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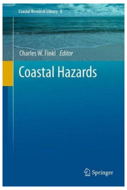

Chapter 16
Spatial and Numerical Methodologies on Coastal Erosion and Flooding Risk Assessment

Jarbas Bonetti, Antonio Henrique da Fontoura Klein, Mariela Muler, Clarissa Brelinger De Luca, Guilherme Vieira da Silva, Elírio E. Toldo Jr., and Mauricio González

Abstract In the last decades the combination of an increasing human occupation along the coast combined with an anticipated intensification in the frequency of meteorological extreme events stimulated the development of different methodological alternatives to assess and predict coastal risk. Conceptually, a global risk analysis may involve susceptibility and vulnerability, in both temporal and spatial scales, with the goal of identifying critical hazard areas. In this work, two different analytical approaches are presented within the perspective of their future integration: spatial analysis based on Geographic Information Systems and numerical modeling. In the first approach, individual information layers associated with various themes (*e.g*. backshore landforms, backshore altitude, shoreline displacement, shoreline exposure to wave incidence and man-made structures at risk) were integrated and allowed the development of a numerical index of coastal vulnerability. In order to define inundation levels, a wave run-up study integrated numerical modeling and *in situ* measurements, allowing the recognition of sensible variations

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along an embayed beach. Finally, an erosional hot spot area was investigated by calculating longshore sediment transport rates. For this, a numerical model of wave propagation defined the coastal wave climate and the average sediment budget was determined in the surf zone. The three case studies of beaches with historical sensibility to erosion and storm surge flooding presented a very good correlation with reality.

16.1 Introduction

During the last few decades there has been an increase in the frequency and intensity of natural disasters (Freeman et al. 2003). Events such as floods and storms seem to have intensified in the last century, especially after the 1950s (EM-DAT 2011; Freeman et al. 2003). In southern Brazil, for example, significant wave height is expected to increase by 2.5 cm/year and sea levels are estimated to rise by 1–3 mm/year (CEPAL-ONU 2011a). Global warming can make these events worse (Pezza and Simmonds 2005), impacting those living close to the coast. Inundations levels, i.e., the topographic level achieved by a certain event, that cause coastal flooding and coastal erosion are closely related to climate changes. Destruction of man-made structures located close to the shoreline as a result of the erosion process depends on the elevation achieved by the water relative to the height of the adjacent beach (Ruggiero et al. 2001).

Coastal erosion is the encroachment of land by the sea and is measured using the average over a period of time that is sufficiently long enough to eliminate the impacts of weather, storm events and local sediment dynamics. Coastal erosion is usually the result of a combination of factors, both natural and human-induced, that operate on different scales. As expressed under the framework of the EUROSION European project (EUROSION 2004), the most important natural factors are as follows: (1) winds, (2) storms, (3) near shore currents (wave-induced and/or tidal currents), (4) relative sea level rise and (5) slope processes (collapse, slippage, or toppling of coastal cliff blocks). On the other hand, human-induced factors of coastal erosion include the following: (1) river basin regulation works, (2) coastal structures in urban, tourist or industrial coastal zones, (3) land claiming, (4) dredging, (5) vegetation clearing (dune areas and on the top of cliffs) and (6) gas mining and water extraction. The resulting coastal erosion can be related to three different types of impacts: (1) loss of land with economic value, (2) destruction of natural sea defenses (usually a dune system) as a result of a single storm event, which causes the backshore to flood more easily and (3) undermining of artificial sea defenses, potentially leading to an increased flood risk.

Coastal flooding is a random phenomenon arising from the combination of various marine processes. In a simplified form, this phenomenon can be represented as shown in Fig. 16.1. At a given time, a point on the coast is characterized by a certain reference sea level comprising the astronomical and the meteorological

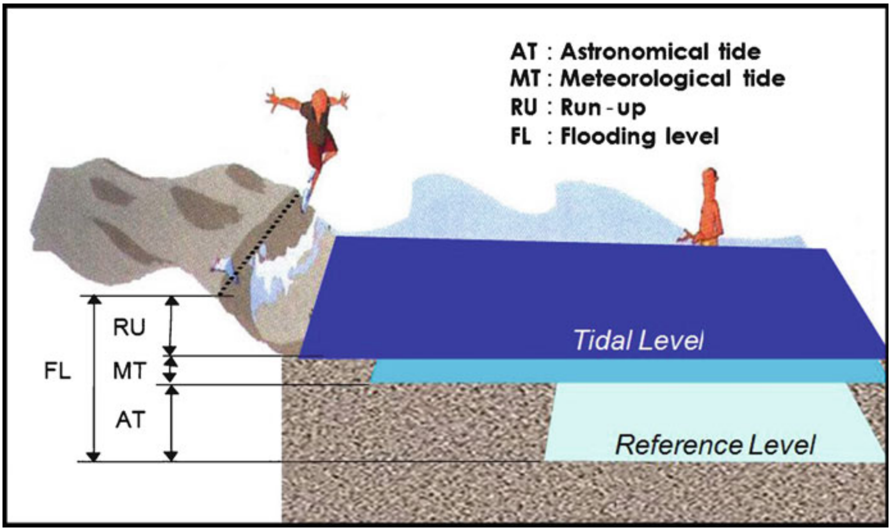

Fig. 16.1 Schematic diagram of the factors affecting the flood level at a certain point on the coast

tides (AT + MT) and the bathymetry. The MT may include super-elevations caused by hurricanes and the effects of el Niño and la Niña (ENSO). In addition to this level are the swell waves which, depending on their characteristics and the bathymetry close to the beach, are propagated toward the coast. When reaching the coast, the swell breaks (on the beach, levee or rockfill breakwater, waterfront, etc.) producing an upward movement of the water mass along the coastal profile, called run-up (RU). All of these factors are inter-related. In addition to the interaction between the elements (tidal level, bathymetry, swell and run-up), the phenomenon of flooding offers the added complication that some factors (waves and winds) cannot be easily predicted in advance due to their random behavior; therefore, their effects are related to a given probability of occurrence.

