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Vulnerability to beach erosion based on a coastal processes approach

Talia Santos de Andrade[a], Paulo Henrique Gomes de Oliveira Sousa[b], Eduardo Siegle[a,*]

[a] Instituto Oceanográfico, Universidade de São Paulo, Praça do Oceanográfico, 191, 05508-120, São Paulo, SP, Brazil
[b] Universidade da Integração Internacional da Lusofonia Afro-Brasileira, Avenida da Abolição, 3, 62790000, Redenção, CE, Brazil

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ABSTRACT

Erosive processes on coasts cause several socioeconomic and environmental losses. Understanding the vulnerability to erosion is fundamental to deal with its consequences. We assess the beach vulnerability to erosion based on environmental indicators. The study area for the present application is in Guarujá, a coastal zone of the state of São Paulo, where the vulnerability of six beaches was evaluated. The indicators used for the vulnerability assessment are: terrain elevation, wave exposure, power and angle of wave incidence and wave run-up. Regarding the wave climate of the region, the most frequent waves are those of the southern, eastern and southeastern quadrants. Significant wave heights are more frequent in the range of 1.0–1.5 m, and the most frequent wave periods are between 8 and 10 s. Perequê, Enseada, Asturias and Pernambuco beaches present low vulnerability and the Pitangueiras and Mar Casado beaches present moderate vulnerability. The study provides an interesting perspective for the management of coastal resources in the Guarujá region and similar coastal areas. In addition, although the analyzed beaches presented low and moderate vulnerability, processes such as climate change or inadequate interventions on adjacent beaches may negatively influence the studied region.

1. Introduction

The coastal zone is an environment of high dynamic complexity that is important in the environmental, socioeconomic and cultural contexts. On the southeastern coast of Brazil, the beach environment was the center of *caiçara*[1] life and the point of articulation with the outside world (Diegues, 1988). Over time, the use and occupation of the coastal zone did not consider the preservation and maintenance of the available resources, and this inadequate management resulted in environmental degradation as well as changes in beach morphology and sedimentary balance (Sousa, 2013).

The coastal environment is very dynamic and morphodynamic changes occur at varied time scales from short to long term. Due to the different spatial and temporal scales in which the processes that condition the existence and evolution of beaches operate, it is difficult to quantify them (Alexandrakis & Poulos, 2014). The evolution of beaches depends on several processes and factors such as sediment availability, storms that cause long-term changes, the energy of the wave climate, the complex interactions between continental and oceanic sedimentary bodies, sea level rise, the geological configuration of the coastal zone and the human intervention on the territory (Alexandrakis & Poulos, 2014; Pranzini, 2004). The morphodynamics and hydrodynamics that model coastal systems generate continuous sediment flows that change over time as a function of the intensity of these processes. The variation between sediment input and output in this system is called sediment budget (Pranzini, 2004; Woodroffe, 2002). When the sediment budget is positive, the beach receives more sediment than it loses. When the sediment budget is negative and the beach loses more sediment than it receives, coastal erosion occurs.

Coastal erosion has natural and/or anthropogenic causes, occurs globally (Bird, 2008), and it is estimated that over 70% of the global coast is currently in the process of erosion (Davis & Fitzgerald, 2004). Therefore, it is important to know the causes and impacts of this process. The main causes are sea level rise, storm intensification, soil subsidence, disorderly occupation, sand extraction for construction, and dams (Nicholls & Cazenave, 2010). Consequently, there may be beach width reduction and coastline retrogradation, loss of fishing resources, potential impaired tourism in the region, loss of public and private property and assets along the coast, loss of socioeconomic activities in the region, landscape value loss of the beach and the coastal region, etc. (Souza, 2009). When natural processes affect or threaten human activities or infrastructures, it becomes an environmental problem. To prevent the impacts of economic, social and cultural losses, coastal managers need to know the vulnerability of the region through

* Corresponding author.
E-mail address: esiegle@usp.br (E. Siegle).

[1] Traditional inhabitants of the Southeastern and Southern coast of Brazil.

