Spotting areas critical to storm waves and surge impacts on coasts with data scarcity: a case study in Santa Catarina, Brazil

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Abstract

The impacts of severe storms on the coastal zone, combined with rapid population growth in this area, have made coastal risk management an urgent need. However, integrated risk assessment can be a challenging task for many locations worldwide, as it normally requires the use of a large amount of data. The Coastal Risk Assessment Framework phase one (CRAF1) is a recently proposed analytical scheme based on empirical models and spatial analysis that combines different indicators to identify storm-induced hotspots. With a high degree of flexibility, the methodology was originally designed to be of broad use. Still, there is little information about the tool applicability in data scarcity conditions. In this study, we show that this approach can be applied, with some simplifications, on data-poor areas, allowing the identification of hotspots considering one or multiple hazards. Here, the coastal risk was assessed for erosion and coastal flooding events with return periods of 10 and 50 years on the Santa Catarina Central Coast. The study area is characterized by the occurrence of storm-induced impacts that historically cause disruption and damage to local communities. Although the components of risk have been assessed using various methods along this sector, to date, no integrated risk analysis has been presented in probabilistic terms. Predicted scenarios for the Santa Catarina Central Coast suggest that extreme episodes may cause several impacts, exposing urban settlements as well local road systems, especially in the municipalities of Tijucas and Florianópolis. The results show that the CRAF1 is an appropriate approach for a first-level risk analysis, even when implemented with poor data resolution, as it effectively points to some of the most vulnerable stretches detected in the study area.

Keywords  CRAF · Flooding · Erosion · Extreme events · Coastal risk
Abbreviations
BU  Business
CI  Coastal Index
CNES  National register of health establishments
CRAF1  Coastal Risk Assessment Framework phase one
DEINFRA  Infrastructure department of Santa Catarina’ state
DHN  Directorate of hydrography and navigation
DTM  Digital terrain model
G.E.V.  Generalized extreme value
GIS  Geographic information system
GOST  Global ocean surge and tide database
Gov. Celso Ramos  Governador Celso Ramos
IBGE  Brazilian institute of geography and statistics
\( i_{\text{exp}} \)  Exposure indicator
\( i_{\text{h}} \)  Hazard indicator
IH-AMEVA  Mathematical and statistical analysis of environmental variables
LU  Land use
RIMPEEX-Sul  Integrated network for monitoring and forecasting extreme events in the southern region
ROW  Regional ocean waves database
SDS  State secretary of sustainable economic development
SEAP  Special secretariat for aquaculture and fisheries
SED-SC  Secretary of education of Santa Catarina’s state
SV  Social vulnerability
SVI  Social vulnerability index
\( T \)  Return period
TS  Transport system
TWL  Total water level
UT  Utilities

List of symbols
\( A \)  Parameter governing the profile steepness
\( A_i \)  Area occupied by the land use class
\( A_t \)  Total area of the sector
\( B \)  Frontal dune height
\( D_{50} \)  Sediment sizes
\( g \)  Gravitational acceleration
\( H_b \)  Breaking wave height
\( h_b \)  Break wave depth
\( k \)  Dean’s constant
\( m \)  Beach profile slope
\( R_\infty \)  Maximum potential retreat
\( R_i \)  Potential retreat
\( S \)  Water level variation
\( T \)  Storm duration
\( T_s \)  Timescale of exponential response
\( V \)  Value assigned to the land use class
1 Introduction

Storm-induced waves and surges can be considered among the most important drivers of coastal impacts such as flooding and erosion. These hydro-meteorological events, often associated with significant losses of infrastructure and, sometimes, lives (Kron 2013; Von Storch 2014), tend to increase over the years due to climate changes and rising sea levels (Vousdoukas et al. 2018; Kirezci et al. 2020). In this scenario, an assessment of current and future risk is required to support coastal management and policy implementation. This is particularly important for developing countries, where scarce resources need to be properly and efficiently allocated. On the other hand, estimating risk in these areas can be challenging though, as data are often unavailable or present poor resolution.

