with intermittent behavior. Therefore, this indicator considers only a small 100 m influence distance around the inlets.

Terrain elevation relates to inundations, overwash and sea-level rise, with its susceptibility being directly related to low elevations. The state in which the ***coastal vegetation*** is can also be an efficient erosion indicator. Exposed roots and inclined or chopped down trees indicate the loss of land.

Coastal engineering structures to contain coastal erosion are built in order to minimize its impacts. These are usually emergency solutions that may cause large negative impacts on the coastline. Although they may provide local short-term protection, they represent areas of instability that may keep unstable in the future (Bush et al., 1999). In Massaguaçú, a seawall was built along part of the central sector of the beach, reason for which this indicator is considered an inland variable.

The ***occupation*** can cause several damages to coasts like the intensification of erosive processes and changes to the overall sediment budget (Sousa et al., 2011) and contribute to relative sea-level rise (e.g.: through coastal subsidence). This indicator will be discussed in more details in a separate topic and is strongly related to soil permeability.

2.1.1. Occupation percentile

As mentioned previously, three sectors have been defined according to its natural and occupation characteristics. The sectors extend 500 m landwards from the waterline and have varying lengths. Sector 1 has an area of 1.8 km^2, while sectors 2 and 3 present an area of about 1.4 km^2, each. In the coastal zone of Massaguaçú, the most significant land use forms are edifications (blocks with houses and small buildings) and roads. The occupied area (A_o) is the sum of all the urban variables (Eq. (1)).

$$A_o = A_b + A_r + \ldots + A_n \tag{1}$$

Where A_b is the edifications area; A_r is the roads area and A_n is the n-th variable. The occupation percentile (P_o) (Eq. (2)) is:

$$P_o = \frac{A_o \times 100}{A_u} \tag{2}$$

Where A_u corresponds to the total area of each sector. Low percentages (<30%) indicate low vulnerability and high percentages (>70%) indicate high vulnerability, while intermediate values indicate moderate vulnerability.

2.2. Index

Although coastal landscapes are the result of the integrated action of coastal processes that may be influenced by anthropogenic agents, here we consider each indicator separately. Each indicator has been assessed taking into account its own role on beach protection.

The first step is to analyze the beach in detail in order to classify it according to its vulnerability to coastal erosion (low, moderate or high) considering the indicators presented in Table 1. A value is attributed to each variable: 0 for low, 5 for moderate and 10 for high vulnerability; and organized in spreadsheets that feed the database.

Outcomes from the indicators build the coastal vulnerability index (I) to erosive processes. The index is a synthesis of the indicators and variables (Table 1) given by a number ranging from 0 to 2.9 (low vulnerability), 3–6.9 (moderate vulnerability) to 7–10 (high vulnerability). Thereby the analysis is conducted on the three pre-defined beach sectors (Fig. 2) according to Eq. (3).

$$I = \left(\frac{1}{n_v}\right) \cdot \sum_v \left(\frac{1}{n_i}\right) \cdot \sum_i x_i \tag{3}$$

Where n_v is the number of variables, n_i is the number of indicators of a determined variable and x_i is the sum of the indicators. Summarizing, the variables are the arithmetic average of the

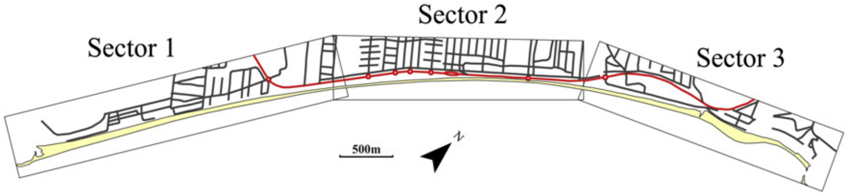


Fig. 2. Indication of the three selected sectors.

indicators, and *I* is the arithmetic mean of the variables. The advantage of this index is the possibility to work at different scales based on the area of interest.

3. Results

To better describe and understand the coastal vulnerability to erosive processes, results for each sector are presented separately below.