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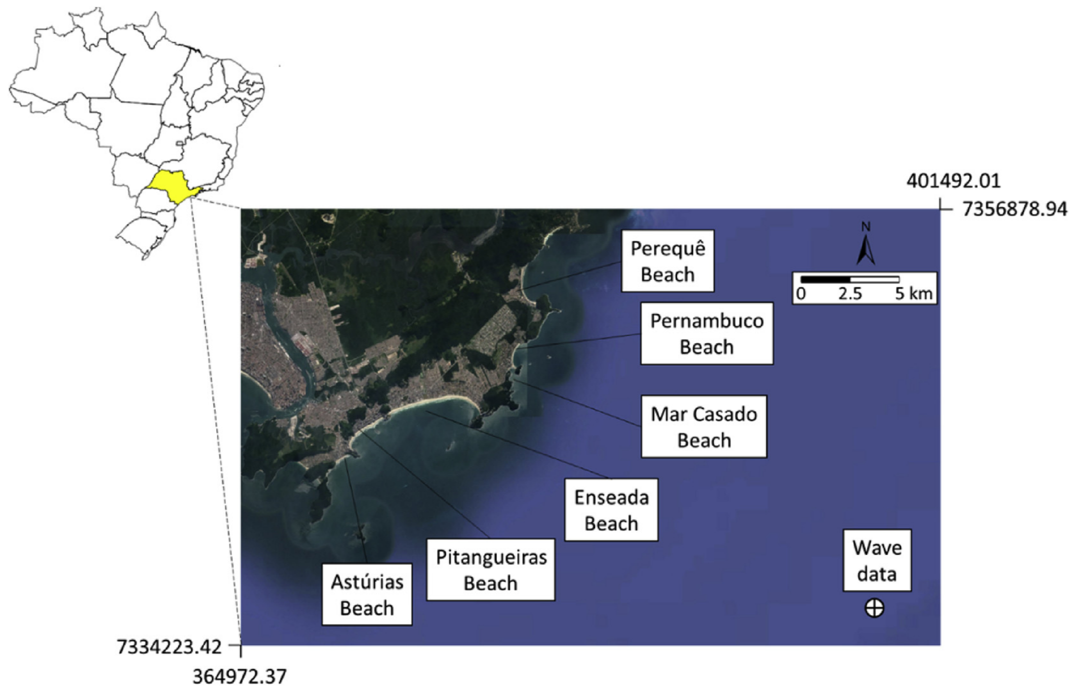

Fig. 1. Map of the study area in southeast Brazil highlighting the six analyzed beaches (Asturias Beach, Pitangueiras Beach, Enseada Beach, Mar Casado, Pernambuco Beach and Perequê Beach). Image: Google Earth.

physical processes of the coastal zone (Rangel-Buitrago & Anfuso, 2009).

The vulnerability of a coastal system to a particular phenomenon can be defined as the potential of a given area to be harmed by the impact of this phenomenon, and it is quantified by comparing the intensity of the impact with the adaptability of the system (Gouldby and Samuels, 2005; Bosom & Jiménez, 2011). The vulnerability to coastal erosion represents a set of variables that characterize greater fragility to the incidence of a phenomenon/event of high energy or destructive potential; in this case, erosion (Mazzer, Dillenburg, & Souza, 2008). Studies were conducted using different methods to address coastal vulnerability in relation to different hazards as follows: sea level rise, coastal flooding, high-energy events such as storms, coastal and beach erosion, and the effects of climate change (Abuodha & Woodroffe, 2006; Alexandrakis & Poulos, 2014; Bosom & Jiménez, 2011; Coelho, D'albuquerque, & Veloso-Gomes, 2006; Kumar et al., 2010; Mazzer et al., 2008; Merlotto, Bértola, & Piccolo, 2013; Narra, Coelho, & Sancho, 2015; Parthasarathy & Natesan, 2015; Perini, Calabrese, Salerno, Ciavola, & Armaroli, 2016; Rangel-Buitrago & Anfuso, 2009; Ribeiro, 2014; Silva et al., 2013; Sousa, 2013).

The estimation of coastal zone vulnerability has received considerable attention, and there is a vast literature in this field using different methodologies. Considering such methods, some classic studies such as Gornitz, Daniels, White, and Birdwell (1994) and Thieler and Hammar-Klose (1999) adopt risk variables, such as geomorphology, shoreline erosion and accretion rates, coastal slope, rate of relative sea-level rise, mean tidal range, and mean wave height to compose a coastal vulnerability index for the U.S. coast.

Sousa, Siegle, and Tessler (2013) proposed and index to evaluate coastal erosion based on the following indicators: beach morphology, shoreline position, dune field configuration, wave exposure, presence of rivers and/or inlets, terrain elevation, vegetation, coastal engineering structures, occupation percentile and soil permeability. It is a simple evaluation indicated for places with little or no previous data available. Furtherly, a method of vulnerability estimation associated with storms has been developed by Alexandrakis and Poulos (2014). The authors present a beach vulnerability index that considers long-shore and cross-shore sediment transport, sea-level change, landform erosion, riverine sediment influx, wave run-up and aeolian transport. In this work, we adopted some indicators from Sousa et al. (2013) and Alexandrakis and Poulos (2014).

The importance of such evaluation lays on 1) the lack of studies for the region, the 2) lack of a long-term database or monitoring data 3) the need of developing novel and low-cost technologies to understand the beach vulnerability and 4) providing information for coastal managers and decision makers to cope with beach problems in the region.

Through the vulnerability assessment of beach erosion, it is possible to identify, quantify and classify regions with different vulnerabilities, since these studies are important contributions to the management and planning of coastal environments in the natural and urban spheres. Thus, the aim of this study is to evaluate the vulnerability to beach erosion on an urban cell in Guarujá, São Paulo, Brazil focusing on features of the beaches, coastal processes and landscapes elements.