To evaluate coastal impacts associated with flooding and long-term erosion processes, one possible conceptual framework is based on the definition of risk as the probability of harmful consequences or expected losses resulting from a given hazard to a given element in danger of peril over a specified time period (Schneiderbauer and Ehrlich 2004). Therefore, risk depends on the specific impact analyzed (e.g., loss of human lives), the probability that the threat will occur (e.g., flooding frequency), the exposure of the studied elements (e.g., presence of urban areas) and their adaptive capacity (e.g., sensitive groups and their resilience).

The hazard assessment is based on the numerical modeling of the dynamics under study (waves, sea level, erosion, etc.) to understand the probability, frequency, intensity, and duration of a hypothetical event, as well as the potentially affected area. Once the hazards have been identified and analyzed, vulnerability assessments are carried out for each identified hazard and for each location. The comparison between hazard and vulnerability assessment results will provide information about the real risk a certain coastal sector is subjected to. The vulnerability assessment of the exposed elements, given the complexity of coastal areas, is based on an integrated approach, which is essential to consider the interrelationships between the various coastal dimensions and spatial variations. This assessment is usually based on the development of a set of themes and descriptors supported by a Geographic Information System that allows for the graphical and spatial representations of physical, environmental, social, economic and infrastructure characteristics of the coast. Different spatial and temporal scales should also be considered because both factors change the amount and type of the exposed elements (susceptibility) and their vulnerability. A final global risk analysis (hazard, susceptibility and vulnerability analyses for every dimension using both temporal and spatial scales) identifies critical areas and the coping capacity weaknesses, allowing the formulation of a set of risk reduction measures.

Coastal vulnerability and hazard assessments are based on the spatial analysis of the exposed elements and the numerical modeling of the dynamics. Some methodological approaches and numerical tools to evaluate these elements are discussed in the following sections and will be illustrated with some case studies applied to southern Brazil.

16.2 Spatial Analysis

The analysis of the exposed spatial elements and their vulnerability is an initial step to evaluate the consequences of coastal impacts and associated risks because it provides, by itself, a comprehensive diagnosis for coastal hazards (flooding, erosion, climate change, etc.). Once existing elements of the coastal landscape that indicate real exposure have been accounted for, hot spots along the coast can be identified with a degree of accuracy.

Although the term vulnerability may be found in the literature associated with different concepts, it is generally related to human interaction with the environment (Cutter 1996; White et al. 2001; Alcántara-Ayala 2002; Wu et al. 2002; Dolan and Walker 2003; ISDR 2004; UNDP 2004). Vulnerability may be considered as a function of a pre-existing condition of hazard exposure (susceptibility) and the capacity for community adaptation, i.e., the combination of natural hazards and the human exposure to them.

Many proposals for vulnerability analysis have been explored internationally due to the apparent increase of natural disasters. In Brazil, serious disasters have been reported concerning river floods and landslides, which in many cases were associated with casualties. Therefore, vulnerability assessments gained importance, becoming highly relevant for the protection of the population. Those assessments identify and characterize risk areas and vulnerable settlements, helping decision makers to effectively determine prevention and mitigation strategies.

There are different alternatives to assess vulnerability. A popular European methodology was presented in the project DINAS-COAST – "Dynamic and

Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-level Rise", that applied a tool called the Dynamic and Interactive Vulnerability Assessment (DIVA). This tool encompasses a global database, an integrated model and a graphical user interface that enable users to produce quantitative information about a range of coastal vulnerability indicators to select climatic and socio-economic scenarios and adaptation strategies (Hinkel and Klein 2009). DIVA is efficient for small-scale analysis but may not be useful for coastal planning, which usually requires more detail than what is visible in national or regional maps.

The vulnerability assessment and methodology for the regional study on the effects of Climate Change along the coast of Latin America and the Caribbean (CEPAL-ONU 2011a, b, c) focus on the physical, socioeconomic and ecologic conditions of the region's coastal areas. Overall, 15,000 units of study representing 5 km in area and variables such as land surface, land uses, croplands, ecosystems, population, infrastructures or coastal typologies were characterized and studied to define a quantitative assessment of the coastal vulnerability and exposure to marine hazards. The methodology for this robust diagnosis was also developed on small to regional scales, which must be taken into account for the practical application of its results.

Another methodology for the vulnerability assessment was designed by the National Oceanic and Atmospheric Administration's Coastal Services Center and is called "The Community Vulnerability Assessment Tool (CVAT)" (Flax et al. 2002). Its goal is to assist emergency managers and planners in their efforts to reduce hazard vulnerabilities by creating hazard maps, overlaying those maps (representing different hazards) and finally using a scoring system, which gives the greatest values to the most vulnerable areas. This approach deals specifically with socioeconomic factors.

The State of Hawaii has an atlas of natural hazard assessments comprised of a technical map series displaying the ranked nominal intensity of each hazard (Fletcher et al. 2002). Those rankings are applied as a relative scale based on a logical interpretation of environmental variables, such as geology and coastal zone slope. Additionally, this publication compiles and constructs a hazards' history in the Hawaiian Islands. With continued monitoring, the aim is to predict the chronology and intensity of hazards, which is extremely important for coastal management.

