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Assessment of the physical vulnerability to erosion and flooding in a sheltered coastal sector: Florianópolis Bay, Brazil

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Abstract

This study aims to characterize the physical vulnerability of the western coast of Santa Catarina Island by applying the Smartline methodology. Erosion and flooding processes can endanger the installed human infrastructure in the coastal zone, with the degree of vulnerability of a given site being dependent on its natural characteristics, or even due to changes induced by human action. The methodology applied in this research adopts a multiscale approach and considers, using coastline segmentation, the specificities of the analyzed coastal sectors. Each identified segment receives a classification regarding its physical vulnerability, resulting from the integration of several attributes, which must be selected according to the coastal hazard that one wishes to represent. In the analysis, three distinct levels of physical support and behavior of the coastal processes are considered. The first-order attributes are structural, and their characteristics are broad; the second-order ones are transitional between structural and dynamic and, the third-order attributes are dynamic, with specific characteristics. The methodology was applied on the west coast of Santa Catarina Island, a sector sheltered from oceanic waves, characterizing a low energy environment. Eight descriptors were selected for erosion and coastal flooding, these being: "geology" having two classes, distributed along 12 segments and "geomorphology", three classes in eight segments, both of which were considered first-order variables. "Average astronomical tide current speed" (five classes in 15 segments), "average backshore height" (four classes in 20 segments), and "degree of exposure to wind waves" (five classes in 28 segments) compose the second order, while "backshore features" (seven classes in 28 segments), "grain size" (five classes in 26 segments) and "beach face slope" (three classes in 30 segments) describe third-order processes. By the integration of first-order attributes an Indicative Map of Vulnerability to Erosion and Flooding was generated, which classified the coast into "very Low", "low", "moderate", and "high" vulnerability classes. As a final result of the analytical process the coastline, first-, second-, and third-order attributes were mathematically integrated by means of spatial analysis techniques, with the studied coastline represented as a segmented line according to the different classes of attributed physical vulnerability, highlighting the sectors with the most propensity to erosion and flooding. This Map of Physical Vulnerability to Erosion and Flood indicated that the west coast of Santa Catarina Island can be divided into sectors of low and moderate vulnerability in similar proportions, with occasional occurrences of high vulnerability in specific sectors.

Keywords Coastal erosion · Coastal flooding · Coastline change · Spatial analysis

Introduction

Coastal erosion and the consequent retreat of the coastline depend on natural and anthropic factors and their interactions. Rangel-Buitrago et al. (2018) mention that this process includes a broad range of factors which result in a net sediment imbalance and subsequent coastal retreat. Among them are: the reduction of sediment supply, sea level rise, destruction of coastal ecosystems, and placement of hard engineering structures.

The intense urban occupation of the coastal zones has generated a series of environmental impacts over the last few decades, from the intensification of urban infrastructure to the alteration of physical and natural properties of the

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environment (Lins de Barros and Muehe 2013). According to Snoussi et al. (2008), about 60% of the population and 90% of the world's industrial activity are located less than 100 km from the sea.

The Intergovernmental Panel on Climate Change estimates that sea level rise will reach rates of 0.26 to 0.55 mm/year by 2100 in a rigorous mitigation scenario (IPCC 2014). On the coast of Santa Catarina, where the Florianópolis Bay is located, a linear historical trend of sea level is observed, with a positive variation of 2.11 mm/year, resulting in an increase of 4.6 cm over the last 22 years (CEPAL 2015).

Thus, as the occupation of the coastal zone increased, occasional inundation and erosive effects previously considered less significant began to be seen as risk factors, as suggested by the growth in the number of emergency events associated with extreme high sea levels, mostly related to large storms (Bonetti and Woodroffe 2017). The consequent relevant socioeconomic issues conferred importance on the investigation of the environmental sensitivity of these zones, most of them based on numerical modeling, spatial analysis, and index/indicator-based approaches (Bonetti et al. 2013a; Nguyen et al. 2016).

Several methodological proposals for the determination of coastal vulnerability have been developed in the last few decades, as detailed by Rangel-Buitrago and Anfuso (2015), and Bonetti and Woodroffe (2017). However, there are still few studies (National Research Council 2007, Jallow et al. 1999, Bayani-Arias et al. 2012) that consider the particular characteristics of the coastal sectors which are sheltered from direct ocean wave action. In such sectors, there is a degree of interaction with the continental systems that are not observed on exposed beaches, so that the processes that regulate the behavior of the physical environment cannot be assessed in the same way.

The morphodynamic classification of beaches is based on the recognition of the hydrodynamic and morphological processes that act on them. Authors such as Wright and Short (1984), Masselink and Short (1993), and Hegge et al. (1996) studied attributes such as the degree of beach exposure, coastal hydrodynamics, declivity, grain size, tidal variation, height, and wave period which, when incorporated in equations, can describe the characteristics of the beach system (Short 1999). Most research on beach dynamics, however, relies on the application of this approach on exposed beaches.

Hegge et al. (1996) studied beaches considered to be sheltered. According to these authors, this specific class of beaches has many similarities to those that are exposed, such as evolution processes and oceanographic forcing, but they differ from them because they are protected from the direct impact of high energy swells. Sheltered systems can, thus, be considered as low energy, taking into account the degree of energetic transfer and the low or null degree of exposure of the coast to the waves generated in the oceans (Goodfellow and Stephenson 2005). The waves acting on sheltered beaches are of small amplitude (Hs <0.25 m) and short period ($T < 5$ s) (Jackson et al. 2002), being commonly generated locally in limited wind fetch conditions.

According to Jackson and Nordstrom (1992), the morphodynamics of sheltered beaches are largely related to the characteristics of those waves, and to the periodic variations of the water level that rework the beachface. In addition, the geological framework is important in the configuration of the beach, as are the sedimentary supply and inherited morphological features along its upper profile.

Physical processes in sheltered systems are not necessarily easy to quantify and model, since many interactions occur in a relatively narrow zone and frequently in a nonlinear way. However, the often-adopted approach of integration of a set of themes and multivariate descriptors, so that they can be combined to spatially represent the characteristics of a portion of coastal space (Bonetti et al. 2013b, Merlotto et al. 2016, Di Paola et al. 2017), is perfectly applicable to the assessment of the physical vulnerability of sheltered areas. For this, the selection of variables that better express the behavior of such environments is a key factor. Also, the adoption of a multiscale approach can be an efficient strategy to better distinguish the roles of structural and dynamic factors that induce susceptibility.