1.1. Study area

The study area is located in the municipality of Guarujá, which is part of the Baixada Santista Metropolitan Region, in the central portion of São Paulo State coast. The Baixada Santista area is the most populous on the coast of São Paulo with around 1.8 million permanent residents in 2015 according to the SEADE Foundation. During the tourist season, this number triples, and the region can have up to 5 million people according to the Metropolitan Agency of Baixada Santista (AGEM). The presence of the largest port in Latin America combined with the growing population related to tourism, nautical activities and oil and gas exploration cause considerable modifications to the coast that severely impact the beach environment (Mahiques et al., 2016). The municipality of Guarujá had a population of 210,207 inhabitants in 1991, and in 2010, this number increased to 290,752; an increase of 80,545 inhabitants over 19 years (IBGE, 2018).

The coast of the São Paulo State has around 430 km of sandy oceanic beaches with varying features along the coast. The Baixada Santista, in the central portion of the São Paulo coast, marks the beginning of the transition between the northern scarps coast and the southern coastal plains and estuaries coast (Mahiques et al., 2016). The beaches of interest are located in the municipality of Guarujá, Santos' coastal plain, in a system of coastal plain and isolated mountains landforms, with altitudes between 100 and 300 m (Moura, 2011). The beach systems adjacent to these plains present a highly variable morphology, separated by headlands that result in longshore transport segmentation between the different sectors, and strongly related to seasonal wave incidence (Souza 1997; Mascagni et al., 2018).

Guarujá is located on the island of Santo Amaro on the coast of the state of São Paulo between the coordinates 24º00′S, 46º19′48″W and 23º54′36″S, 46º08′58″W with 22.31 km of beaches (Fig. 1). Santo Amaro Island is part of Santos' estuarine system. It is separated from the mainland by the Bertioga Channel and the Santos Estuary. It is bordered to the north by the municipality of Bertioga, to the south and east by the Atlantic Ocean and to the west by São Vicente Island.

Climate in the region presents alternated domain of the two Tropical and Atlantic Polar systems, with tropical hot and humid weather, undefined dry season and annual average temperature above 22 °C. The annual rainfalls are higher than 2000 mm, with spatial and temporal variability, but concentrated in the summer (Santos, 1965).

Tidal regime of São Paulo coast is micro-tidal, with amplitude lower than 1.5 m, semi-diurnal with little influence on currents along the coast. It is a wave dominated coast. The same occurs on the ocean face of Santo Amaro island, where tidal currents are weak and effects of wave and currents generated by waves are more significant (Harari, Camargo, & Cacciari, 2000). Waves that reach the region are more energetic during autumn and winter months, when they approach from the southern quadrant with significant heights of 2–3 m (with peaks of 4.5 m) and periods of 10–12 s (Pianca, Mazzini, & Siegle, 2010).

The six beaches included in this study are Asturias Beach, Pitangueiras Beach, Enseada Beach, Mar Casado, Pernambuco Beach and Perequê Beach; extending for approximately 12.7 km. According to Souza (2012) and data obtained on the website of the City of Guarujá, Asturias Beach has a N-W orientation, a length of 0.88 km, fine and very well sorted sand, an average slope of 2° and characteristic sedimentary features of longitudinal sandbars and a flat profile. Pitangueiras Beach has a N-E orientation, a length of 1.8 km, an average slope of 2°, fine and very well sorted sand and characteristic sedimentary features of longitudinal sandbars and a flat profile. These two beaches are very urbanized and feature tall buildings on the waterfront. Enseada Beach is oriented N-E with a length of 5.6 km, making it the largest beach in Guarujá. It has an average slope of 2°, fine and very fine, very well sorted sand and characteristic sedimentary features of longitudinal sandbars and a flat profile. Mar Casado and Pernambuco Beach have a N-E orientation, a length of 2 km, an average slope of 2°, fine and very fine sand, moderately sorted and very well sorted and characteristic features of cusps and a flat profile. Finally, Perequê Beach has a N-S orientation, a length of 2.4 km, an average slope of 2°, very fine and very well sorted sand and characteristic sedimentary features of longitudinal sandbars and a flat profile. The Peixe River reaches the ocean at this beach and it is the largest fishing colony in Guarujá with more than 200 boats.

2. Methods

The methodological procedures include field surveys and the analysis of available data for the region, in order to apply a vulnerability assessment method. Based on the results, the vulnerability of the studied beaches is spatialized in a distribution map.

Data collection in the field was conducted in May 2016, and the beach recognition and topographic surveys were performed using Geodetic GPS in differential mode at each beach. The mobile receiver used was a Trimble R4, and the fixed receiver was a Trimble 5700. The data obtained were processed with the Trimble Business Center (TBC) software, and the output data were spreadsheets with position and altimetry data. These data were processed using Surfer 13.0 software to create topographic surfaces for the beaches based on Kriging interpolation. The geographical positions were converted to the Universal Transverse Mercator (UTM) system Zone 23S, and Digital Elevation Models (DEM) were made for the beaches.