3.1. Sector 1

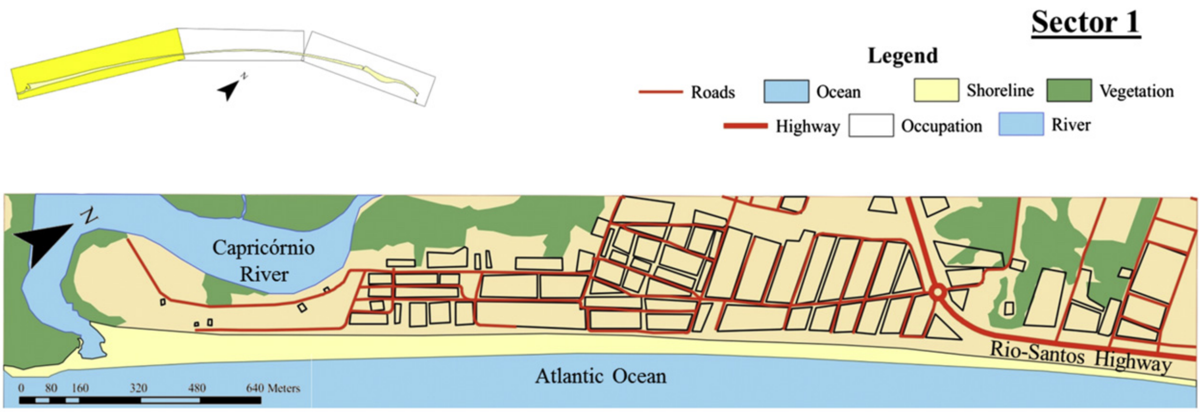
The index for this sector is 5.5. Classified as being of moderate vulnerability (Fig. 3), the beach morphology has a profile wider in the South (90 m) and narrower toward the North (34 m) with an average of 62 m. Nuber (2008) observed that the beach presents erosional and accretional events, but has been accreting during the last decades.

The Capricórnio river inlet is closed most of the time and channel flows have no competence to remove the sand that block the channel (Fig. 4). The opening of the channel occurs only during high wave energy events, when a storm surge results in sand barrier overwash, creating a connecting channel that lasts for short periods only. Channel flows during the openings are not able to balance wave energy, resulting in channel closure shortly after the storms. There is also no indication of inlet migration during these short openings; the inlet is anchored by a rocky headland to the south and the adjacent river banks are well established and fixed by vegetation.

There are no natural obstacles such as dunes or submerged features to absorb the wave attack on the coast in this sector. Even the São Sebastião Island (Fig. 1) does not provide enough cover for the action of waves that reach the beach with great intensity.

The occupation in the region is recent and conducted without proper planning along the narrow non-paved streets holding mainly holiday homes. Occupation percentile is the lowest with 24.2%. Being an area of recent occupation, there is a strong tendency for real estate speculation, especially toward the river banks. This sector is less accessible for beach goers when compared to the other sectors adjacent to the Rio-Santos highway.

The terrain presents elevations of up to 5 m that decrease closer to the river banks. The dominant vegetation is the high and dense Mata Atlântica Forest, preserved only near the river mostly because of the landform. The soil permeability is not strongly affected by



Coastal Variables	
Beach profile	Potential interruption of sediment supply and moderate to narrow beach profile
Shoreline position	Progradation
Dune field configuration	Absence of dunes
Offshore settings	No obstacles
Presence of rivers and/or inlets	< 50m

Urban Variables	
Terrain elevation	3 – 6 m
Vegetation	Well established with grass and bushes
Coastal engineering structures	Absence of coastal structures
Occupation rate	< 30%
Soil permeability	Moderate permeability due to occupation/urbanization

Fig. 3. Map of Sector 1 and its classification according to coastal and inland variables.

Fig. 4. The closed Capricórnio river inlet.

occupation, with the exception of the denser urban settlement areas in the northern part of this sector.

3.2. *Sector 2*

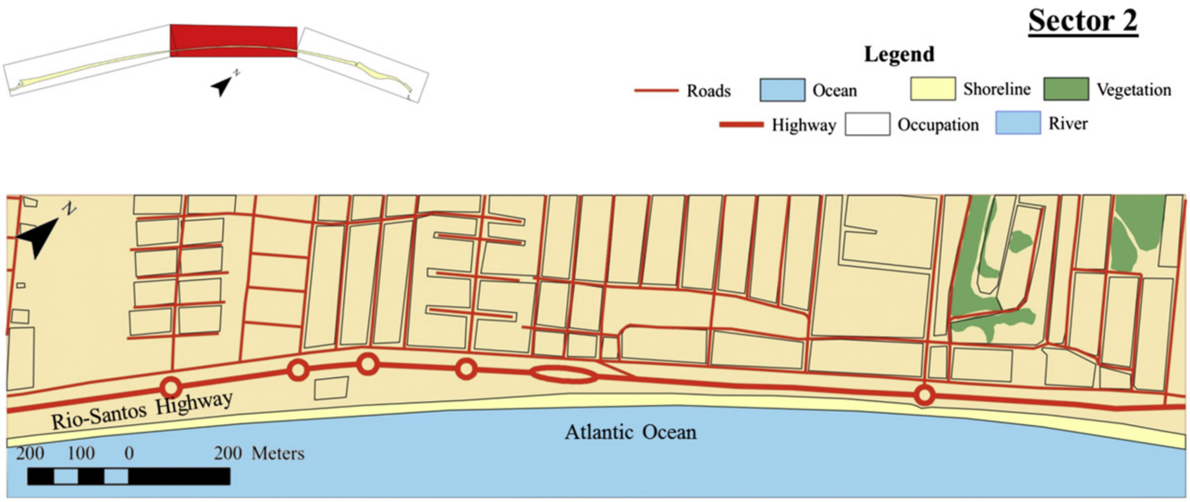
The central part of Massaguaçú Beach (Sector 2) presents high vulnerability with an index of 7.5. The 2.5 km long shoreline is the most impacted area in Massaguaçú Beach (Fig. 5). This sector comprises the concentration of the urban settlements with residences, hotels and small buildings erected at a 5 m high terrain. The erosive signals are clear and the shoreline has been retreating about 1.5 m year^{-1} (Nuber, 2008). The occupation percentile is of 48.5%.