The southern region of Brazil is historically affected by storm-induced waves and surges, often associated with the passage of cold fronts and extra tropical cyclones (Parise et al. 2009). On the coast of Santa Catarina state, episodes of flooding and erosion linked to these events are recurrent and have caused serious damage to the local community (Rudorff et al. 2014). In response, several approaches have been applied in this area to assess the exposure of the population and urban assets on the local scale (Mazzer et al. 2008; Rudorff and Bonetti 2010; Muler and Bonetti 2014; Klein et al. 2016a; Mussi et al. 2018; Santos and Bonetti 2018; Silveira and Bonetti 2019; Lima and Bonetti 2020) and regional scale (CEPAL 2012; Serafim and Bonetti 2017; Bonetti et al. 2018; Serafim et al. 2019). Nevertheless, the existing research is focused on vulnerability and does not take into account the probability of the impact of coastal hazards in different time frames, which is important for stakeholders when defining a target safety level.

An approach that considers the probability of occurrence of extreme events was recently developed within the RISC-KIT project (Van Dongeren et al. 2018). The so called CRAF methodology was designed for the identification and selection of critical areas caused by storm tides and surges. This tool comprises two levels of analysis: the first phase (CRAF1) consists in an index-based screening process destined to highlight potential hotspots in a regional scale and the second phase (CRAF2) corresponds to a more advanced approach to increase the resolution of the risk assessment at the hotspot scale (Vivavattene et al. 2018). Created to be of broad use, the framework has been successfully tested in different European coastal settings (cf. Armaroli and Duo 2018; Auclielli et al. 2018; Christie et al. 2018; De Angeli et al. 2018; Jiménez et al. 2018; Plomaritis et al. 2018). Still, a major constraint to apply this methodology is the poor availability and accessibility of high-quality data (Ferreira et al. 2018; Narra et al. 2019) and despite its high degree of flexibility, there is little information about the tool applicability in such conditions.

Within this context, the aim of this paper is to identify hotspots for the storm-induced impacts along the Santa Catarina Central Coast by applying CRAF1, in spite of a scarce data condition. For this, our paper proposes an adaptation in the use of the originally recommended risk descriptors as the main strategy to overcome the aforementioned data limitation.

The tool was applied with simplifications to the area of interest, and the critical sectors were identified through a combination of empirical methods and spatial analysis, highlighting, in a comparative way, priority areas for management actions and providing valuable
information for further detailing. The study also prioritized the identification of hotspots in the management unit proposed in the Brazilian Coastal Management Program sectorization, which facilitates the applicability of results by decision-makers.

Considering that vulnerability-related terminology varies widely among researchers, which reflects the lack of consensual definitions for such terms (Bonetti and Woodroffe 2017), it is worth clarifying that, in this study, risk is defined as the product of the probability occurrence of a hazard and its consequences (UNISDR 2009). Susceptibility expresses the natural potential level of losses associated with the characteristics of the hazard, and vulnerability is defined as the propensity of a receptor (human assets; ecosystems) to suffer damage (Viavattene et al. 2015). In addition, the term exposure is applied to express the direct and indirect losses that receptors may have in contact with the hazard.

This article is structured as follows: Sect. 2 describes the study area and the available data; Sect. 3 presents the CRAFl framework and the simplifications adopted to allow the implementation of the method to the study site; Sect. 4 shows the results; Sect. 5 discusses the hotspots identified and finally, Sect. 6 summarizes the main conclusions of the work.

2 Santa Catarina Central Coast and available data

2.1 Site description

The area of interest is located in South Brazil and comprises the beaches of the Santa Catarina Central Coast, according to the sectorization proposed by the Brazilian Coastal Management Program (Santa Catarina 2006). It covers more than 100 km of coastline and includes the state capital, Florianópolis, and the municipalities of Palhoça, Gov. Celso Ramos and Tijucas (Fig. 1).

Waves and storm surges affect the beaches located inside the sheltered coastline between Santa Catarina Island and the mainland differently (Mussi et al. 2018; Silveira and Bonetti 2019), and hence this sector of the coast was not considered in the analysis. The southern sector of Tijucas municipality coastline has not been analysed either because it is a tide-dominated beach with an upper shoreface basically composed of mud flats, which induce a particular hydrodynamical behaviour to this segment (Klein et al. 2016b).

This coastal sector is exposed to waves from four main directions: low-energy conditions usually coming from the northeast quadrant, and high-energy waves arriving from east, south and southeast, with significant heights up to 6 m and a recorded maximum of 13 m individual height (Araújo et al. 2003; Melo Filho et al. 2006). This coastal area is under a microtidal regime, with average spring tides reaching up to 1 m (Klein et al. 2016b), whereas the meteorological component of the water level (storm surge) can be as high as 1 m as well (Truccolo et al. 2006).