In this sense, this work aims to analyze a set of coastal vulnerability descriptors in a sheltered system, adopting the Smartline methodology. This methodology, developed by Sharples (2006), uses a multi-scalar approach to represent the specificities and interrelations of a given coastal sector by means of coastline segmentation.

Florianópolis Bay

The coastal province of the state of Santa Catarina, located in southern Brazil, trends from south then southwest for about 922 km of open coasts and bay shorelines, and consists of two major geological units: Precambrian bedrocks and Quaternary sediments (Klein et al. 2016).

Florianópolis Bay, which separates Santa Catarina island from the mainland (Fig. 1), is located in the central sector of the state. It presents morphological features resulting from strong indentation (peninsulas, coves, bays, etc.) and typical beach morphology of discontinuous coastlines (Horn Filho 2003).

This bay forms a semi-confined body of water, physiographically divided into the North and South bays, which are connected in the central portion of the system through a constriction of approximately 400 m wide at its narrowest point (Bonetti et al. 1998).

North Bay

North Bay has a longitudinal length of approximately 19 km, a maximum width of 12 km, and an average depth of 3.30 m. It

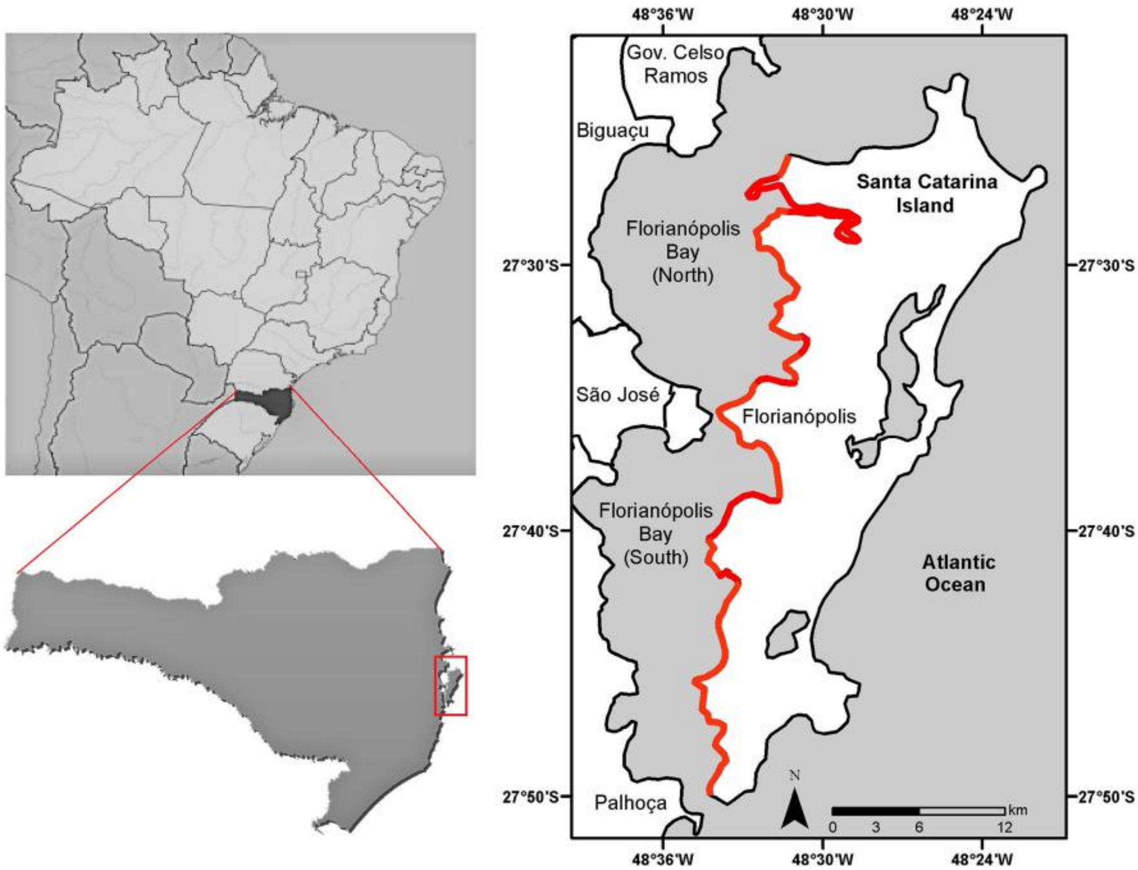


Fig. 1 Location of Florianópolis Bay, Santa Catarina Island, with the studied coastline highlighted in red

communicates with the ocean by an inlet at the north extremity which is 4.5 km wide and is 11 m deep at its maximum depth. The total area of this sector is estimated at 146.17 km^2 and its waters have predominantly marine characteristics (Bonetti et al. 1998).

South Bay

South Bay has a longitudinal length of 27 km, an average width of 6.8 km and a maximum of 10.8 km, with an average depth of approximately 3.06 m and a total area of 125 km^2. It communicates with the ocean through an inlet about 830 m wide and 30 m deep. Like North Bay, the waters of this bay primarily have marine characteristics (Franklin-Silva 2002).

As highlighted in Fig. 1, the performed vulnerability assessment comprises the western coastline of Santa Catarina Island (which corresponds to the coastline on the east margin of the Florianópolis Bay), encompassing a total length of 82.4 km.

Methodology

Sharples (2006) proposes, as a framework for vulnerability analysis, the division of the coast into segments and the assignment of a number of characteristics to each one of them (Fig. 2). The elements observed in the vector line segments are stored in a spatial database so that classifications can be performed by GIS query into broad categories corresponding to different degrees of susceptibility to hazard impacts. As described by Bonetti and Woodroffe (2017) “it proposes a pragmatic approach aiming at indicative mapping, intended as the first stage in a hierarchical sequence of assessments, which identifies shoreline landform types that are potentially vulnerable to sea-level rise”.

In the analysis, three distinct levels of physical support and operation of the coastal processes are considered. First-order attributes are related to the structural framework of the environment, whose characteristics are more comprehensive and influence the process of coastal vulnerability as a whole. Second-order attributes present a transitional condition between structural and dynamic, whose characteristics are regionalized, but show relevant points of change in physical conditions. The third-order attributes are related to the dynamic properties of the environment and their characteristics are more specific, sometimes punctual, showing great variation along the coast.