Another singularity of this sector is the presence of the Rio-Santos highway that runs close and parallel to the shoreline. Under stormy conditions the waves undermine the road basis affecting the highway. Such periods are critical, since the absence of sandbars allows waves to reach the shore with high energy levels. Aiming the protection of the road, coastal engineering structures were built along part of Sector 2 (Fig. 6). However, this seawall proved not to be effective since the waves rapidly caused its destruction and still reach and damage the road. The beach morphology presents a narrow profile, with an average width of about 50 m, including stretches with less than 10 m. There are no rivers/inlets reaching the region and no direct sediment sources available in this sector. Vegetation is scarce, representing only 0.4% of the studied perimeter. Although the area is densely occupied, with the exception of the highway, streets are not paved.

The analysis of this sector shows clearly that the type of occupation, with the road close and parallel to the shoreline, combined with the absence of a natural sediment source affects the sediment balance resulting in economic damages.

3.3. *Sector 3*

Sector 3, in the northern part of Massaguaçú, presents some similarities with sector 1, like the extensive beach morphology and the presence of a river inlet (Fig. 7). The index in this sector is 5, classifying the beach as being of moderate vulnerability. The Bracuí river, a small river artificially diverged from its natural course reaches the ocean in the middle of this sector. Longshore transport overcomes channel flows causing inlet closure. In order to keep the drainage and to avoid the flooding and damages to the low-lying hinterland areas, it is being artificially opened at a daily basis. The daily opening of the channel releases the dammed water, but as



Coastal Variables

Beach profile	Narrow beach with sediment supply interrupted or compromised
Shoreline position	Retrogradation
Dune field configuration	Absence of dunes
Offshore settings	No obstacles
Presence of rivers and/or inlets	> 100m

Urban Variables

Terrain elevation	<3 m
Vegetation	Little or no vegetation
Coastal engineering structures	Presence of coastal structures
Occupation rate	Between 30 – 70%
Soil permeability	Moderate permeability due to occupation/urbanization

Fig. 5. Map of Sector 2 and its classification according to coastal and inland variables.

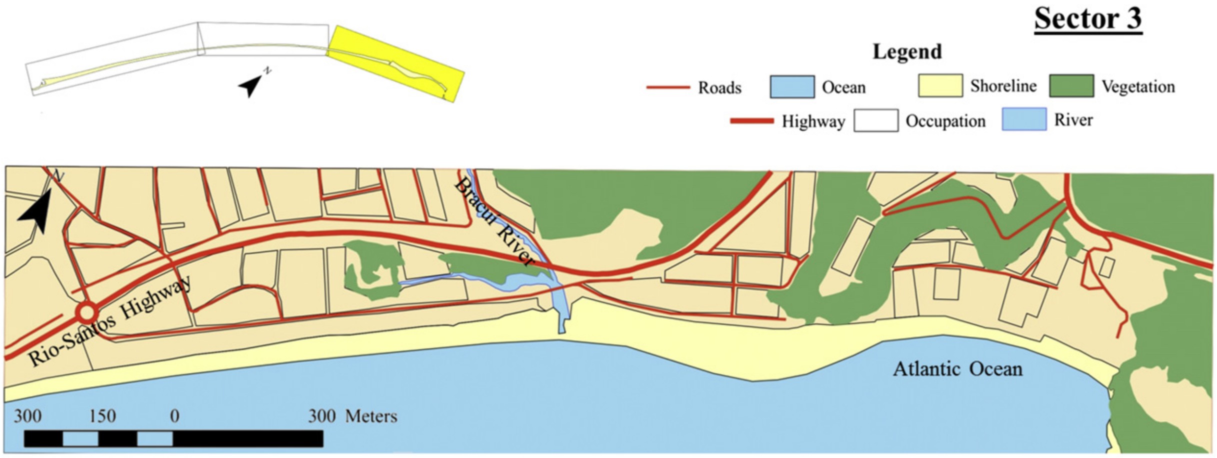
Fig. 6. Coastal engineering structures in Sector 2 (2006).

soon as the lowering pressure gradients reduce flow velocities, longshore transport causes the inlet closure. The occupation in this sector is of 36.4%. The small percentile of occupation is due to the raised and irregular terrain associated to the proximity of the Serra do Mar Mountains, which also cause the road to be diverged inland in this region. The terrain elevation ranges from 5 m at the coastal plain to approximately 20 m close to the road in the northern part of this sector.