The central coast of Santa Catarina state presents a high economic value, offering important goods and services (Scherer and Asmus 2016). Nonetheless, this area is particularly prone to storm-induced impacts, which cause serious property damage and demand a large amount of financial investment by the government, as highlighted by several studies (Simó and Horn Filho 2004; Horn Filho 2006; Rudorff et al. 2014; Klein et al. 2016b).
2.2 Data accessibility

To accomplish the desired analysis, data on coastal morphology, waves and water levels are required. Here, topography and bathymetry were characterized using a 1 m × 1 m Digital Terrain Model (DTM) obtained from aerial images with an original 0.39 m resolution performed by the state’s ‘Secretaria de Estado do Desenvolvimento Econômico Sustentável (SDS)’ and from nautical charts produced by the Brazilian Navy’s ‘Diretoria de Hidrografia e Navegação’ (DHN). Possible discrepancies regarding the different datums used for topography and bathymetry charting were minimized as proposed by Klein et al. (2016a); beach morphology and sediment grain sizes along the coast were acquired in the field in the scope of the project RIMPEEX-Sul (‘Rede Integrada de Monitoramento e Previsão de Eventos Extremos na Região Sul’; Bonetti et al. 2018) and wave and water level data were obtained from the Regional Ocean Waves (ROW) and Global Ocean Surge and Tide (GOST) databases, a reanalysis dataset specifically validated for Santa Catarina coast (Rodríguez and Lasa 2016) that include a 31-year period (1979–2010) with hourly temporal resolution.

Since the coastal exposure depends on the receptors characteristics and their associated vulnerability, we used different types of data to characterize the receptors that may have interaction with the hazard: land-use data for the study area was provided by Mussi (2017); socio-economic information was obtained from the IBGE (2011) census (see details in Supplementary Material, Annex A); transport system was characterized with information supplied by DEINFRA (2018) and OpenStreetMap platform (OSMF 2018);
business information was obtained from SEAP (2008) and, finally, the utility information was extracted from CNES (2018) and SED-SC (2018).

3 Methodological framework

The tool CRAF1 consists of a screening process that allows the identification of hot-spots on a large spatial scale by assessing the potential impacts for every coastal sector of approximately 1 km along the shore length. Two groups of indicators are required for the risk assessment: hazard-impact indicators and exposure indicators (Fig. 2).

Fig. 2 Methodological flow chart of the risk assessment performed in this research
The approach combines the hazard-impact \((i_h)\) and exposure \((i_{\text{exp}})\) indicators into a single value, the Coastal Index (CI), which is estimated for each sector (Eq. 1) (Viavattene et al. 2018):

\[
\text{CI} = \sqrt{i_h \times i_{\text{exp}}}
\] (1)

Here, two types of hazard effects are considered: flood and erosion. It was not possible to apply the recommended level of analytic detail, especially in the hazard assessment model, due to the non-existence of a fine grid and high-resolution DTM and bathymetric charts, necessary to obtain the morphological parameters at the land–ocean interface. Moreover, despite having a long time series of wave and water level data, several hydrodynamic parameters required for the application of the chosen empirical models had to be simplified, as the lack of regular bathymetry data makes it difficult to take into account the wave transformation and attenuation process in shallow waters. A comparative review showing the main challenges faced when applying the tool in the study area in its simplified form is presented in the supplementary material, Annex B.

The magnitude and extent of the different hazard effects and exposure indicators were computed separately following some assumptions and found alternatives, as described in the next sections.

### 3.1 Coastal hazard assessment

To estimate \(i_h\), the magnitude of the hazard effect must be computed for a certain return period by using empirical models and converted to a hazard scale from 0 to 5 (none, very low, low, medium, high, and very high). To this end, the study area was divided into 83 representative sectors, each one covering up to a 2.5-km length of sandy beaches.

As the impact driver is strongly dependent on storm wave direction and shoreline orientation (Masselink et al. 2016), the sectors were classified according to the degree of exposure to the main wave directions that reach Santa Catarina Island: South, Southeast, and East. When possible, the classification presented here was based on previous studies (Muler and Bonetti 2014; Klein et al. 2016a, b). Otherwise, the simple relation between the shoreline orientation and the main wave direction was considered for the categorization. Hereafter, ‘exposed sectors’ refer to the sectors exposed to waves, where there is a high angle of incidence between the main wave direction and the coastline, and ‘semi-sheltered’ sectors refer to those sectors where waves have small or no effect on flooding/erosion (Fig. 1).