The wave climate has been defined based on data extracted from the global wave generation model WaveWatch III, hindcast reanalysis, developed and run by the National Center for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA) (Tolman et al., 2002). The model solves the spectral action density balance equation for wave number-direction spectra. The physical processes included in the model are: refraction and straining of the wave field due to temporal and spatial variations of the mean water depth and of the mean current, wave growth and decay due to the actions of wind, nonlinear resonant interactions, dissipation by whitecapping, and bottom friction (Tolman et al., 2002). The data is available at the NOAA ftp repository (ftp://polar.ncep.noaa.gov/pub/history/waves/multi_1/). For our study, wave information has been extracted at the 24.5° S and 46° W coordinate for an eleven-year period (2005–2015) at 3-h intervals.

The indicators used to assess vulnerability are: terrain elevation, exposure to waves, wave power and angle of incidence (Sousa, 2013) and wave run-up (Alexandrakis & Poulos, 2014). The choice of these indicators considered the availability and reliability of the data to assess the vulnerability of the study site. In order to understand the vulnerability of the beach, we did not consider occupation as an indicator because the entire study site is densely occupied with residences and hotels with little socioeconomic discrepancy between them. If this index is applied in a beach with different landscape and socioeconomic characteristics, occupation should be considered as an additional indicator.

Terrain elevation considers that the most vulnerable areas have low elevations. Areas considered to be of low vulnerability are higher than 6 m, moderate vulnerability areas are between 3 and 6 m in elevation, and high vulnerability areas are below 3 m in elevation.

As proposed by Bush et al. (1999) as a vulnerability indicator, exposure to waves is defined by the degree of exposure of the coast to the attack of incident waves. The presence of natural barriers (islands, reefs or beach rocks) indicates low vulnerability; the presence of migratory features, such as sandbanks, indicates moderate vulnerability and a broad wind course with no obstacles to minimize wave exposure indicates high vulnerability.

The wave power (P) is determined from the wave energy, which is transmitted by particles with potential energy, kinetics and pressure. The wave power equation (1), given in W/m, is as follows:

$$\boldsymbol{P} = \frac{\rho g^2 H^2 T}{32\pi} \tag{1}$$

where ρ is the water density (1027 kg/m^3), g is the gravity acceleration value (9.8 m/s), H is the wave height (m) and T is the period (s).

The maximum height and period of the most energetic wave was used according to the orientation of each beach. In general, the Asturias, Enseada and Pitangueiras beaches receive waves from the southern and southeastern quadrants, and the most energetic wave is from the southern quadrant. The Pernambuco and Mar Casado beaches receive waves from the south, southeast and east, and the most energetic waves are from the south. Finally, Perequê Beach receives waves from the east, which were the most energetic waves for this beach.

Based on the values defined for the region, the range of 0–0.3 (x 10^5) W/m was considered as low vulnerability; 0.3–0.6 (x 10^5) W/m as moderate vulnerability and 0.6–0.9 (x 10^5) W/m as high vulnerability.

The maximum transport capacity is achieved when the waves arrive at the beach at a 45° angle and null transport capacity is at 90° (Komar, 1998; Longuet-Higgins, 1970). Based on that, the vulnerability parameters were defined. The range of incident angles indicating low vulnerability are 75º-90° and 91º-105°; 60º-74° to 106º-120° indicate moderate vulnerability and 45º-59° to 121º-135° indicate high

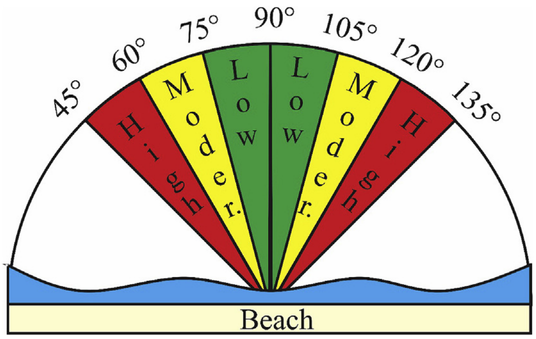

Fig. 2. Range of angles with respective vulnerabilities (Sousa, 2013).

vulnerability (Fig. 2).

For the definition of the angle of wave incidence, the orientation line of each beach was adopted as a straight line (shallow angle). Based on the beach orientation, determined using Google Earth PRO, the angle of rotation of the orientation for this shallow angle was obtained using Surfer 13.0. The addition of this angle to the direction of the most frequent waves for each beach resulted in the angle corresponding to a particular vulnerability.

For the Asturias, Pitangueiras, Enseada, Mar Casado and Pernambuco beaches, the most frequent waves came from the south. At Perequê Beach, the most frequent waves came from the east.

The wave run-up (Alexandrakis & Poulos, 2014) is given by:

$$\mathbf{WR} = 100\left(\frac{\mathbf{R}_{2\%}}{\mathbf{B}}\right) \tag{2}$$

where B is the maximum beach elevation that is considered as the maximum value. $R_{2\%}$ is the wave run-up for the 2% of maximum waves arriving at the coast, which is calculated using:

$$\mathbf{R}_{2\%} = 1.1\left(0.35\,\beta\sqrt{\frac{\mathbf{H}_0}{\mathbf{L}_0}} + \frac{[\mathbf{H}_0\,\mathbf{L}_0\,(0.563\beta^2 + 0.004)]^{1/2}}{2}\right) \tag{3}$$

where H_o is the offshore significant wave height (m), L_o is the offshore wavelength and β is the beach slope (in radians). The beach slope is influenced by the asymmetry of the flow due to infiltration, which is determined by the particle sizes of the sediments present in the foreshore.