The "Geomorphic Stability Mapping – GSM", an Australian approach proposed by Sharples (2006), is an indicative and descriptive mapping of geomorphic vulnerability to coastal hazards. It considers the basic coastal geological and geomorphic characteristics that may be related to vulnerability, such as intertidal landforms, backshore landforms, backshore profiles, shoreline exposure and rock types. For this method, the shoreline is segmented, bringing multiple pieces of information attached to the vector lines representing the coast. Because descriptive maps are not always easy to compare or interpret by decision makers, this approach is an important first step to investigative the effort necessary to recognize an area of interest.

Another important methodology is the Coastal Vulnerability Index (CVI) proposed by Gornitz (1991) and the United States Geological Survey (USGS). This approach is a relative ranking based on scaled indexes wherein each factor receives a value for vulnerability classification. Those factors are relief, rock types, landform, relative sea-level change, shoreline displacement, tidal range and maximum wave height and are integrated in a mathematical relation (weighted sum) to obtain to the final vulnerability indication.

It is important to underline that, although the CVI (Gornitz 1991) and the GSM (Sharples 2006) work well in applied studies, they consider vulnerability exclusively related to physical factors. In practical terms, it is essential to include human factors, taking into account that damage occurs due to human presence/influence in the environment. In other words, an effective vulnerability assessment has to consider human losses; otherwise, it may be considered a susceptibility measurement.

These approaches all try to recognize relationships and integrate descriptors to generate new information and spatial analysis using Geographic Information Systems (GIS) is the tool usually adopted for this type of research.

Vulnerability assessments require a structured database that integrates environmental, social, economic and political factors to be used as proxies for the evaluation of the degree of vulnerability.

In Brazil, specifically, the lack of reference data has been a strong limitation to a comprehensive understanding of coastal environments on a more complex or extensive analysis. Although an improvement is expected in the next years, at the moment the available data are accessible from different sources that are not always interoperable and sometimes lack metadata because they are not obtainable from centralized spatial data infrastructures (SDI).

Once obtained, the data can be inserted and represented in a GIS using two basic models: raster and vector. The choice of the data model will depend on how they will be individually categorized into classes of vulnerability and crossed, aiming for a final integrated assessment. Most of the time, different scales and legends have to be harmonized, causing technical difficulties in model construction and forcing researchers to spend a considerable amount of time on structuring the database. To improve the flux of activities, geodatabase models are important in the edifice of the correct structure that will be used to establish the relations and interactions between the data. Currently, it is essential to adequately choose the spatial data model that best fits the selected data. For instance, the GSM presents its results as vectors while the CVI has both vector and raster representations (Gornitz 1991; Thieler and Hammar-Klose 2000).

16.2.1 Case Study

In this example, spatial analysis was used to assess coastal vulnerability to storm surges. The adopted geoprocessing technique was the weighted sum of data layers applied to the creation of an index that could represent the vulnerability in a

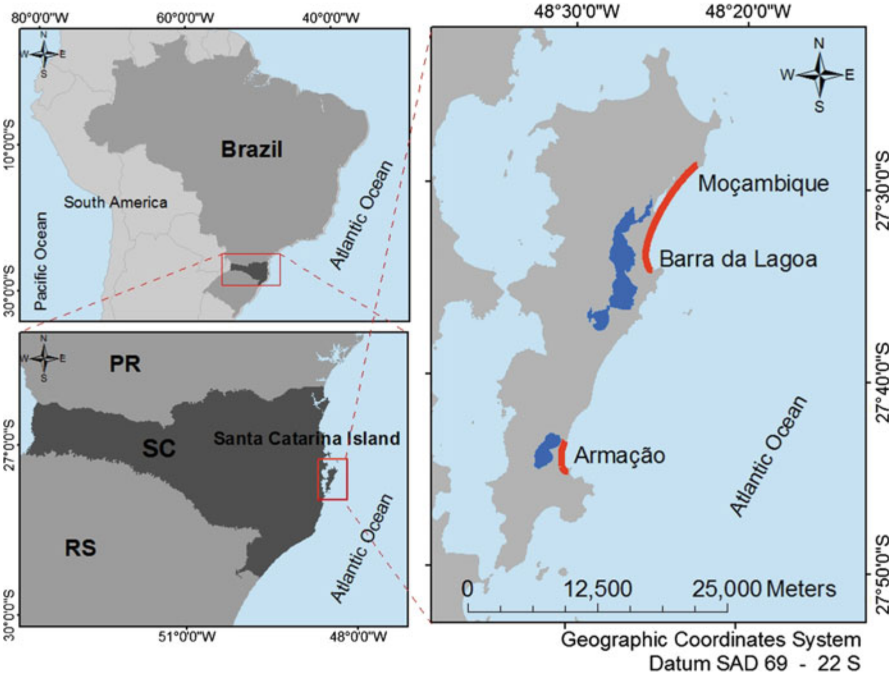

Fig. 16.2 Location of the interest areas in southern Brazil with details of Santa Catarina Island and the studied beaches (*red lines*)

practical and efficient way. This index was based on the CVI (Gornitz 1991); however, the variables considered were different because they were adapted to a local scale taking into account the availability of data for study area. Thus, this research aimed to identify the best descriptors for the vulnerability analysis in the local context.

Extreme events affect the coast disproportionately and damage will depend on the environmental, social and economic characteristics of the coastal sector. Therefore, it is efficient to segment the coastline in homogeneous parts and to classify them individually. Vector representation was chosen, thus relevant information related to vulnerability was attached to the shoreline feature.