#### 3.1.1 Flood

The flood magnitude was estimated through the extreme values of the total water level (TWL), which consists of the sum of tides, storm surge, and wave run-up. The two fist components were obtained by using deep water wave data (Fig. 1) whereas the storm-induced run-up was computed by applying the formula proposed by Holman (1986) that considers the significant wave height, the wave length and the beach face slope.

Most recent studies on coastal flooding apply the formula from Stockdon et al (2006) to estimate wave run-up, as it was developed with data measured from several beaches. However, previous works have tested such formula for Santa Catarina coast and verified an overestimation of run-up values in this area (Gomes da Silva 2014; Gomes da Silva et al.
2016; Klein et al. 2016a; Vieira da Silva et al. 2016). Here, a sensitivity analysis was performed with different formulas (Hallermeier 1981; Birkemeier 1985; Holman 1986; Stockdon et al. 2006) (analysis not shown), and Holman (1986) resulted in more coherent values for the study area. This is consistent with the analysis presented by Gomes da Silva et al. (2020) who verified that Holman (1986) results in an accuracy comparable to more recent formulae, which support the use of this formulation in our work. Furthermore, the semi-sheltered sectors were assumed to be influenced little or very little by wave action, therefore, in this case, the wave run-up was not taken into account and the analysis was carried out considering only the effect of tides and storm surge on the TWL.

Once computed, the TWL time series were fitted to the G.E.V. (Generalized Extreme Value) distribution using annual maxima values. Despite the existence of different methods to define the maxima, this approach was applied here because it does not require the definition of a threshold over which a level is considered an extreme event. As defining such level is not simple (Muis et al. 2020), especially in sites with data scarcity, the chosen method allowed the assessment in this case. The analysis described was carried out in IH-AMEVA (IH-Cantabria 2013), and the extreme water levels associated to return periods of 10 (T10) and 50 (T50) years were used to characterize different scenarios.

The area potentially flooded by those extreme events was delineated by using the bath-tub approach, which consists in assuming that all areas connected to the sea with an elevation below the TWL will be flooded (Viavattene et al. 2018). In a Geographic Information System (GIS) environment, the outlined surface was computed for each sector, considering the beach topography and the corresponding water level for the selected return periods. Finally, a simple rectangle generated from the maximum flood potential in each sector was used to illustrate the potential ‘hazard extent’ (according to the terminology adopted by the RISC-KIT assessment framework; Viavattene et al. 2015).

### 3.1.2 Storm-induced erosion

Erosion was assessed in the exposed areas using the model of Kriebel and Dean (1993). This approach proposes an adaptation of the Bruun Rule (1954) to estimate the changes in the beach profile due to storm waves, and the respective coastline retreat/advance. The maximum potential retreat ($R_\infty$) is expressed by Bruun (1954) as (Eqs. 2 and 3):

$$ R_\infty = \frac{SX_b}{B + hb - S/2} $$

(2)

$$ X_b = \left( \frac{hb}{A} \right)^{3/2} $$

(3)

where $S$ is the water level variation, $hb$ is the wave-breaking depth, $B$ is the frontal dune height, $X_b$ is the distance from the wave-breaking depth and $A$ is the parameter related to the sediment size that characterizes the profile slope.

According to Kriebel and Dean (1993) the proportional and rapid retreat due to storms must be determined taking into account the characteristic timescale of the exponential response ($T_s$) and the storm duration ($T_D$). $T_s$ was computed with Eq. 4, whereas $T_D$ was assumed to be the typical storm duration in the study area, a value obtained from the literature (Table 1).
Table 1 Data used to compute the storm-induced shoreline retreat