For the present work, eight attributes were selected. First-order structural attributes correspond to geology and geomorphology. The second-order transitional attributes are: degree of exposure to wind waves, average backshore height, and average astronomical tide current speed. The third-order dynamic

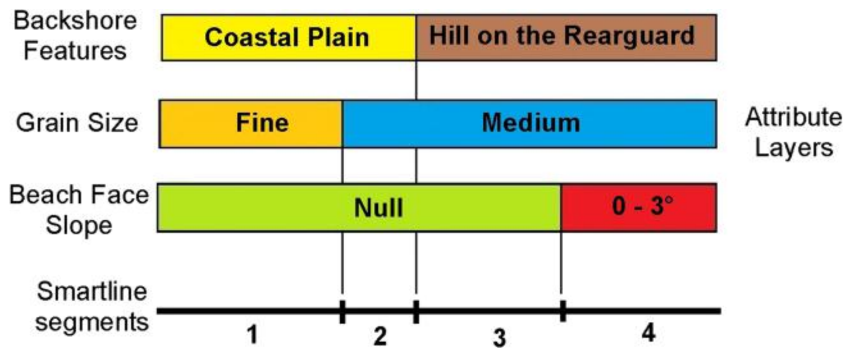


Fig. 2 Schematic representation of the methodological procedure for coastline segmentation. Adapted from Sharples et al. (2009)

attributes are represented by the backshore features, grain size, and beach face slope. The relation between the selected attributes and their sources are listed in Table 1 below:

The first step in the application of the Smartline methodology is the extraction of information regarding the selected attributes, to which weights have been assigned. Each identified feature (class) of these attributes was classified according to its minor or major influence on the occurrence of erosion and flooding processes. After extracting the information from the variables, they were integrated and standardized, and through a multicriteria evaluation the physical vulnerability of each segment was assigned to an overall vulnerability score.

The used data integration method was based on the elaboration of a vulnerability index as originally proposed by Gornitz et al. (1992), known as the CVI - Coastal Vulnerability Index. This index was adapted to assess coastal vulnerability to the erosion and flooding of sheltered systems, resulting in the Weighted Coastal Vulnerability Index (WCVI) bellow.

$$\mathrm{WCVI} = \frac{\{(G*0.1) + (GM*0.1) + (C*0.2) + (BH*0.3) + (E*0.2) + (BF*0.3) + (GS*0.1) + (D*0.3)}{1.6}$$

Where:

G geology
GM geomorphology
C average astronomical tide current speed
BH average backshore height
E degree of exposure to wind waves
BF backshore features
GS grain size
D beach face slope

The weights of the features of each attribute were distributed within the range of 0 to 3, where values that tend towards 0 represent low vulnerability and values that tend towards 3 represent high vulnerability (Table 2). Values

Table 1 Data previously available to build the attribute layers, those produced, and their sources

First-order attributes	Source
Geology	Horn Filho and Livi (2013)
Geomorphology	IPUF (1992)
Second-order Attributes	Source
Average astronomical tide current speed	Reprocessing of numerical modeling developed by Czizeweski (2016)
Average backshore height	Digital Elevation Model processing obtained by SRTM, 90 m resolution
Degree of exposure to wind waves	Application of the Wind Fetch Model (USGS)
Third-order Attributes	Source
Backshore features	Mussi et al. (2018)
Grain size	Horn Filho (2006)
Beach face slope	Mussi et al. (2018)

Table 2 Attributes used to build the vulnerability map, their respective weights and bibliographical sources consulted to assign weight values

First-order attributes	Features	Weights	Variable weighing reference
Geology	Precambrian rocks	1.0	Nordstrom (1992)
	Cenozoic rocks	2.0	
Geomorphology	Leste catarinense range	1.0	Nordstrom (1992)
	Tidal plain	3.0	
	Sandy plain	3.0	
Second-order attributes	Features	Weights	Variable Weighting Reference
Average astronomical tide current speed	0.0–0.126 ms^{-1}	1.0	Pierce (2004)
	0.127–0.252 ms^{-1}	1.5	
	0.253–0.378 ms^{-1}	2.0	
	0.379–0.504 ms^{-1}	2.5	
	0.505–0.63 ms^{-1}	3.0	
Average backshore height	Class 1 (0.0 m)	3.0	Jackson and Nordstrom (1992)
	Class 2 (0.0–2.5 m)	2.5	
	Class 3 (2.5–4.5 m)	2.0	
	Class 4 (4.5–24 m)	1.5	
Degree of exposure to wind waves	Low exposure	1.0	Goodfellow and Stephenson (2005), Jackson et al. (2002)
	Medium low exposure	1.5	
	Medium exposure	2.0	
	Medium high exposure	2.5	
	High exposure	3.0	
Third-order attributes	Features	Weights	Variable Weighting Reference
Backshore features	Hill on the rearguard	1.0	Sharples et al. (2009), Abuodha and Woodroffe (2010), Mussi et al. (2018) (adaptations)
	Dunes and littoral strands	3.0	
	Mangrove and marshes	2.5	
	Urban under coastal plain	3.0	
	Urban with hill on the rearguard	2.5	
	Urban under mangrove	3.0	
	Coastal plain	2.0	
Grain size	Fine sand	3.0	Hegge et al. (1996)
	Medium sand	2.0	
	Coarse sand	1.0	
	Embankment	1.0	
	Rocky shores	2.0	
Beach face slope	Null	1.0	Sharples et al. (2009), Mussi et al. (2018)
	0–3°	3.0	
	3–8°	2.0	

were assigned by the authors based on their experience and on the literature.

The resulting values of this weighted average were distributed in four class intervals, with respective associated vulnerabilities (Table 3).

Results and discussions

First-order attributes

Geology: geological features were associated to the classes Precambrian and Cenozoic (all of them Quaternary, largely dominating Holocene sediments), comprising 12 segments along the coast. Precambrian rocks and Cenozoic deposits are distributed over 6 segments each (Fig. 3). On the studied coast, there is a predominance of friable sediments (64,89 km, 78,75%) over consolidated rocks (17,51 km, 21,25%). Cenozoic rocks correspond to anthropized area (coastal settlements are located over the Quaternary coastal plain) and the deposits Technogenic, Marine Beach, Paludal, Bay, Alluvial Fan and Colluvial. Precambrian rocks correspond, in this sector of Santa Catarina Island, to "Ilha Granite", presented as sieno or monzogranites of pink or light gray color, equigranular texture (possibly porphyry, thick or medium) and show little or no ductile deformation (Tomazzoli & Pellerin 2015). According to Basei (1985), Rb-Sr dates determined ages of 524 ± 68 Ma.