The study sites were two beaches located on Santa Catarina Island (Florianópolis – SC, Brazil) that have suffered damages due to storm surges in the last few years: (1) the beach arc between Barra da Lagoa and Moçambique, which is located on the central-east coast and (2) Armação beach, which is located on the southern coast (Fig. 16.2).

Among Santa Catarina's coastal municipalities, Florianópolis is the most threatened by storm surges, experiencing damage most often (Rudorff et al. 2006), which causes severe consequences to coastal communities, such as the destruction of facilities and tourism devaluation.

The proposed index includes five descriptors for the vulnerability assessment. The first refers to backshore landforms and considers the main characteristics related to land use, vegetation, dune features, etc. of the areas adjoining the sandy beaches. The results were obtained by visually classifying high resolution satellite images. The second variable was the backshore altitude, considering that flat areas are more susceptible to inundation. Heights were obtained from detailed planialtimetric charts with a scale of 1:2.000.

The third input variable was shoreline displacement to obtain a better understanding of the dynamics of this feature over the last few decades. The five decades time series of shorelines was extracted from aerial photographs processed by the ArcGIS extension (DSAS – Digital Shoreline Analysis System; Thieler et al. 2009 by USGS) that calculates the shoreline displacement rate (meters per year) for the period covered by the photos.

A fourth descriptor was shoreline exposure to wave incidence. The mean shoreline orientation was associated with wave incidence direction and with the frequency of extreme events registered for each direction. Another ArcGIS extension from the USGS, the Wind Fetch Model (Finlayson 2005), was used to estimate the wind fetch. For the statistical analysis of extreme events, a wave database covering the period from 1948 to 2008 was used.

The fifth implemented variable in the vulnerability assessment was related to population and buildings at risk. Structures facing the sea were quantified from 2009 Quickbird images and then the constructed area was delimited as a polygon feature. The inland extent of the vulnerable area was determined by considering its predicted position in the next 50 years from the trend identified in a 52-year series of aerial photos. Using census data (IBGE 2010), it was possible to estimate the number of residents in the risk area.

The final index calculation followed the formula: $CVI = \frac{\left(\sqrt{a \times b \times c \times d \times e}\right)}{n}$, where a, b, c, d, e are the variables described above after categorization (attribution of vulnerability intervals, from 1 to 5) and n is the number of considered parameters. The final vulnerability classification (from very low = 1 to very high = 5) was based on percentiles obtained from the CVI results. This estimate can be easily performed using ArcGIS by combining the shoreline segments containing information on the five parameters.

The results showed areas of very low and low vulnerability in the north sector of Armação beach and in the central and north sections of Barra da Lagoa/Moçambique arc (Fig. 16.3), all of which have very low populations. In the central part of Armação beach, the vulnerability reaches moderate values and to the south, where effective erosion problems are concentrated, vulnerability presents high and very high values. This sector of very high vulnerability coincided with the area where houses were destroyed by waves in a storm surge event in the year 2010. The same thing happened at Barra da Lagoa/Moçambique (Fig. 16.4), where its southern sector had more vulnerable index values (moderate and high).

This proposed index is relatively simple to apply, but it should not be considered a fast preliminary approach because it requires specific data from different nature and a diversity of sources. Because the required data are not always available in