| Data                              | Source                                           | Range of values for the exposed sectors in T10 | Range of values for the exposed sectors in T50 |
|----------------------------------|--------------------------------------------------|----------------------------------------------|-----------------------------------------------|
| Frontal dune height ($B$)        | RIMPEEX-Sul Project (Bonetti et al. 2018)        | 0.2–4.0 (m)                                  |                                               |
| Sediment size ($D_{50}$)         | RIMPEEX-Sul Project (Bonetti et al. 2018)        | 0.17–1.36 (mm)                               |                                               |
| Beach profile slope ($m$)        | Trigonometric relations                          | 0.01–0.06                                    |                                               |
| Parameter governing the profile steepness ($A$) | empirical approach (Dean 1987)            | 0.09–0.23                                    |                                               |
| Breaking-wave height ($H_b$)     | empirical approaches: Komar and Gaughan (1973) and Weggel (1972) | 6.4–6.5 (m)                                  | 7.1–7.2 (m)                                  |
| Break-wave depth ($h_b$)         | empirical approaches: Komar and Gaughan (1973) and Weggel (1972) | 6.1–7.7 (m)                                  | 6.7–8.4 (m)                                  |
| Water level variation ($S$)      | TWL computed for each scenario                  | 1.7–6.0 (m)                                  | 1.9–6.6 (m)                                  |
| Storm duration ($TD$)            | Piçarras Project (Dalinghaus et al. 2015)       | 192 (h)                                      |                                               |
where $H_b$ is the wave-breaking height; $g$ is the gravitational acceleration; and $m$ is the beach profile slope.

Finally, the proportional retreat ($R$) over time ($t$) was calculated from the maximum potential retreat ($R_{\infty}$) as a function of $\beta$ (the ratio between the erosion timescale and the storm duration) (Eqs. 5, 6, and 7):

$$R(t) = \frac{1}{2} \left\{ 1 - \frac{\beta^2}{1 + \beta^2} \exp \left( -\frac{2\sigma t}{\beta} \right) - \frac{1}{1 + \beta^2} \left[ \cos \left( \frac{2\sigma t}{\beta} \right) + \beta \sin \left( \frac{2\sigma t}{\beta} \right) \right] \right\}$$

$$\beta = 2\pi \frac{T_s}{T_D}$$

$$\sigma = \frac{\pi}{T_D}$$

The biggest challenge to applying the chosen empirical model was the scarcity of detailed topography and bathymetry data on a regional scale, which allows the extraction of parameters related to the morphodynamics of sandy beaches, such as the depth of closure and the beach profile slope. Therefore, these parameters were estimated empirically according to the following simplifications (Table 1): first, the depth of closure was computed using the formula proposed by Hallermeier (1978). For this purpose, nearshore wave data were extracted from the GOST database at a depth of 15 m, positioned in front of the exposed sectors (Fig. 1). Afterwards, the cross-shore distance from the shoreline was obtained through Dean’s equilibrium profile Eq. (Dean, 1977). The parameter that defines the profile slope ($A$) required in this stage was estimated according to the empirical approach proposed by Dean (1987), considering $k = 0.51$. Finally, the beach profile slope was computed using trigonometric relations between the depth of closure and its respective distance from the coast.

The breaking-wave height ($H_b$) and break-wave depth ($h_b$) time series were also obtained empirically by employing the formula proposed by Komar and Gaughan (1973) and Weggel (1972), respectively (same approach proposed by Eftimova et al. 2017). The first component was obtained using the deep-water wave dataset (Fig. 1-P1-P2), whereas the second one was estimated from the $H_b$ series and the beach profile slope. Furthermore, in specific situations of erosion hazard in the absence of dunes, the dune height (0 m in this case) was set to 0.2 m, to allow a hazard assessment.

The computed time series of shoreline retreat were fitted to a G.E.V. function, and the values associated with the selected return periods were obtained. The hazard extent was outlined by a 50 m buffer zone from the maximum shoreline retreat in each scenario. The buffer value, first proposed by Mazzer et al. (2008), was chosen on the basis of the minimum-security distance considered by the ORLA project (MMA 2004) for management purposes along the entire Brazilian coast.
3.1.3 Hazard-impact indicator ($i_h$)

The hazard-impact indicator was determined individually for each hazard and each sector along the coast. To obtain the flood impact indicator, the maximum extent of the flooding scenario was subtracted from the corresponding beach width. The resulting extent was then scored as shown in Table 2. The classification of positive values was based on equal intervals, which were chosen to maximize the visual representation of the obtained results. Negative values indicate areas where the extent of flooding is restricted to the beach; therefore, the hazard index is null. Positive values indicate areas where the TWL exceeds the backshore elevation, and the hazard-impact indicator increases progressively with extent of enlargement.