The most frequent wave data were used for each beach according to its orientation. The most frequent waves in Perequê Beach were the easterly waves, and in the remaining beaches the waves come mainly from the southern quadrant. The beach slope was defined according to the surveyed morphological data of each beach.

After calculating the indicators, the beach vulnerability index was determined through the method proposed by Sousa et al. (2013). The authors work with ten indicators, being five coastal variables and five inland variables. They calculate their index based on the arithmetic average of the indicator for each variable, and then the arithmetic value for the variables resulting in a coastal vulnerability index to coastal erosion (more details about this index can be found in Sousa et al., 2013). In this paper we use the same principle to evaluate the indicators approached in this work and create a beach vulnerability index:

$$I = \frac{TE + EtW + WF + AoI + WRU}{5} \tag{4}$$

Where: TE is the terrain elevation, EtW is the exposure to waves, WF is wave power, AoI is the angle of incidence (Sousa, 2013) and WRU is the wave run-up. To calculate this average, zero is assigned for low vulnerability, 5 for moderate, and 10 for high vulnerability. The index values are classified into beach vulnerability classes as low, moderate and high. For this indicator, a numerical value was determined. The 0–33 interval was considered to be low vulnerability, 33.1–66 as moderate vulnerability and 66.1–100 as high vulnerability.

3. Results and discussion

Perequê Beach has a minimum elevation of −0.5 m and a maximum elevation of 2.3 m. In the three portions of the beach, fine to very fine sand predominates throughout the profiles, with sediment sorting varying between well sorted and very well sorted. Enseada Beach is the largest beach in the region with a length of 5.6 km. The lowest elevation observed was −0.4 m, and the maximum was 4.0 m. The profiles have predominantly fine sand and very well sorted sediments. Asturias Beach is 0.88 km long, and its shoreline is highly urbanized with tall buildings. It is located next to Pitangueiras Beach, which is 1.8 km long, and its shoreline is also highly urbanized with tall buildings. Along the beach, there are warning signs indicating rip currents. The minimum elevation observed at Asturias and Pitangueiras beaches was −0.4 m, and the maximum elevation was 3.2 m. The beaches are predominantly composed by fine and very well sorted sediment. Pernambuco and Mar Casado Beach are 2 km long and are less urbanized than the other beaches analyzed in this study. The lowest observed elevation was −0.6 m, and the maximum elevation was 3.0 m. At Mar Casado Beach, very fine sand is dominant, and the sediment is very well sorted. At Pernambuco Beach, fine sand dominates, ranging from moderately sorted to very well sorted. Fig. 3 shows the topographic elevations of each beach.

Based on the data extracted from the global wave generation model WaveWatch III (NOAA), directional histograms were obtained (Fig. 4). The most frequent waves in the region originate predominantly from the S (44.92%), E (28.38%) and SE (26.15%) directions in the range of 1.0–1.5 m, with periods between 8 and 10 s.

Regarding the wave power indicator, the most energetic waves are those from the southern quadrant, with a power of 0.471×10^5 W/m. For the calculation of the wave run-up indicator, the mean slope was established based on the morphology measured for each beach. Table 1 presents the slope values in degrees, radians and calculated $R_{2\%}$ values of the beaches.

Table 2 shows the calculated indicator values for each beach as well as the value and classification of vulnerability to erosion. Perequê, Enseada, Asturias and Pernambuco beaches showed low vulnerability to erosion. Pitangueiras and Mar Casado beaches showed moderate vulnerability. In summary, Fig. 5 shows an erosion vulnerability map of the beaches studied in the region of interest.

The erosion vulnerability of the studied beaches was classified as low vulnerability (Perequê, Enseada, Asturias and Pernambuco Beaches) and moderate vulnerability (Pitangueiras and Mar Casado Beaches). This result may be due to the beaches being surrounded by rocky headlands that protect them from the most intense waves.

Among all the indicators, the terrain elevation and the angle of incidence of the waves can be highlighted. Terrain elevation is even more important when considering the phenomena of sea level rise, coastal flooding and wave action during high-energy events. The angle of wave incidence is an important indicator, since it defines the level of exposure of the beach and its response to wave action. In a recent study, Ahmed, Nawaz, Drake, and Woulds (2018) developed a raster GIS-based model to analyze susceptibility to coastal erosion. They used several parameters to their model and one of them is surface elevation in classes from 0 m (very high vulnerability) to > 12 m (very low vulnerability). They highlighted the importance of surface elevation to evaluate the susceptibility of coastal erosion.

