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Research article

Coastal vulnerability to wave impacts using a multi-criteria index: Santa Catarina (Brazil)

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ABSTRACT

The damage of coastal infrastructure due to wave action has stimulated the need for vulnerability assessments for integrated coastal management. Vulnerability is described as the ability of people living in an area to anticipate, cope with, resist and recover from the impact produced by a coastal hazard. This study aims to develop a multi-criteria index to assess coastal vulnerability to waves. Therefore, we analyze the Santa Catarina State (southern Brazil) coastline vulnerability to the incident wave climate. The applied coastal vulnerability index (CVI) was obtained by integrating the adaptive capacity index (ACI), composed of socioeconomic and locational variables, and the susceptibility index (SI), composed of physical variables. The resulting coastal dynamics from nearshore wave processes were analyzed through numerical models and integrated with other variables in a geographic information system (GIS). The relevance of the variables to the index was obtained by the analytic hierarchy process (AHP). The variables and indices were hierarchized into five vulnerability classes and represented in the administrative sectors defined by the local State Coastal Management Plan. Based on the AHP results, the physical variables were considered more relevant than the socioeconomic and locational variables. In general, the southern portion of the state presented higher susceptibility degrees, a lower income per capita and a lower number of second residences than the northern portion. At the same time, the northern portion presented higher percentages of developed areas, which are predominantly situated along susceptible and vulnerable segments. The numerical modeling of wave propagation has a large impact on the vulnerability as a function of the higher weights assigned to the related variables by experts and the high variability of the significant wave height along the state's coastline. Our results emphasize the importance of the inclusion of physical variables, such as waves, when defining coastal management measures in coastal zones.

1. Introduction

Beaches are transitional features over which terrestrial, oceanic and atmospheric processes dynamically interact. They constitute environments with a strong propensity to be impacted by the effects of sea level rise, increased frequency and intensity of extreme events and changes in the wave climate (e.g. Komar and Allan, 2008; Dodet et al., 2010; Young et al., 2011; IPCC, 2013). Although the majority of coastal vulnerability studies focus on the effects of sea level rise, extreme events of high-energy waves can result in environmental changes that are much more significant on a shorter scale (Bonetti and Woodroffe, 2017).

The severity of the impacts caused by high-energy waves strongly depends on the level of exposure and vulnerabilities (IPCC, 2012). Vulnerability can be described as the ability of people living in an area to anticipate, cope with, resist and recover from the impact produced by a coastal hazard through physical/environmental and socioeconomic elements (CEPAL, 2011). The impacts can be mitigated by the adaptive capacity, reflected by the resilience of the affected natural and human systems (ISDR, 2004).

One of the most widespread methods to assess the vulnerability from coastal hazards is the application of multi-criteria indices to support preventive management measures (Nguyen et al., 2016). The coastal vulnerability index (CVI), described by Gornitz and Kanciruk (1989) and Gornitz (1991), has been widely applied, with adjustments to the local variables and available data. Geoprocessing and numerical techniques are commonly employed in these studies, for example, geographic information systems, remote sensing and numerical modeling (Bonetti et al., 2013). A major inadequacy in the case of most vulnerability assessments is that they focus only on the physical parameters of vulnerability, with little inclusion of socioeconomic and

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infrastructure factors (Gornitz, 1991; Adger, 2006; Kantamaneni, 2016; Kantamaneni et al., 2018). In this sense, here we encourage the use of combined physical and socioeconomic variables, incorporating both factors to indices adapted from the CVI. In this study the CVI is obtained by integrating an adaptive capacity index (ACI), composed of socio-economic and locational variables, and a susceptibility index (SI) – consisting of physical variables. We also improved the original CVI method by applying the analytical hierarchical process (AHP) to estimate relative weights for the variables set. The use of logically derived weights was raised by Gornitz (1991) as a possible future contribution to coastal vulnerability assessments. The analytical hierarchical process is efficient in estimating the weights required for further processing of multi-criteria indices. The method allows to translate the information from experts, simple models, and data into comparable quantitative data and to aggregate it into a single multi-criteria framework (Le Cozannet et al., 2013). Furthermore, the AHP method is of great value in the case of coastal vulnerability assessment as the data is highly heterogeneous in terms of its scale and temporal resolution and there is a lack of a purely deterministic method owing to the huge data involved from different sources (Le Cozannet et al., 2013; Mani Murali et al., 2013).

There are few examples of the use of AHP integrated to coastal vulnerabilities assessments. Chang et al. (2012) applied the method to rank different coastal protection in Miaoli coast, Taiwan. Yin et al. (2012) have made an assessment of the coastal vulnerability to sea level rise for the Chinese coast. Le Cozannet et al. (2013) extensively discusses the advantages, disadvantages and uncertainties of the incorporation of AHP into coastal vulnerability assessments. Mani Murali et al. (2013) combined socioeconomic and physical variables with AHP-derived weights to calculate the coastal vulnerability index for the Puducherry coast, India. Apart from these applications, the use of AHP is rare in coastal vulnerability studies.