The erosion impact indicator was attributed by ranking the shoreline retreat values (Table 2). This time, scores were assigned differently for T10 and T50 due to discrepancies between the ranges of values. The Natural Breaks segmentation method (Jenks and Caspall 1971) was used to obtain the categorization in each scenario, also seeking to improve the discrimination between sectors under different levels of impact.

3.2 Coastal exposure assessment

The exposure analysis consisted of determining a General Exposure Indicator ($i_{exp}$), which is composed of different types of receptors: Land Use (LU), Social Vulnerability (SV), Transport System (TS), Business (BU), and Utilities (UT). The $i_{exp}$ is estimated by (Eq. 8):

$$i_{exp} = \left( \frac{i_1 \cdot i_2 \cdot \ldots \cdot i_n}{n} \right)$$

where $n$ is the number of the considered types of receptors.

The exposure assessment was carried out individually for each hazard impact and scenario. The five exposure categories were evaluated according to specific methods as described in this section, then ranked from 1 to 5 (None or Very Low, Low, Medium, High, and Very High) before the overall integration. In the same way, the $i_{exp}$ was scored into five categories and then reclassified from 1 to 5. The obtained values are registered in Annex C (Supplementary material).

| Extent of flooding T10 and T50 (m) | Extent of erosion T10 (m) | Extent of erosion T50 (m) | Hazard-impact indicator |
|-----------------------------------|--------------------------|--------------------------|-------------------------|
| −20–0.0                           | 0.0–0.2                  | 0.0–19.2                 | 0                       |
| 0.0–100                           | 0.2–0.4                  | 19.2–41.5                | 1                       |
| 100–200                           | 0.4–0.7                  | 41.5–54.8                | 2                       |
| 200–300                           | 0.7–1.4                  | 54.8–70.6                | 3                       |
| 300–400                           | 1.4–3.4                  | 70.6–126.3               | 4                       |
| > 400                             | > 3.4                    | > 126.3                  | 5                       |
3.2.1 Land Use ($i_{\text{exp\_LU}}$)

This indicator measures the relative exposure of different land uses along the coast, considering the area and the importance of the land use class for human activities. Based on the scale developed by Perini et al. (2016), each class received a representative value from 1 to 4. Therefore, areas with a high degree of human activity, such as urban settlements and croplands, were considered critical and received higher exposure values (4 and 3), while areas with little or no human activity such as sandy beaches, dunes, forests, and mangroves received lower exposure values (2 and 1).

It is important to recognize that different classification schemes could have been adopted to express the distinct levels of relative exposure of natural and anthropic features along the coast. Here, we chose to prioritize a classification structure already available for the area (provided by Mussi 2017) and developed in the scope of a multidisciplinary long-term research network—the “Programa Ecológico de Longa Duração—PELD”, because it allows a more comprehensive comparison among areas in the case of methodology replication. Details about the classification are presented in Supplementary Material, Annex D. Afterwards, the $i_{\text{exp\_LU}}$ was estimated for each sector according to Eq. 9 and the final values were scored into five categories as described in Sect. 3.2.

\[ i_{\text{exp\_LU}} = \sum_{i} \frac{V_i A_i}{A_t} \]  

where $V_i$ is the value assigned to the class, $A_i$, the area occupied by the class and $A_t$, the total area of the sector.

3.2.2 Social vulnerability ($i_{\text{exp\_SV}}$)

The social vulnerability exposure indicator ($i_{\text{exp\_SV}}$) measures the relative exposure of different communities along the coast, considering their socio-economic characteristics according to the most common indicators used in the literature (Lima and Bonetti 2020). The $i_{\text{exp\_SV}}$ was computed on the basis of a Social Vulnerability Index (SVI) built for the Santa Catarina Central Sector. To build the SVI, six components were considered, as presented in Table 3. The variable’s interaction adopted to obtain each component from the IBGE dataset are detailed in Annex A (Supplementary Material).