Considering the use of the Coastal Vulnerability Index (CVI) (Gornitz, 1991; Thieler & Hammar-Klose, 1999), Onat, Marchant, Francis, and Kim (2018) used a GIS-based CVI method to evaluate coastal exposure of Hawaiian Islands. They pointed out that geomorphology and waves have an important role on coastal exposure in their study area. In this work, the wave exposure indicator does not contribute significantly since, as previously mentioned, the beaches are surrounded by headlands and fronted by small islands. However, the action of these barriers in the studied area is not very significant

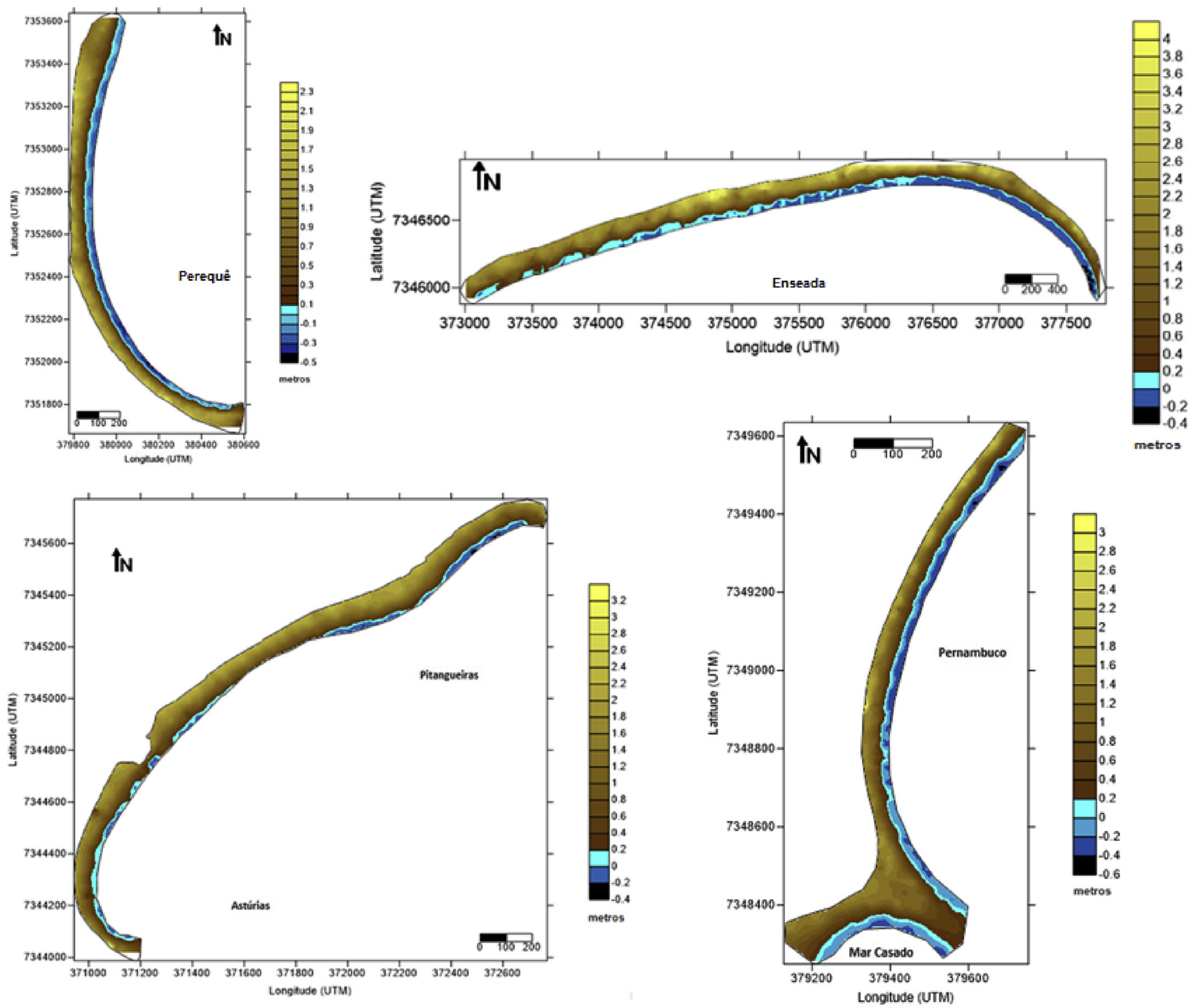

Fig. 3. Topographic elevation of the beaches. From top to right: Perequê, Enseada, Asturias, Pitangueiras, Pernambuco and Mar Casado beaches.