The beach morphology, characterized by beach profiles, has been accreting at a rate of about 3.5 m year^{-1} (Nuber, 2008), presenting average extension of about 59 m, with stretches of up to 149 m in the shadow area of the Cocanha Island (Fig. 1), visible as a protuberance in the coastline. The island is approximately 500 m from the beach with an area of about 5300 m^2. The relative shelter provided by the island makes this area an attractive destination for many beach goers. The sheltering effect of the island is considered to be only partial for this sector, since there are no other obstacles for the incoming waves, leaving mainly the southern part of this sector exposed to direct wave action. There are neither dunes nor coastal engineering structures in this sector and the soil permeability is not compromised by the occupation when compared to the other sectors.

4. Discussion and conclusions

The scales involved in studies of coastal vulnerability are of prime importance when defining the best approach to understand a specific region. Delimiting the area of interest will relate directly to the scale and accuracy of the assessment. Vulnerability assessments are important tools for coastal management and decision-making, however, depending on the scale, methods can ignore important details related to this type of approach, like differences in landscape and land use/human intervention. Compared to similar methods (e.g. Dal Cin and Simeoni, 1994; Thieler and Hammar-Klose, 1999; Gornitz et al., 1994; Kumar et al., 2010), the present application presents a simple method that can be robustly applied at different scales, and at areas scarce in long-term data. Therefore, trying to reduce errors caused by the subjectivity in weighting indicators (Villa and McLeod, 2002), all indicators are considered to have the same weight on the definition of the overall index. Trying to provide a simple method that can be applied to areas without much background information is the reason to use arithmetic mean instead of weighted mean for defining the index. Its application can help in defining the land use at different sectors of a given coastal area. Nevertheless, we suggest to increase the complexity level of the estimates by including other indicators



Coastal Variables	
Beach profile	Potential interruption of sediment supply and moderate to narrow beach profile
Shoreline position	Progradation
Dune field configuration	Absence of dunes
Offshore settings	Presence of a island
Presence of rivers and/or inlets	< 50m

Urban Variables	
Terrain elevation	3 – 6 m
Vegetation	Well established with grass and bushes
Coastal engineering structures	Absence of coastal structures
Occupation rate	Between 30 – 70%
Soil permeability	Moderate permeability due to occupation/urbanization

Fig. 7. Map of Sector 3 and its classification according to coastal and inland variables.

(related to waves, sediment transport, numerical modeling and socioeconomic data) and to assign different weights for the indicators, when possible.

In the specific application to Massaguaçú Beach, the indicators chosen represent general parameters for vulnerability assessment of such environments. In a range from 0 to 10, results have shown vulnerability between 5 and 8. The remote sensing analysis showed that the sector 2 has been eroding along the last decades, whilst sectors 1 and 3 have been accreting. The lack of sediment sources in Massaguaçú added to the erosion in the center and the progradation in the North and South of the arc may be an indication of a divergent sediment transport pattern from the central part to both north and south edges of the bay.

Cooper and Mclaughlin (1998) stated that the reliability of statistical methods is obtained with the comparison of its results with field measurements. The site has no monitoring before 2006 and only little quantitative information about the region is available. Methods of previous work include the GIS analysis and the one-year monitoring carried out by Nuber (2008). These results, although collected over a limited period of time, are coherent with those reached through the present work. Coherence between the index results and observations is also seen when looking at historical series of inundations caused by the Bracuí river and the recent partial destruction of the Rio-Santos highway and private properties located close to the beach.

Despite the limitation related to available historical data and other specific information, the indicators used in this paper are useful to provide background information for further analyses. The index was applied on a beach with just 7.5 km of extension, nevertheless, this index should give better results if applied to larger areas with tens or hundreds of kilometers. It can be used as first evaluator at large areas with no or little information in order to select specific spots potentially vulnerable to coastal erosion.

The capability of analyzing the indicators individually and aggregating them in one number is a useful tool for coastal management both for small and large areas. Furthermore, the advantage in working with different scales is paramount for the understanding of the vulnerability in its most significant limitations.

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