In order to enable the integration of components, the values obtained were standardized, and the SVI was determined following the approach proposed by Tapsell et al. (2002). The

| Categories         | Components                                      |
|--------------------|-------------------------------------------------|
| Financial deprivation | Percentage of households living in poverty ($A_{sv}$) |
|                     | Per capita income ($B_{sv}$)                     |
| Education           | Percentage of literate household heads ($C_{sv}$) |
| Household structure | Number of residents per household ($D_{sv}$)      |
| Gender              | Percentage of households headed by young women ($E_{sv}$) |
| Age                 | Vulnerable age group ($F_{sv}$)                  |
original equation was adapted to summarize the five chosen categories (Table 3): financial deprivation, education, household structure, gender, and age (Eq. 10).

\[
SVI = 0.5(A_{sv} + B_{sv}) + C_{sv} + D_{sv} + E_{sv} + F_{sv}
\]  

(10)

Finally, to compute the \(i_{exp, SV}\), the procedure described in item 3.2.1 (Eq. 9) was performed.

3.2.3 Transport system \((i_{exp, TS})\), business \((i_{exp, BU})\), and utilities \((i_{exp, UT})\)

These indicators are considered to better represent the exposure of structures, which can lead to systemic impacts or to a higher order of losses. Each one was represented by points in a GIS environment and quantified at the sectorial level with the Spatial Join resource. They were subsequently computed in terms of density, dividing the number of points by the total area of the sector. The range of values obtained from the exposure analysis are detailed in Annex C (Supplementary Material).

The transport system indicator was estimated as the density of roads and local road network; the business indicator was determined accounting for the number of establishments linked to commercial, industrial, and agricultural activities in each sector, and finally, the utility indicator was defined by the number of health (hospital and clinics) and education units in the area of the hazard impact extent. Other utilities suggested by CRAF1 methodology (e.g. drinking water intake and electrical transmission substations) were not observed within the extent of the hazard areas.

3.3 Identification of hotspot areas

Hotspots were identified through application of the Coastal Index, which was computed for each hazard impact and each associated return period. The relation between the hazard-impact indicator \((i_h)\) and the general exposure indicator \((i_{exp})\) was established following Eq. 1. A sector was considered critical when CI was higher than 3.2, as this value is obtained exclusively by the combination of medium to very high indicators (Viavattene et al. 2018). The CI values were, accordingly, classified into five categories (None or Very Low, Low, Medium, High, and Very High) to allow a qualitative representation of the hotspots along the area.

4 Results

Here, flood and erosion risk assessment are addressed separately, followed by an examination of the concurrent occurrence between the two.

4.1 Storm-induced flood risk assessment

When considering the exposed sectors, TWL varied from 2.3 to 6.6 m for T10 and from 2.5 to 7.2 m for T50 (Table 4); in semi-sheltered sectors, the TWL varied from 1.2 to 1.3 m, taking into account both scenarios. The highest levels occurred in areas reached by higher wave energy and steeper beach slopes in Tijucas and Florianópolis.
The flood hazard indicator show that, considering the longer return period, the hazard level in approximately 55% of the sectors lies within classes 1 and 2. Still, the classes of high and very high susceptibility (4 and 5) were representative, corresponding 32.5% of the sectors for T50. In an analysis of the differences between the T10 and T50 scenarios, an increase in hotspots was observed in the most populated city, Florianópolis (Fig. 3A and Fig. 4A).

Considering both scenarios, the main flood-prone sectors comprised the following beaches: Tijucas, Palmas, Daniela, Canasvieiras, Cachoeira do Bom Jesus, Ponta das Canas, Ingleses, Moçambique-Barra da Lagoa, Campeche, Armação, and Pinheira (Fig. 3A and 4A). Higher values of $i_h$ were concentrated in Tijucas and Florianópolis municipalities: both sites included up to 78% of the most hazardous sectors (levels 4 and 5) in T50. Also, in this case, Gov. Celso Ramos was the municipality with lower $i_h$ values (more than 73% of its total sectors belonged to the very low and low-level classes, 1 and 2).

### Table 4

| Municipalities with exposed sectors | TWL T10 (m) | TWL T50 (m) |
|------------------------------------|-------------|-------------|
|                                    | Max  | Min  | Mean | Max  | Min  | Mean |
| Tijucas                            | 6.6  | 4.9  | 5.7  | 7.2  | 5.4  | 6.3  |
| Gov. Celso Ramos                   | 4.4  | 2.6  | 3.4  | 4.7  | 2.8  | 3.7  |
| Florianópolis                      | 6.4  | 2.3  | 3.9  | 7.0  | 2.5  | 4.3  |
| Palhoça                            | 4.4  | 2.3  | 3.4  | 4.8  | 2.5  | 3.7  |
| **Whole Central Coast**            | **6.6** | **2.3** | **3.9** | **7.2** | **2.5** | **4.2** |

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**Fig. 3** Alongshore distribution of the flood (A) and exposure (B, C) indicators for T10
The study area exhibits large variability when considering the exposure categories (Figs. 3B and 4B). For the $i_{\text{exp LU}}$, the very-high exposure class (5) predominates, followed by the low and high categories (2 and 4). Notably, most sectors that present very high levels of LU exposure are concentrated in the Gov. Celso Ramos municipality and the north of Santa Catarina Island. High values are mainly related to the presence of urban settlements close or very close to the shore.