Geomorphology: geomorphological features encompassed a total of eight segments along the coast. The Leste Catarinense range is distributed along four segments (43.81 km, 53%), the tidal plain in two segments (23.93 km, 29%) and the sandy plain in two other segments (14.66 km, 18%). The position of these segments is shown in Fig. 4, where it is possible to observe the predominance of the elevated and high slope terrains represented by the Leste Catarinense range. On this segmented map, small units were not considered given the overall scale proposed for the

Table 3 Classes and numerical intervals adopted by the WCVI

Classes	Very Low	Low	Moderate	High	Very High
WCVI	1,0 – 1,2	1,3 – 1,7	1,8 – 2,2	2,3 – 2,7	2,8 – 3,0

vulnerability analysis and the variable resolution of the different attribute layers.

Second-order attributes

Average astronomical tide current speed: five classes of average maximum daily astronomical tide current speeds were distinguished: 0–0.126 ms^{-1}; 0.127–0.252 ms^{-1}; 0.253–0.378 ms^{-1}; 0.379–0.504 ms^{-1}, and 0.505–0.63 ms^{-1} (Fig. 5). The speed intervals allowed the recognition of 15 segments along the coast. The minimum range of 0–0.126 ms^{-1} predominates in five long segments (43.27 km), covering a total of 52% of the coastline. The second interval, 0.127–0.252 ms^{-1}, is distributed in six segments (25.97 km), making up 32% of the coast. The other intervals are presented in a smaller number of segments and extensions: 0.253–0.388 ms^{-1} in two segments (6.91 km, 8%), 0.379–0.504 ms^{-1} (2.16 km, 3%) and 0.505–0.63 ms^{-1} (4.09 km, 5%) in one segment each.

Average backshore height: the average altimetric variation between the coastline and a distance of 100 m in the direction of the Santa Catarina Island was calculated at several points in the area. From the obtained results, four classes were assigned according to the proximity of the coastline to potential sources of sedimentary supply, using the quantile classification scheme. The classes of smaller variation correspond to the plain and the ones of greater variation show the presence of hills. The four classes correspond to: Class 1: 0.0 m (44 km, 54%); Class 2: 0.00–2.5 m (12.59 km, 15%); Class 3: 2.5–4.5 m (14.9 km, 18%); Class 4: 4.5–24 m (10.89 km, 13%) (Fig. 6).

Degree of exposure to wind waves: through the application of the Wind Fetch Model extension, in ArcGIS 10.1, simulations were generated for three wind directions: North (0°), more frequent; South (180°), more intense; and West (270°) due to its direct incidence over the analyzed coast, determining the extent of the available wind fetch in meters. The three calculated fields were unified in a single product, using the ArcGIS Raster Calculator tool, and the obtained values were regrouped also using the quantile classification. Five classes of wind distribution were proposed (Fig. 7), totaling 28 segments along the coast: low exposure is distributed along 10 segments (55.38 km, 67%); medium low exposure in 10 segments (16.9 km, 20%); medium exposure in two segments (4.66 km, 6%); medium high exposure in two segments (1.72 km, 2%); and high exposure in four segments (3.74 km, 5%).

Third-order attributes

Backshore features: the backshore features total 27 segments along the coast (Fig. 8). The class hill on the rearguard is distributed along six segments (11.2 km, 13%), dunes and littoral strands (3.39 km, 4%) in one segment each, mangrove and marshes in six segments (29.76 km, 36%), urban under coastal plain in another six segments (22.74 km, 28%), urban with hill on the rearguard along five segments (7.98 km, 10%), urban under mangroves in tow segments (4.97 km, 6%), and coastal plain (2.36 km, 3%).

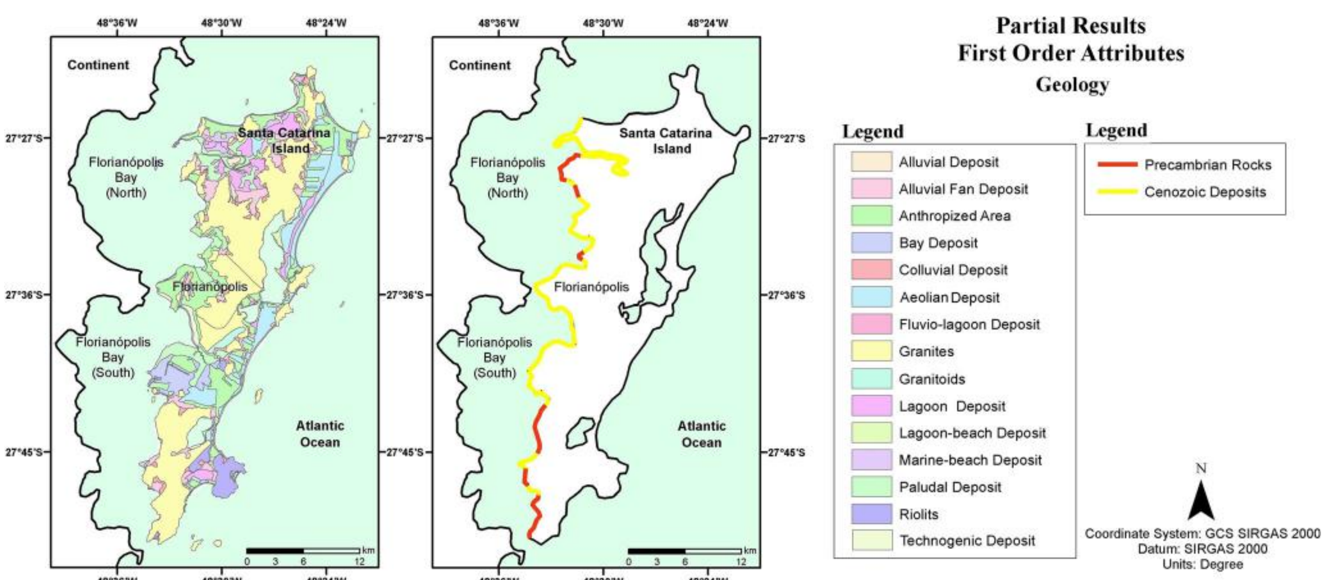


Fig. 3 Geological map of the area, adapted from Horn Filho and Livi (2013), and its linearized representation for vulnerability analysis