. The state of Santa Catarina is located in a transition zone of meteorological and oceanographic processes occurring in the South Atlantic Ocean (Klein et al., 2016). The coast is strongly influenced by the passage of cold fronts, which favor the occurrence of marine storm events (Rudorff et al., 2014). Considering this exposure, previous studies have aimed to recognize coastal vulnerability along the state (Serafim and Bonetti, 2017; Bonetti et al., 2018). However, the wave-related descriptors used by these authors were limited, and their results prioritized the geological and geomorphological setting more than the dynamic characteristics of the coast. According to Muler and Bonetti (2014), it is a common practice among coastal vulnerability studies to consider only the hazards (e.g., storm waves) and not the exposure of the coastal settlements to the incident waves. In this sense, we studied in detail the hydrodynamic processes capable of generating impacts on the coast by means of integrated numerical modeling. The numerical wave models were based on wave data, selected from a global wave generation model, that have a higher frequency of occurrence, a higher impact on coastal settlements, and storm surges.

The purpose of this study is to assess the coastal vulnerability of the state of Santa Catarina by adapting the CVI in order to develop a simple index, with the potential to be applied to broader scales that could cover areas lacking data. The methodological approach based exclusively on indirect techniques (numerical modeling and spatial analysis in GIS) facilitates its replication to other mesoscale or macroscale areas. Our objectives are: 1) to develop a multi-criteria index to assess coastal vulnerability to waves, 2) to encourage the inclusion of socio-economic variables along with locational and physical variables, 3) to include modeled nearshore waves, 4) to improve the CVI using AHP-deduced weights.

1.1. Considerations regarding the terminology

A lack of consensus about the terminology is observed in vulnerability studies as a function of the variety of research objectives and phenomena studied (Adger, 2006; Bonetti and Woodroffe, 2017). Since there is a wide range of areas in which vulnerability can be applied, a clear explanation of the adopted terminology is needed to support this research.

In this study we consider hazard as being the physical phenomena, natural process or human activity with the potential to generate damage to the population (IPCC, 2014). Vulnerability is the ability of people living in an area to anticipate, cope with, resist and recover from the impact produced by a coastal hazard through physical/environmental and socioeconomic elements (CEPAL, 2011). Therefore, vulnerability can be assessed by the integration of susceptibility and adaptive capacity models. The susceptibility is the propensity of a system to be impacted by a hazard that changes a dynamic equilibrium condition on the basis of its physical characteristics (Muler and Bonetti, 2014). Adaptive capacity is assessed by social and economic factors that allow the population to adapt or evolve to accommodate the impacts caused by a hazard (UNISDR, 2009).

1.2. Study area

Located in southern Brazil, the coastline of the state of Santa Catarina is limited by the parallels 25°57′41″ S and 29°23′55″ S and lies in the proximity of the meridian 49 W. To the east, the coastline borders the Atlantic Ocean and extends 564 km or 1874 km when the extension of the bays and islands are included (Santa Catarina, 2006). Fig. 1 represents the study area and its division in the five administrative sectors defined by the state's Coastal Management act (GERCO/SC): North, Central North, Central, Central South and South (Fig. 1), which covers 36 municipalities.

Santa Catarina is composed of different coastal features and habitats, including dunes, beaches, headlands, bays, lagoons, estuaries, inlets and mangroves. The diversity of coastal environments combined with a mild subtropical climate resulted in the use of the coast traditionally for fishing and more recently for housing, recreation and tourism. The concentrated urban development in some sectors of the coast started in the middle of the 1970s and resulted in extensive habitat loss including coastline degradation and the armoring of specific sectors (Klein et al., 2016).

The sandy beaches are the most common geomorphic feature along the coastline, representing 58% of the coastline's extension (Klein et al., 2016). These environments have a high social and economic value, as a result of the different activities and of the high concentration of residential area and of the population in the coastal municipalities, 36% of the state's population (approximately 2,2 million people; IBGE, 2011), which represents 258 inhabitants per kilometer square.

The presence of 246 individual sandy beaches mostly characterizes the state's coastline. The beaches have headlands bordering a wide continental shelf on the adjoining Atlantic Ocean (Bonetti et al., 2018). While the Central and Central North sectors of the state are dominated by headland-bay beaches, the southern portion is composed of long and continuous straight coastlines.

Nearby continental shelf isobaths follow the NE/SW orientation of the coastline, inducing longitudinal differences in the shallow-water wave behavior (Siegle and Asp, 2007). Consequently, the sectors from the north to the center of the state are sheltered in comparison with the southern sectors. Therefore, wave refraction is more significant in the North sector and the waves approach at a greater angle in the South sector (Siegle and Asp, 2007).

The coastline is heavily influenced by storms induced by the passage of cold fronts and of extratropical cyclones, with a monthly average of 3–4 events (Rodrigues et al., 2004). Associated meteorological tides and storm waves lead to episodes of coastal erosion and inundation that can heavily damage the coastal zone – especially when associated with astronomical spring tides.

Rudorff et al. (2014) described the impacts of extratropical storms over the state's municipalities by accessing damage reports from the