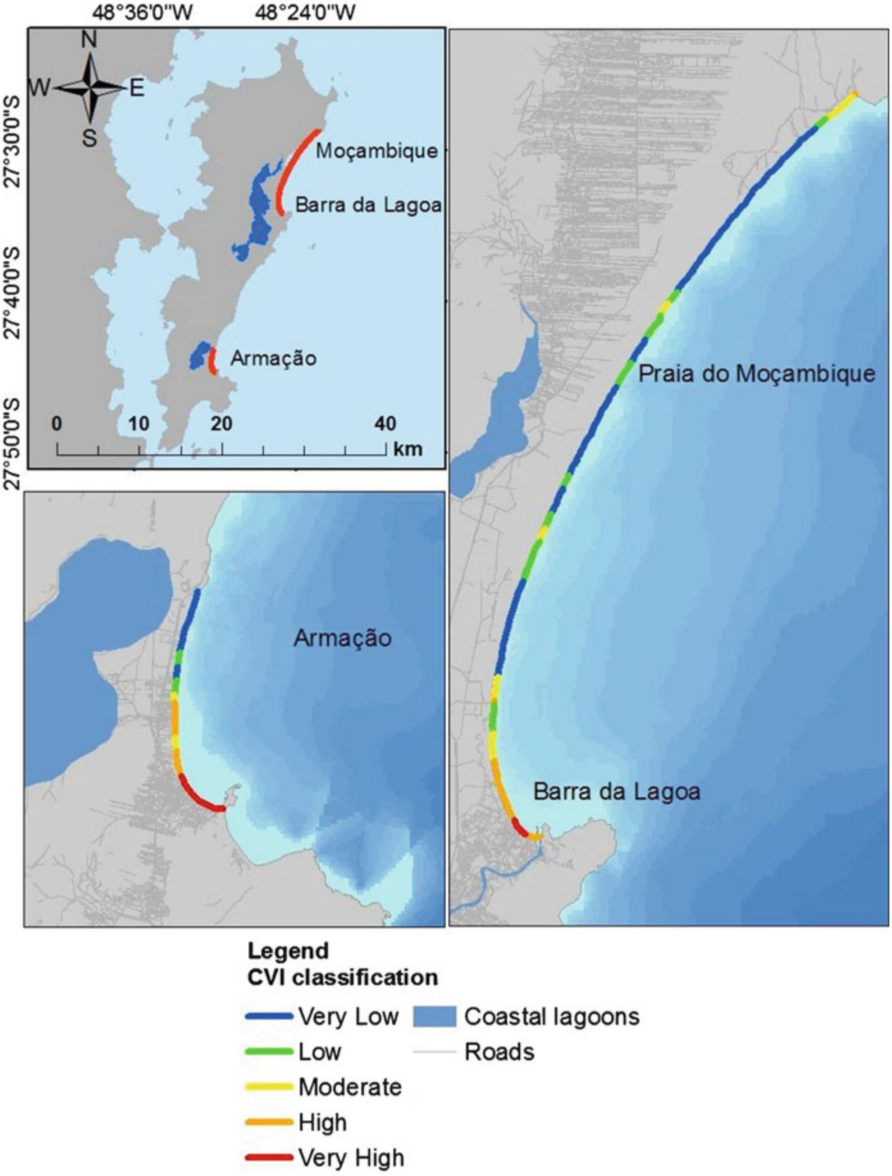

Fig. 16.3 Resulting vulnerability index map obtained for Moçambique, Barra da Lagoa and Armação beaches

an appropriate GIS format, the assembly and treatment of the reference data can be very time consuming.

Although the index still generates only an indicative coastal vulnerability assessment, such as the GSM or the CVI methodologies, there are two important differences that will be explored in more detail in future studies. First, this new

Fig. 16.4 Morphological impacts of an extreme storm event (April 2010) along the beaches of Barra da Lagoa and Moçambique (Photos by J. Bonetti)

index is suitable for local scale assessment, which allows it to more efficiently support applied development planning. Second, the effects of population and man-made structures were incorporated, allowing the quantification of the losses that may result from erosional processes induced by extreme storm surges.

16.3 Numerical Modeling

The practice of numerical modeling has grown during the last few years due to the improvement in both the knowledge of coastal dynamics and computer processing capability. Numerical modeling uses data from the past (e.g., a hindcast of waves, wind, currents, tides, and total levels) to understand the ocean processes according to a given spatial scale and tries to predict coastal behavior (forecasting). Considering the wide range of numerical models available, it is important to choose the one that best fits the aim and the spatial/temporal scale of the project. That choice will depend on: (a) the model operability, (b) the type of dynamic to be analyzed and (c) the spatial scale to be considered.

Ease of model operation combined with a poor understanding of the modeled dynamics can lead to incorrect results, which may induce misinterpretation. Misinterpretation can be avoided by having a good theoretical background and by critically analyzing the results.

Despite the increase in computer processing capabilities, it's still not possible to calculate/account for the transformation that happens on macro scales (kilometers/centuries) by integrating mega or micro scale processes (centimeters/minutes) (Cowell and Thom 1997). Processes that occur on different scales must be analyzed using a wide range of models and formulations. Because of this, it is very important to define the scales (both spatial and temporal) that processes should be modeled to apply the best model.

The database characteristic used as an input in the modeling process is an important point to be considered. Data with high spatial and temporal resolutions are necessary in coastal hazards studies, such as inundation levels and beach erosion because they guarantee a detailed study about the environment and fortify the decision making process.

After defining a problem, the processes that govern it, the spatial and temporal scales, and the data available, a model should be chosen and applied to the study area. As examples, two model applications will be shown in this section to assess coastal hazards: (a) inundation levels and recurrence intervals and (b) beach erosion.

16.3.1 Case Studies

16.3.1.1 Common Aspects of the Methodology

To assess both recurrence times of inundation levels and beach erosion it is important to have a wave climate established near the study area. To do that, a 60-year dataset was used. The astronomical tide data (1948–2008) was generated by a TPXO (TOPEX/Poseidon Global Inverse Solution) model (Egbert et al. 1994; Egbert and Erofeeva 2002) using eight tidal harmonic constants (M2, S2, N2, K2, K1, O1, P1 and Q1). Meteorological data were obtained using a numerical model (ROMS – Regional Ocean Modeling System) developed by the Rutgers Ocean Modeling Group; its formulations were described by Shchepetkin and McWilliams (2003). The 60-year wave hindcast dataset was transferred from deep water to shallower water by using a SWAN model (Booij et al. 1999), and its parameters were obtained at the study area. The wave hindcast data were calibrated using satellite data (TOPEX), Reguero et al. (2012). This was performed by propagating 200 wave cases using a case selector (MaxDiss) and re-constructing the complete series using an interpolation method (RBF), as proposed by Camus et al. (2011a, b).