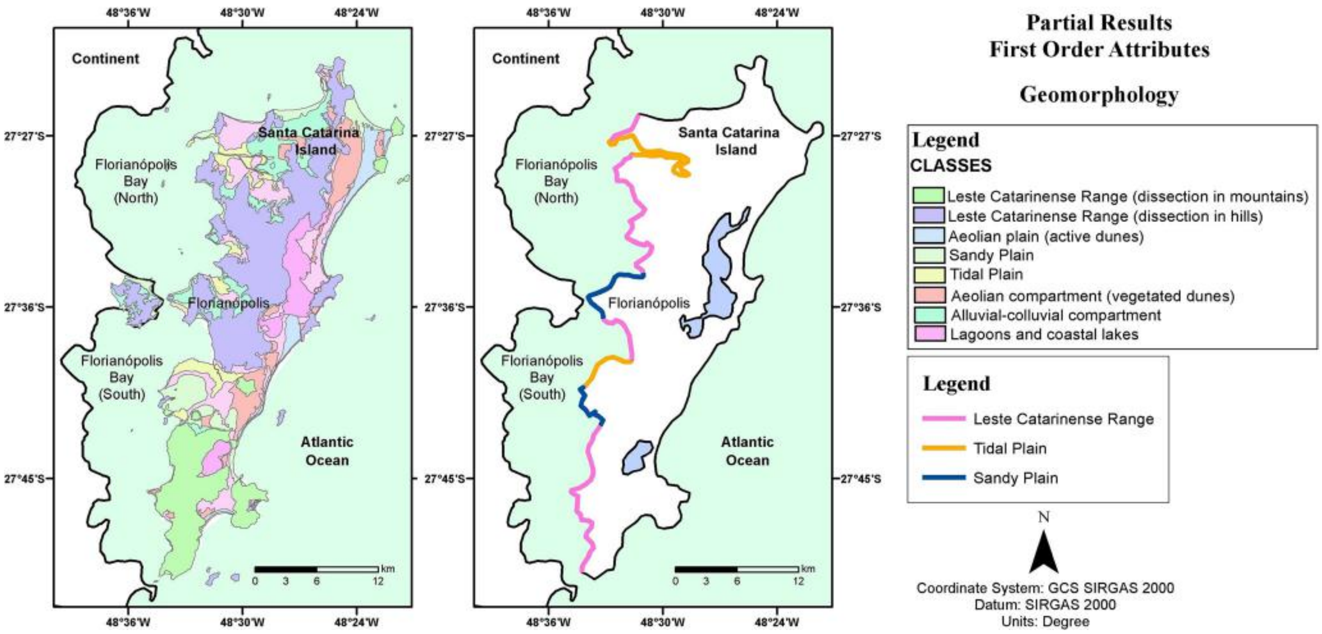


Fig. 4 Geomorphological map of the area, adapted from IPUF (1992), and its linearized representation for vulnerability analysis

Grain size: the grain size attributes comprise a total of 26 segments along the coast (Fig. 9). Fine sand is distributed along three segments (28.11 km, 34%), medium sand in three segments (4.06 km, 5%), coarse sand in eight segments (25.68 km, 31%), rocky shores in 11 segments (19.78 km, 24%), and embankment in only one segment (4.77 km, 6%).

Beach face slope: three classes were identified: null slope and headlands, 0–3° and 3–8° (Fig. 10). The slope classes total 33 segments along the coast. The null slope occurs in 14 segments (41.9 km, 51%), the range 0–3° in six segments (9.04 km, 11%) and the range of 3–8° in 13 segments (31.47 km, 38%).

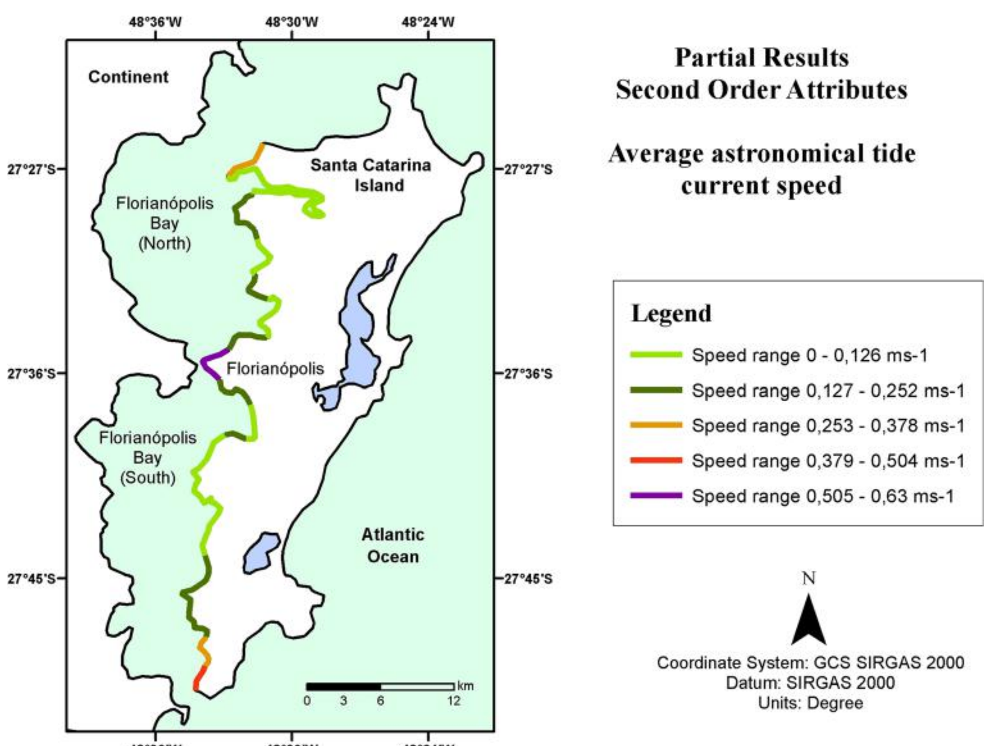


Fig. 5 Linear representation of average astronomical tide current speeds along the coastline