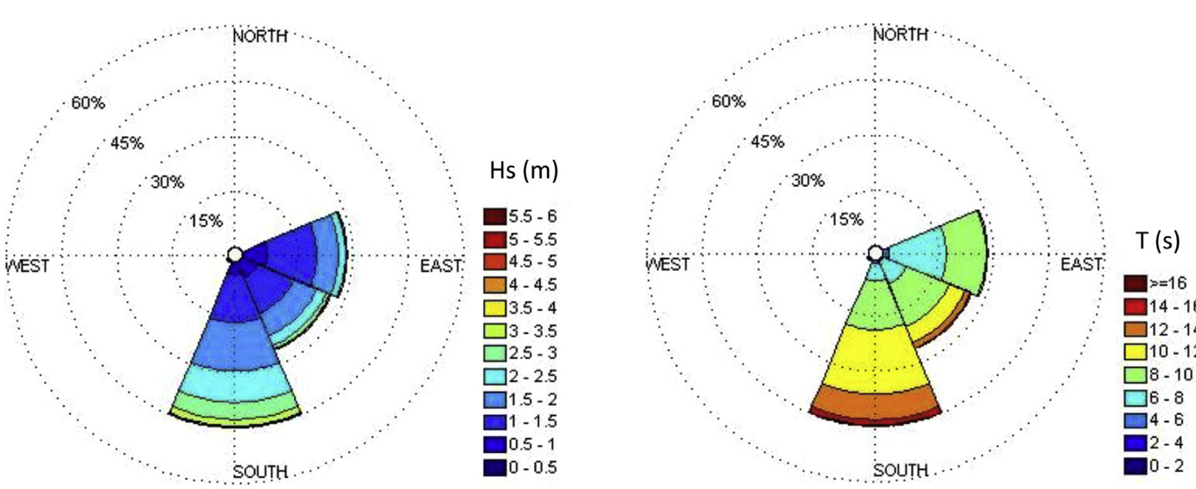

Fig. 4. Directional histograms of the significant heights (Hs) and the peak periods (T) of the waves from 2005 to 2015.

Table 1
Mean slope (in degrees and radians) and $R_{2\%}$ values used for the calculation of the wave run-up indicator for each beach.

Beach	Slope (º)	Slope (radians)	$R_{2\%}$
Perequê	0.76	0.0133	0.3925
Enseada	0.95	0.0166	0.3953
Asturias	1.15	0.0200	0.3987
Pitangueiras	1.15	0.0200	0.3987
Pernambuco	1.53	0.0267	0.4072
Mar Casado	0.76	0.0133	0.3925

because of the size of these features, different from what was observed in the northern sector of Massaguaçú Beach (Ribeiro, Sousa, Vieira, & Siegle, 2013; Sousa et al., 2013) where the set of islands directly affects the beach morphodynamics. Regarding the wave run-up indicator, the beaches have a smooth profile with a low slope. Because the variation of the water height in the dynamics of the wave run-up movement is slower and reaches lower levels and the speeds (in the rise and fall of the water) are also lower, the flow is not as intense as for steeper profiles.

According to Short and Masselink (1999), beaches bounded by rocky headlands are relatively stable coastline sections. They further claim that the headlands, rocks, reefs and other structures impact the beach and the surf zone through wave attenuation and refraction and by limiting the development of large longshore and rip currents.

The wave power indicator for most beaches showed moderate vulnerability. By relating this indicator to the presence of islands, one can consider the processes of attenuation of the wave power in beaches protected by rocky headlands. The analyzed variables can have different levels of relevance for different beach types. This occurs due to the landscape, climate, oceanographic, morphological and land use characteristics. In this context, climate change will generate unprecedented impacts on coastal zones, such as increased coastal flooding and erosion (Nicholls & Cazenave, 2010) and changes in the mean and extreme wave climate (Semedo et al., 2013).

Boateng (2012) conducted a study to evaluate coastal vulnerability in Vietnam based on GIS tools and identified expressive areas susceptible to flooding. Li, Zhou, Tian, Kuang, and Wang (2015) used physical and socioeconomic variables in a GIS-based method to demonstrate the real conditions of risk to coastal erosion of a muddy coast in China. They found that the risk of coastal erosion has increased due to land use and management. Additionally, Chang et al. (2018) proposed a typology for disaster risk reduction based on ten indicators to identify groups of communities with similar vulnerabilities. Sousa et al. (2013) showed the increased vulnerability during the last decades at Massaguaçú Beach (Caraguatatuba, São Paulo), a beach that is experiencing an intense erosive process. The vulnerability oscillated due to the indicators "beach width" and "coastline position", with longshore drift gradients playing an important role in the erosive process.

All these studies propose methods to assess coastal vulnerability under different natural and socioeconomic contexts. The present study proposes a different analysis for the beaches of São Paulo, considering physical variables to assess beach vulnerability. It is shown that it is essential to analyze the beach morphology and the different processes resulting from the incidence of waves on the coast to assess its vulnerability to erosion. Additional indicators are suggested for future studies in the region. Additionally, it would be interesting to evaluate the vulnerability in relation to other processes, such as coastal flooding, sea level rise, etc.

Busman, Amaro, and Souza-Filho (2016) evaluated methods of natural and environmental vulnerability to the relative increase of mean sea level through multivariate statistical analysis for the physical variables. Thereby they identified vulnerability hotspot areas to sea level rise in some coastal areas of the Rio Grande do Norte State, in Brazil. Thus, the vulnerability assessment is an important tool to better manage the impacts resulting from coastal erosion and flooding to which many coastal zones are already subjected. To better understand the environment and how it can be changed due to anthropogenic and/or natural forces, and to plan its sustainable use, vulnerability studies including different processes and variables are necessary. According to Abuodha and Woodroffe (2006) the vulnerability results of a region cannot be directly compared to others that did not use the same index. Vulnerability classifications can be performed in several ways, and several classes can be defined for evaluation. The specificities of the indices are not too important because preliminary vulnerability assessments rarely provide absolute predictions, but they are useful for prioritizing decisions.