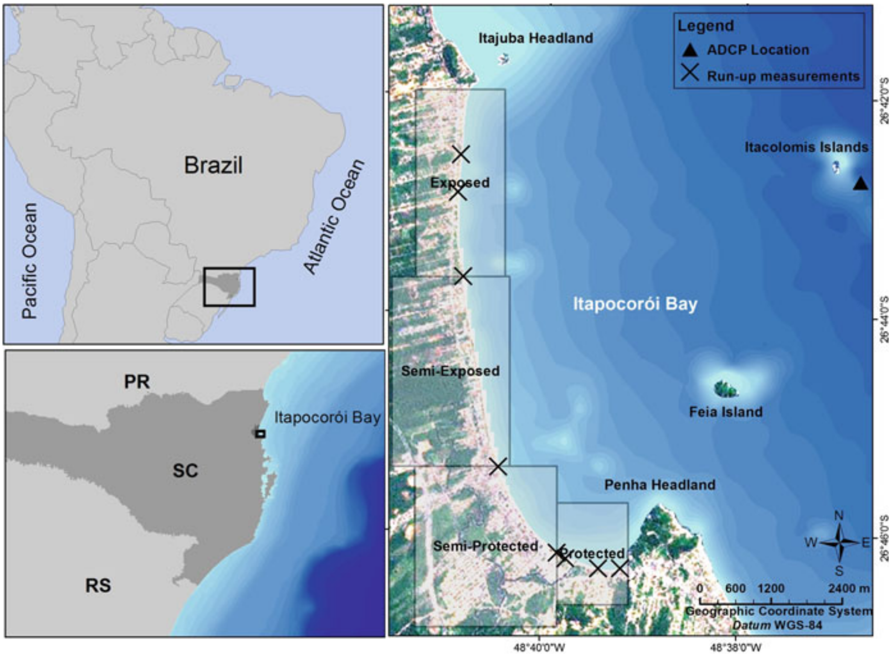

Fig. 16.5 The wave run-up measurement points on the beach face (X) and the ADCP (*triangle*) moored at Itapocorói Bay in the northeastern state of Santa Catarina (Background satellite image source: Google Earth)

16.3.1.2 Inundation Levels

The case study area is a 9 km long embayed beach located in southern Brazil (Fig. 16.5). Its southern part (Itapocorói beach) is protected from wave action by the presence of a headland. Araujo et al. (2010) classified it as a dissipative beach, being its southernmost part composed by fine sands and a narrow beach profile (about 50 m wide). Toward the north, the energy increases and the beach (Piçarras) becomes reflective, characterized by medium sand and a wider (up to 200 m), sub-aerial beach profile.

To assess the wave run-up behavior along the embayed beach, a numerical model was used in conjunction with a methodology to evaluate the headland influence over the wave run-up. Field work was carried out to calibrate the wave run-up formulations. Wave and tidal data were obtained for a period of 1 month (by mooring an ADCP-AWAC) and, on separate occasions, wave run-up data were determined over 30 min at each of the seven points along the shoreline (Fig. 16.5) using a dynamic positioning system (GPS-RTK). The beach profile has been measured using a trigonometric method (with a total station) to calculate the

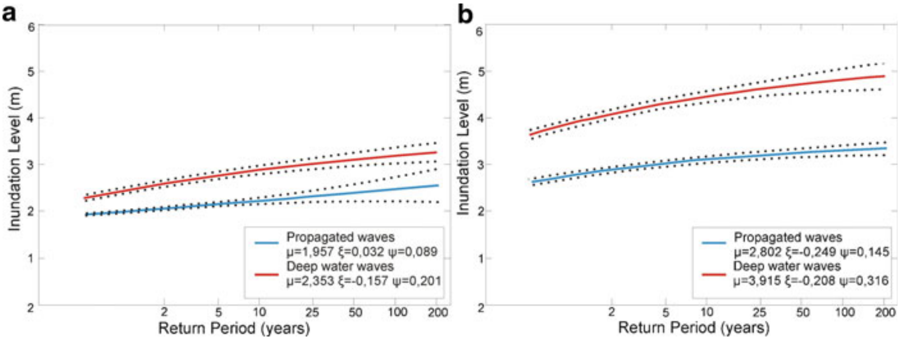

Fig. 16.6 Return period calculated for protected (**a**) and exposed beaches (**b**)

beach face slope. As expected, the available wave run-up formulation worked for the exposed area but did not present a good performance for the protected sector. Formulation developed by Nielsen and Hanslow (1991) was then calibrated for four distinct beach sectors: protected, semi-protected, semi-exposed and exposed, according to a best-fit linear regression.

The calibrated equations for each sector are as follows:

Protected: $R_{2\%protected} = 0.269 \times R_{2\%Nielsen\,and\,Hanslow\,(1991)} + 0.360$
Semi-protected: $R_{2\%semi-protected} = 0.195 \times R_{2\%Nielsen\,and\,Hanslow\,(1991)} + 0.59$
Semi-exposed: $R_{2\%semi-exposed} = 0.529 \times R_{2\%Nielsen\,and\,Hanslow\,(1991)} + 0.421$
Exposed: $R_{2\%exposed} = 0.601 \times R_{2\%Nielsen\,and\,Hanslow\,(1991)} + 0.603$

Having the wave climate near the study area (same position as the ACDP-AWAC was moored, at 15 m depth) and the hourly astronomical tides, meteorological tides and wave run-up data, the inundation levels were calculated by summing these data for each hour of the series, resulting in an hourly inundation level from 1948 to 2008. A return period was also calculated for each beach sector. To do that, a maximum annual significant wave height was identified and then a Generalized Extreme Value (GEV) function was applied over the series. To compare the efficiency of the wave propagation method used to assess coastal flooding, the inundation levels were calculated for both propagated and offshore wave data. The results are shown in Fig. 16.6.

By analyzing Fig. 16.6, the importance of using a wave model to transfer wave data to the study area and the importance of calibrating the wave run-up equations becomes clear. Wave models can reproduce most of the processes that a wave undergoes as it propagates to shallower water, and the propagated waves are more realistic to assess coastal hazards because they represent the real sea state of the study area. Additionally, wave run-up calibration has an important role in assessing coastal flooding on embayed beaches. The available formulations were developed for exposed areas, and if they were applied without a calibration the results would be overestimated (over 2 m), especially in the protected sectors of the beach.