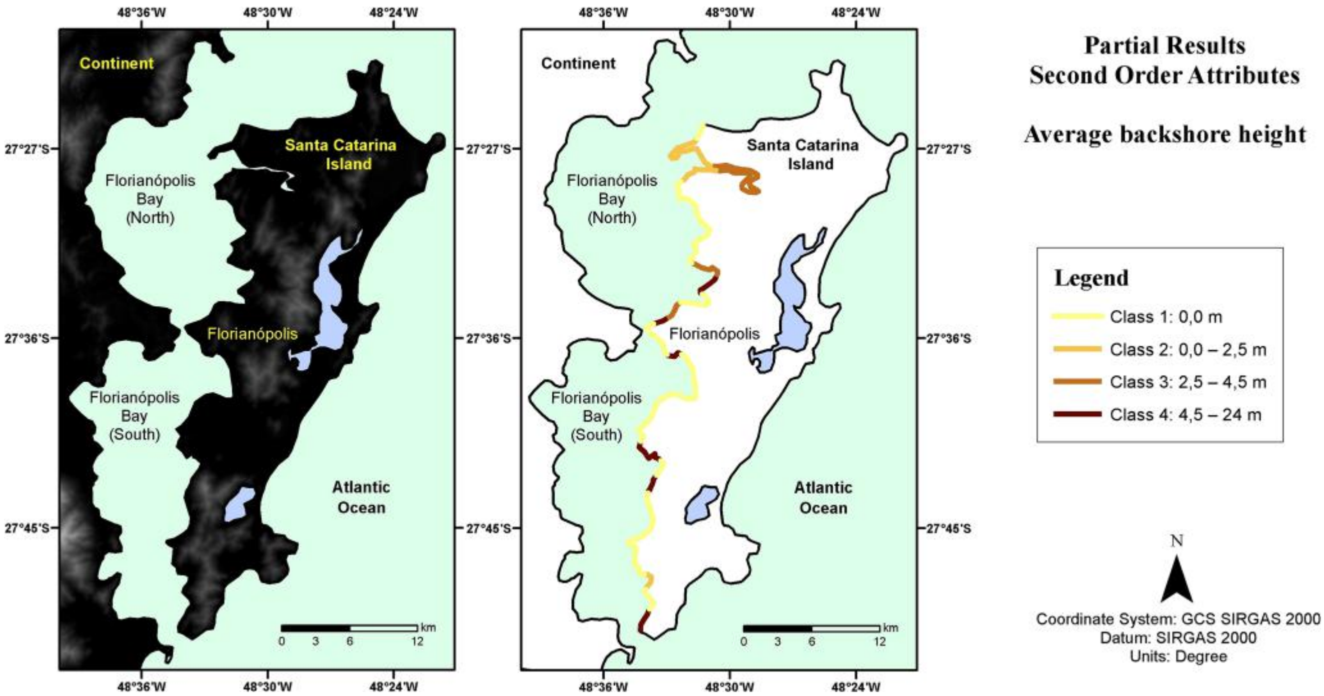


Fig. 6 Linear representation of average backshore height along the coastline

Map of physical vulnerability to erosion and flood

The integration of the proposed attributes resulted in low to very high vulnerability, showing a predominance of the moderate (49.42 km, 60,1%) and low (25.83 km, 31,3%) classes. The two most vulnerable classes occur at low frequencies, namely: high with 7,6% (6.3 km) and very high 1% (0.85 km) (Fig. 11).

The occurrence of low vulnerability sectors is mainly due to the presence of weak tidal current speeds, low or medium-low exposure to wind-generated waves, and of non-urbanized or urbanized areas with a backshore whose terrain characteristics promote resistance to erosion and flooding. Where moderate vulnerability is observed, astronomical tidal current speed increases, the beach face presents a steeper slope, and

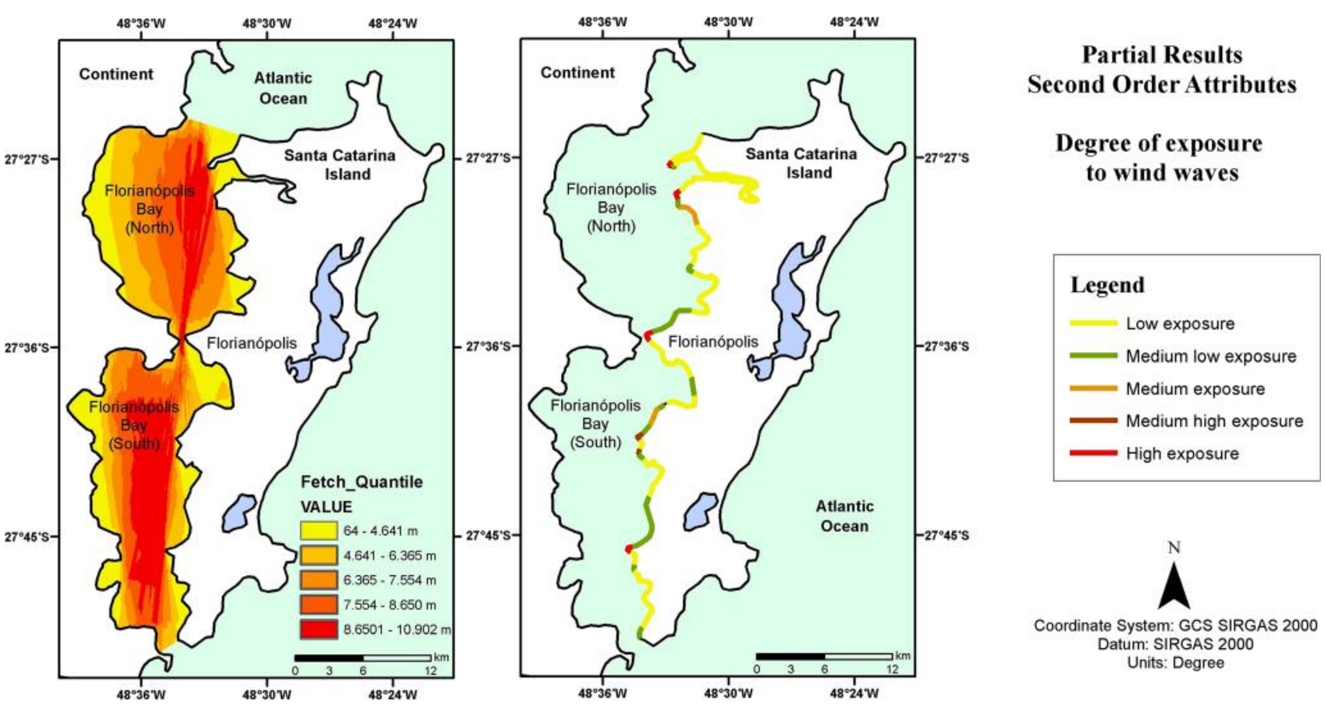


Fig. 7 Linear representation of the degree of exposure to wind waves along the coastline