4. Conclusion

In this study we addressed the vulnerability of beaches to erosion, focusing on six beaches of Guarujá (São Paulo, Brazil). The analysis was performed based on beach characteristics and coastal processes (waves). The studied area presented low and moderate vulnerability. The analyzed parameters showed a close relationship between terrain elevation and the angle of wave incidence.

Our application did not consider the occupation adjacent to the beaches, which would result in higher vulnerability due to increasing population density in the region. Additionally, direct impacts of climate change, such as sea-level rise and coastal erosion, will result in increased vulnerability of the area over time. However, the analyzed variables are of great value for the management of natural resources and for the maintenance of the urban infrastructure of Guarujá beaches.

Anthropogenic interventions that change the environmental dynamics of the studied area can trigger erosive processes at the studied beaches. The study provides an interesting tool for the management of coastal resources in the Guarujá region and similar coastal areas. In addition, although the analyzed beaches presented low and moderate vulnerability, processes such as climate change or inadequate interventions on adjacent beaches may negatively influence the studied region.

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Table 2
Values and classification of the five indicators used and the value and classification of vulnerability to erosion of each beach.

Beach	Indicators					
	Terrain elevation	Wave exposure	Wave power	Angle of incidence of waves	Wave run-up (WR)	Vulnerability
Perequê	2.3 m - High	Presence of island - Low	0.177×10^5 Low	37.5° - 7.5°: High	17.06 - Low	4 - LOW
Enseada	4.0 m - Moderate	Presence of island - Low	0.471×10^5 Moderate	157° - 202°: High	9.88 - Low	4 - LOW
Asturias	3.2 m - Moderate	Presence of island - Low	0.471×10^5 Moderate	64.5° - 109.5°: Moderate	12.46 - Low	3 - LOW
Pitangueiras	2.8 m - High	Presence of island - Low	0.471×10^5 Moderate	130.5° - 175.5°: High	14.24 - Low	5 - MODERATE
Pernambuco	3.0 m - Moderate	Presence of island - Low	0.471×10^5 Moderate	73.5° −118.5°: Moderate	13.57 - Low	3 - LOW
Mar Casado	2.0 m - High	Presence of island - Low	0.471×10^5 Moderate	155.5° - 202.5°: High	19.62 - Low	5 - MODERATE

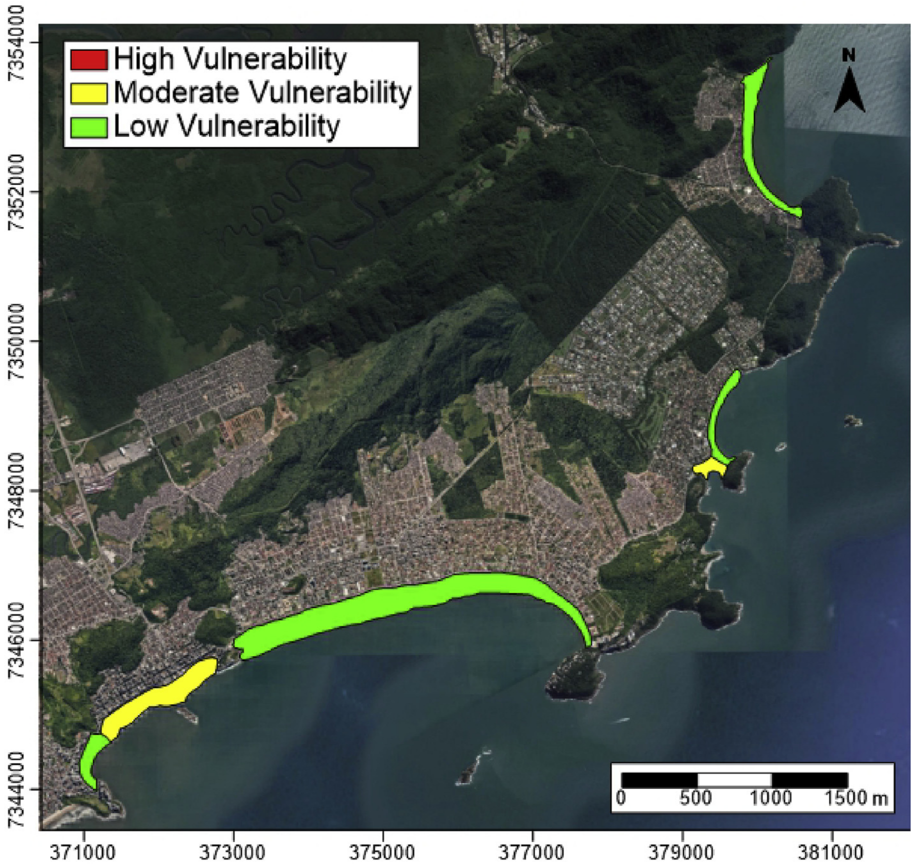

Fig. 5. Classification of the erosion vulnerability of beaches studied in the region of Guarujá, coast of São Paulo State. Image: Google Earth.

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