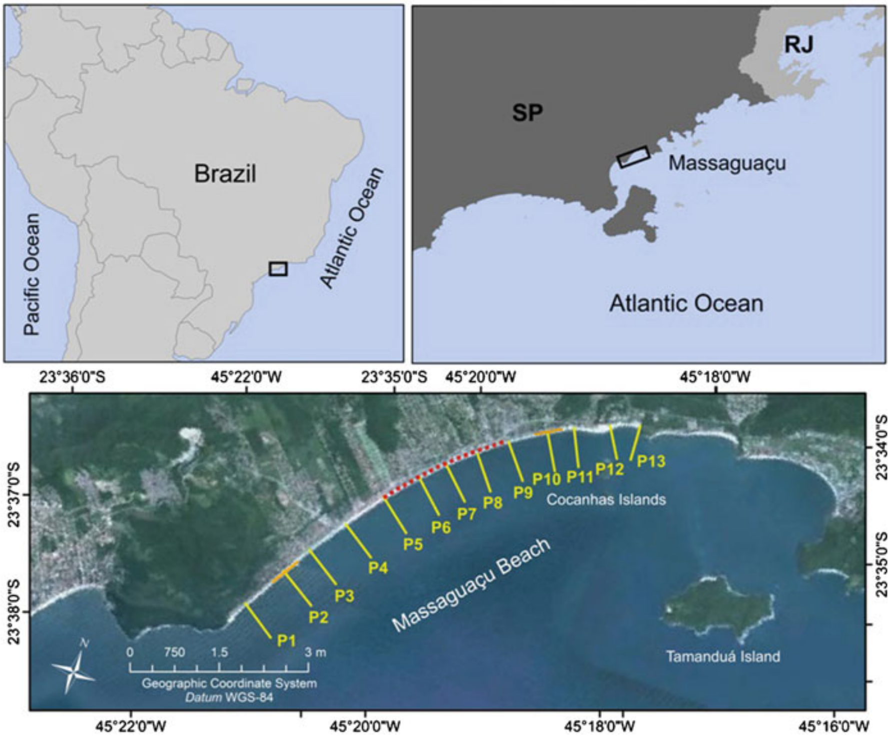

Fig. 16.7 Location of beach profiles at Massaguaçu beach, state of São Paulo. The littoral drift was calculated for the surf zone (*yellow lines*), the shoreline position of each profile appears in *orange* and the erosional hot spots identified by Nuber (2008) are the *red points* (Background satellite image source: Google Earth)

16.3.1.3 Beach Erosion

The chosen area for this study is an embayed beach located in Southeastern Brazil that is approximately 7.5 km in length called Massaguaçu (Fig. 16.7). Over the past few decades, this beach has been experiencing erosion, with high retreat rates in some segments, commonly termed as Erosional Hot Spots (EHSs; singular EHS). Nuber (2008) identified these areas along the central part of Massaguaçu during the period from 2006 to 2008 (Fig. 16.7). According to Kraus and Gangano (2001), depending on the cause of the erosional hot spot, the redistribution of the eroded material may create or preserve one or more accumulation areas along the beach (Erosional Cold Spot, ECS).

Waves, currents and the sediment supply are the primary controls of the longshore sediment transport process, and the evaluation of the causes and consequences of erosion requires an understanding of the processes involved in sediment transport and the local sediment budget. In this example, erosion is represented on a local scale by the sediment transport generated by wind waves in the surf zone.

To calculate the longshore sediment transport in the surf zone, the wave climate had to be transferred to coastal areas (Camus et al. 2011a, b), and a numerical model of wave propagation had to be run (OLUCA-SP; González et al. 2007, 2010; Raabe et al. 2010). The purpose was to obtain the wave climate at specific points in the surf zone, where it was considered relevant to calculate sediment transport. The CERC (1984) formula (Shore Protection Manual, modified by Del Valle et al. 1993) was used to predict the total rate of the longshore sediment transport.

The following results represent the annual average of net longshore sediment transport rates during the period from 1948 to 2008 (Table 16.1 and Fig. 16.8). The estimate was carried out using values corresponding to D50 (mean grain size) in the studied profiles and the shoreline position, assuming that each profile represents the mean transport condition for the area in which it is located.

Waves and currents can transport considerable amounts of sediment along the coast and the longshore sediment transport will often be the dominant factor in the sediment budget. This is particularly important on an embayed coast, where the presence of large physical barriers (headlands) trap alongshore-moving sediment, resulting in net erosion/accretion at the updrift/downdrift ends of the beach (Harley et al. 2011). In this study, this process is represented by italic (erosion) and bold (accretion) numbers, respectively, in Table 16.1.

The values of net sediment transport in Table 16.1/Fig. 16.8 show an irregular transport in both directions between profiles 1 and 4 (Fig. 16.9) due to the presence of a rocky ledge that causes irregular currents in the SW part of the beach. As a result, consecutive erosion and accretion zones can be observed there.

Between profiles 5 and 6, it is possible to identify an erosional process that extends to profile 10 due to divergent directions of sediment transport and the occurrence of oblique waves resulting from local shoreline instability. The results obtained by Nuber (2008), using sedimentological and morphological data, show that Massaguaçu beach, in this zone, can be characterized as an erosional hot spot.

Furthermore, it is important to emphasize that the sediment accumulation in profiles 11, 12, and 13 are the result of a decrease in the sediment transport rates (possible cold spot areas). Nuber (2008) observed a shoreline progradation of up to 15 m in this section during the period from 2006 to 2008.

An appropriate transport dynamic representation was obtained from Massaguaçu beach by numerical modeling, which corroborates the real environment situation. After analyzing the sediment transport at Massaguaçu beach and the beach plan and profile forms using long-term models, it can be concluded that the existing erosion process in the central part of this beach is due to a non-equilibrium in plan-form from profile 5 to profile 11. This the lack of equilibrium generates a current system that is highly dependent on incident waves, which transport fine sediments from SW to NE. This system favors an accelerated erosion process in the central portion of the beach (erosional hot spot area) and sediment accumulation on its NE side (a possible cold spot area).