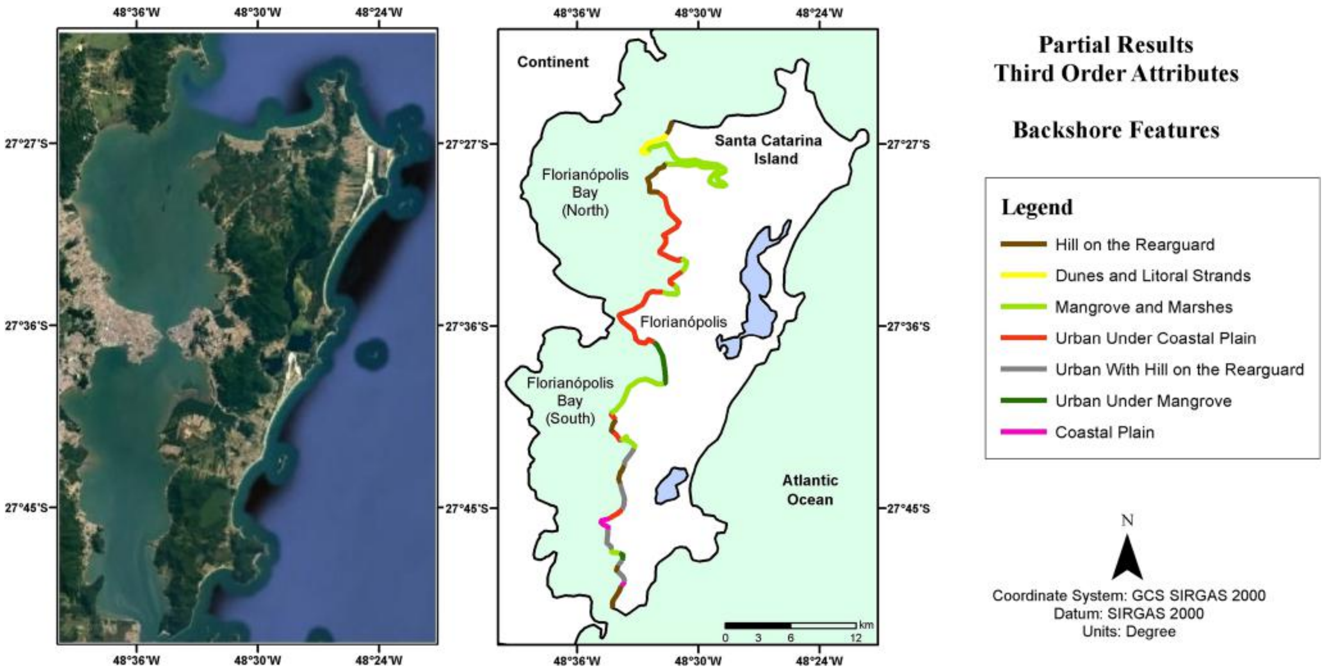
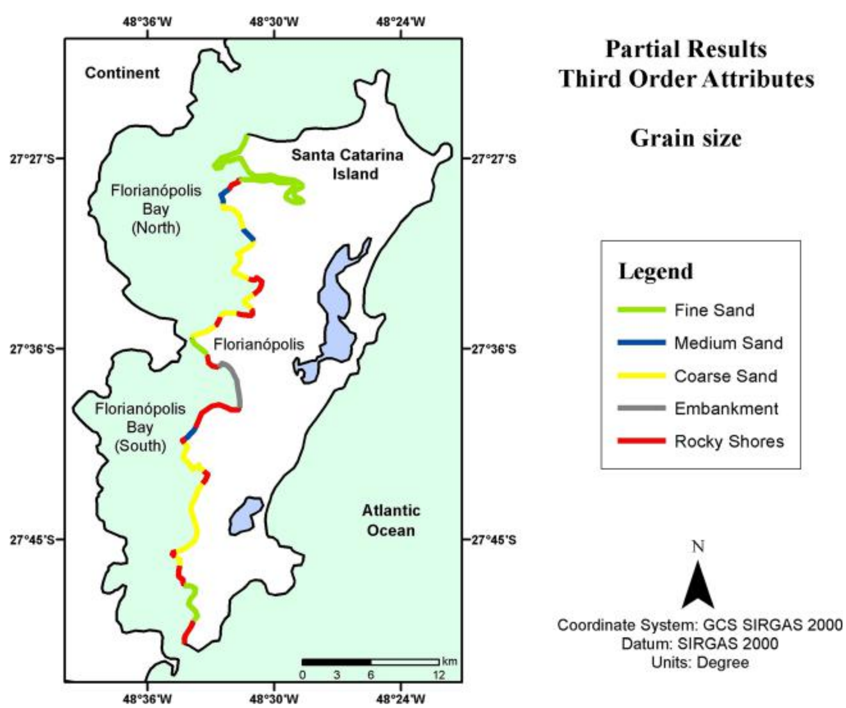


Fig. 8 Linear representation of the backshore features along the coastline

urbanized or non-urbanized sectors with low resistance to the local physical conditions occur, such as coastal plain and mangrove-marshes environments. High vulnerability is present in a segment at the north of Pontal de Daniela, in the central area and in a small extension of Sambaqui Beach and Tapera da Base Beach. In these three locations, strong astronomical tidal current speeds and a high degree of exposure to wind-generated waves are observed and, in the central area, dense urbanization and the susceptible coastal plain classes dominate. The Pontal de Daniela is the only sector that presents very high vulnerability, mainly due to its high exposure to the waves generated by the wind and the presence of the backshore feature dunes and littoral strands, highly susceptible to erosion.

These results can complement, to a certain extent, those obtained by Ruddorf and Bonetti (2010), Muler and Bonetti (2014) and Mussi et al. (2018); authors that assessed the coastal vulnerability of exposed environments over Santa Catarina

Fig. 9 Linear representation of the grain size distribution along the coastline, based on Horn Filho (2006)