Table 16.1 Sediment transport rates at Massaguaçu beach (105 m^3/year)

Profiles	1	2	3	4	5	6	7	8	9	10	11	12	13
Positive (+)	0.32	0.45	0.61	0.61	2.45	0.16	0.095	0.0001	0	0	0.005	0.61	4.28
Negative (−)	0.45	0.44	0.92	0.58	0.12	1.02	1.40	2.0	3.5	4.16	1.15	1.76	0
Liquid	*−0.13*	**0.01**	*−0.31*	**0.03**	*2.33*	*−0.86*	*−1.31*	*−2.0*	*−3.5*	*−4.16*	**−1.15**	**−1.15**	**4.2**

Positive values represent the net sediment transport in the NE-SW direction and the negative values represent the opposite transport direction (SW-NE). Liquid transport values in *bold represent accretion* and *italic values represent erosion processes*

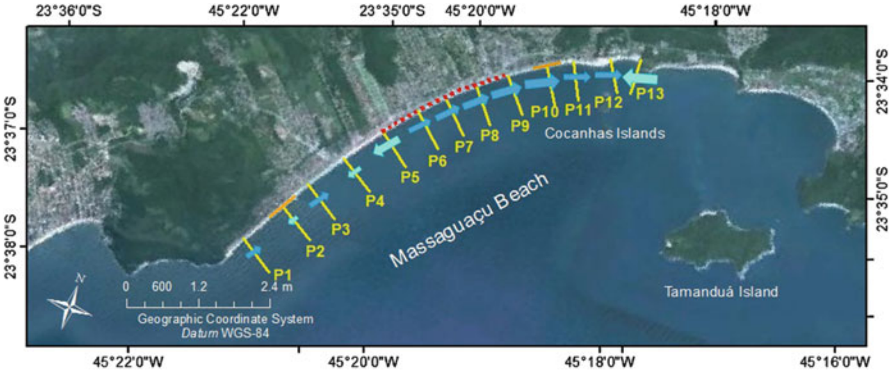

Fig. 16.8 A conceptual model of net sediment transport variability at Massaguaçu beach. *Cyan arrows indicate* the net sediment transport to the NE and the *blue arrows* represent the opposite transport direction. *Red points* are the erosional hot spots (Nuber 2008) (Background satellite image source: Google Earth)

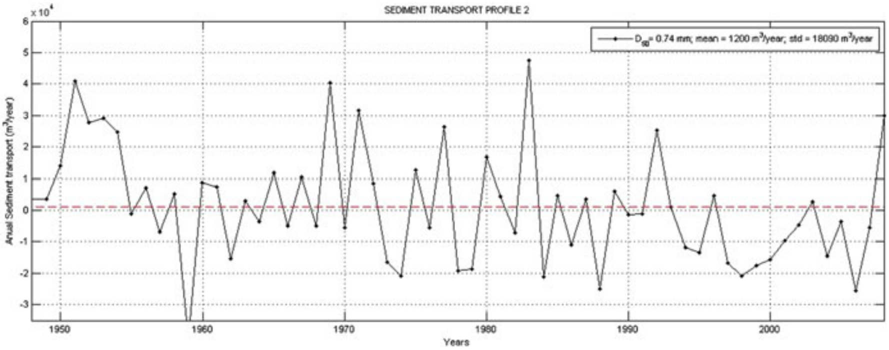

Fig. 16.9 Annual average of net long shore sediment transport in profile 2

16.4 Concluding Remarks

16.4.1 Spatial Analysis

The organization of spatial data in open and integrated infrastructure services is a relatively new task and, due to the lack of structured information in many countries, vulnerability maps tend to be subjective and based on the perception of the exposure to coastal hazards. However, in the last decade, many quantitative approaches for susceptibility mapping have been proposed, most of which were developed at regional or national levels, using small-scale data and not directly quantifying human exposure in the assessment (vulnerability).

The dichotomy of spatial model selection (raster vs. vector) seems to have been overcome, being the main actual challenge the adequate selection of the representative variables and their categorization in significant intervals.

In this chapter, an alternative that incorporates previous approaches related to the coastal vulnerability index calculation is proposed. The inclusion of a shoreline change forecast associated with sea level rise rates allowed for the quantification of the zone at risk under the worst case scenario. Additionally, the statistical analysis of the wave climate and the weighted integration of the most important wave directions with the areas of urban settlements allowed for a more precise definition of the areas sensitive to coastal flooding by storm surges and other extreme events.

16.4.2 Numerical Modeling

A robust method to quantify the level achieved by an instantaneous event (inundation level) and its return period was also presented here. The errors caused by imprecise data, especially by estimating wave run-up on bay beaches, have been minimized by calibrating equations and by transferring wave data close to the study point. In this study, the observed overestimation (not considering wave propagation) could reach over 1 m. In terms of affected surface, it can be even more important. Considering that, this work may be very valuable for coastal managers because it indicates the area that may be affected by coastal flooding without overestimating the levels achieved by an event within a certain recurrence period.

The beach erosion model was able to quantify the sediment transport rate through simulations, and the results corroborated field data. Thus, numerical modeling of sediment longitudinal transport at embayment beaches can be used as a valid tool to determinate the final form of a beach after a period of time, indicating the sectors that are more sensitive to erosion in an intermediate spatial scale between run-up and assessment estimations.

Although spatial analysis and numerical modeling have been applied separately in the presented examples, the authors expect that both approaches will be used in an integrated methodology to assess/define exposure to coastal hazards. Further studies are needed to define how spatial assessment results obtained in different spatial scales could feed numerical forecast models.

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