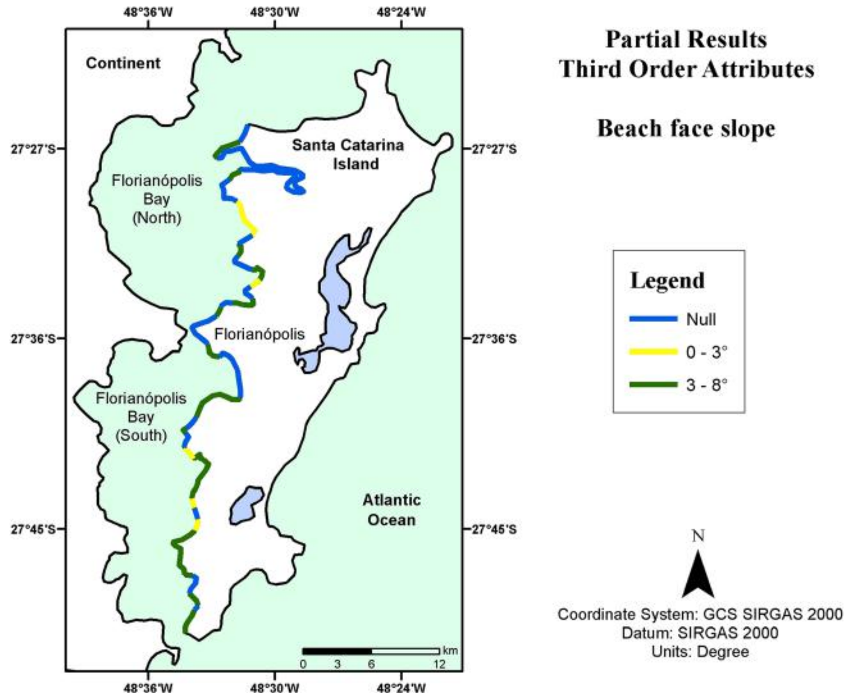


Fig. 10 Linear representation of the beach face slope along the coastline

Island. In their physical vulnerability assessments, Rudorff and Bonetti (2010) used Geoindicators, Muler and Bonetti (2014) the Coastal Vulnerability Index (CVI), while Mussi et al. (2018) applied a modified Smartline methodology.

Due to the greater variability in the morpho- and hydrodynamic behavior of the open coastal environments, they present a greater range of physical attributes and vulnerability levels, such as degrees of exposure to different wave heights and directional energies, meteorological tide amplitude exposures, dune configurations (height and state of frontal and interior dunes), and beach state morphology (reflective, dissipative, or intermediate; for example). Thus, the vulnerabilities obtained by the mentioned authors are, accordingly, more comprehensive, being usually adopted of a wider range of variables, research approaches and classification schemes.

The lower exposure of the sheltered environments to physical hazards forcing is the main difference between sheltered and the exposed environments. For example, in sheltered environments while astronomical tidal currents may be more effective, there is limited response ocean wave incidence.

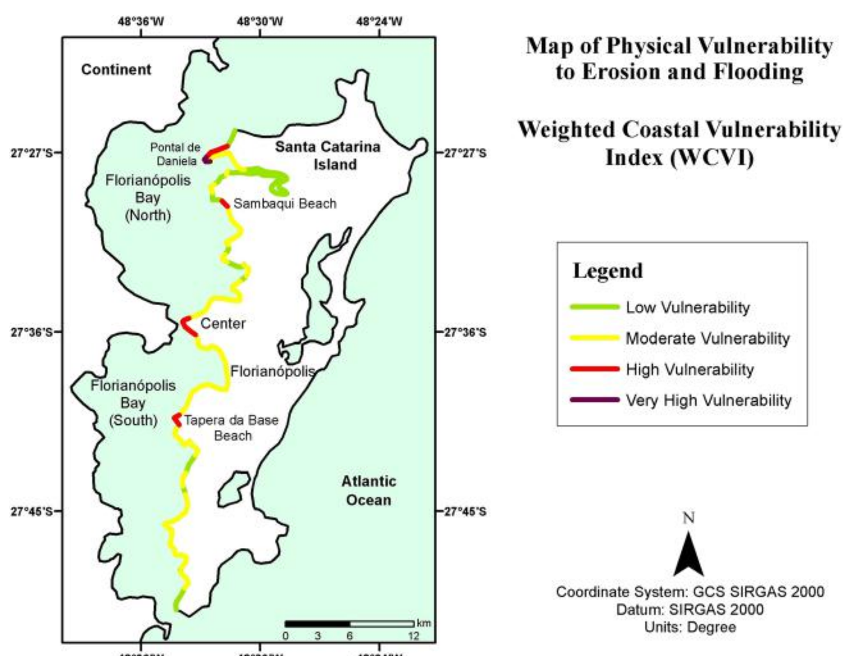


Fig. 11 Map of physical vulnerability to erosion and flooding along the studied coastline

Thus, waves generated by the local wind play an essential role in the hydrodynamics, with greater response of the environment, but with a lower capability of modifying the coastal morphology or allowing water intrusion into inner sectors of the backshore.

The tendency is that exposed coasts present greater variability in their degrees of vulnerability, while sheltered ones can be segmented basically into a few classes. The area investigated in this paper, therefore, is dominated by low and moderate sectors, with occasional and very short segments of high vulnerability.

The results obtained by Mussi et al. (2018) also cover the sheltered coast of Santa Catarina Island. Thus, it was possible to compare two applications of the same model in the area under investigation. In their research, the authors used the same attributes for both sheltered and exposed systems, so the response of the sheltered coast was limited in some aspects, being classified between sectors of very low and low vulnerability. On the other hand, in the present research the sheltered environment was valued by using specific attributes that imply greater responses from this environment, resulting in an increased degree of costal vulnerability. Thus, it is noticeable that the choice of the physical descriptors influences the final classification of the system vulnerability. The amount and variability of the coastal segments depend on the data scale/resolution of the original data, but the degree of vulnerability (very low to very high) is directly reliant on the physical attributes that are considered.

Another aspect, related to the aforementioned lower energy availability in sheltered coasts, is the dominance of geological and morphological factors on the determination of the overall physical vulnerability, which may be locally modeled by second- and third-order elements. In this sense, it must be noticed that the chosen first-order variables Geology and Geomorphology (which represent the structural framework of the site) have a high degree of redundancy. Considering that sedimentary deposits may induce different morphologies and that different degrees of vulnerabilities could be assigned to them in a more representative way, we propose the use of the sole variable Geomorphology as first-order structural data in future researches.

Conclusions

The Smartline Methodology was smooth to perform, and the proposed scheme of attribute hierarchization contributed to a better perception and representation of the factors involved in the physical vulnerability of sheltered coastal environments.

Following this methodology, most of the study area was classified almost equally among sectors of low and moderate vulnerability, with occasional occurrences of high vulnerability. Some moderate vulnerability segments, such as in the central portion of the study area, present high urbanization very close to the coastline and may deserve special attention from public management agencies.

From the comparison of this research with coastal vulnerability investigations carried out in exposed areas of Santa Catarina Island it was observed that exposed coasts offer greater variability of physical elements for analysis, allowing the use of broader approaches for the assessment.

The obtained assessment of physical vulnerability to coastal erosion and flooding in local scale can be useful in public management policies, such as urban development and risk management plans, as well as in the prevention of environmental disasters. However, this research also pointed out the a scarcity of studies about physical vulnerability of sheltered coasts, so the effectiveness of its practical use is a topic that requires more investigation.

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