Considering the Social Vulnerability Indicator ($i_{\text{exp VS}}$), intermediate to low values characterized most of the stretches. In the longer return period, it predominates the medium class (3) for approximately 35% of the sectors, followed by the class of low social vulnerability (2), which represented 30%. Higher exposure rates are located in the northern sectors of Tijucas, and east of Santa Catarina Island. Notably, categories that contributed the most to the very high values were ‘per capita income’, ‘vulnerable age group’ and ‘number of residents per household’.

In respect to the transport system (Figs. 3B and 4B), the results showed that most of the sectors presented very low exposure of their transport network: in the longer return period, only 13.2% were marked by very high exposure and were mainly concentrated in the Florianópolis and Gov. Celso Ramos municipalities, which pointed to a higher density of the transport system close to the shore in these locations. The predominance of very low exposure in the area can be explained by the absence of infrastructure near the shoreline. Still, it was possible to identify those areas where the transport network could be affected.

The Business indicator was mostly represented by units linked to commerce, followed by entities related to the industry. Considering the T50 scenario, 10.8% of the sectors were characterized by very high exposure (class 5), mostly in the municipality of Gov. Celso Ramos, and the northern portion of Santa Catarina Island. Low and very

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**Fig. 4** Alongshore distribution of the flood (A) and exposure (B, C) indicators for T50
low exposures were dominant when considering both return periods, accounting for up to 60% of the sectors.

The utility indicator was restricted in the study area: 80% of the sectors presented a very low exposure class, considering the maximum hazard extent. The predominance of low exposure classes was also mainly due to the absence of large infrastructure networks close to the shore. The very high exposure class was concentrated exclusively in the municipality of Gov. Celso Ramos. High classes (4) also appeared in the municipalities of Tijucas and Florianópolis. There was a significant number of educational units close to the shore, which were mainly represented by municipal elementary schools. Health units were rarer within the considered area and were mostly represented by small medical centres.

For the overall exposure index \( i_{\text{exp}} \), categories of Low and Very Low exposure were predominant in the study area, covering up to 57% of the sectors. High and very high classes represent 20.4% of the total sectors for T10 and 25.3% for T50. The municipalities of Tijucas and Gov. Celso Ramos were predominantly characterized by the medium exposure class; however, they had the highest percentages of classes 4 and 5, when compared with other locations. The municipality of Florianópolis presented a predominance of very low and low exposure. Still, 22.4% of its sectors are represented by classes 4 (high) and 5 (very high) in the T50 return period, which are concentrated mainly on semi-sheltered locations at the north end of the Island. In the municipality of Palhoça, the low exposure class predominates, with only 12.5% of the sectors classified as high exposure for both scenarios. Considering the longer return period, eight sectors were classified with very high coastal exposure and included the following beaches: Tijucas, Calheiros, Gancho do Meio, Fazenda d’Armação, Canasvieiras, Ponta das Canas, Ingleses, and Armação (Figs. 3C and 4C).

The flood risk analysis identified 18 critical areas for T10 and 20 for T50, and the study area presented a CI average of up to 2.4. The hotspots included the beaches of Tijucas, Palmas, Calheiros, Fazenda d’Armação, Daniela, Jurerê Internacional, Canasvieiras, Cachoeira do Bom Jesus, Ponta das Canas, Ingleses, Barra da Lagoa, Campeche, Armação, and Pinheira (northern sector) (Fig. 5).

The critical areas represented 24% of the total sectors analysed in the longer return period scenario. The municipality of Florianópolis showed the highest flooding risk for both return periods, comprising up to 50% of the hotspots. The municipality of Tijucas also stood out for the concentration of extreme values with a CI average of up to 4.4 and the totality of its sectors classified as critical in T50 (Fig. 5B). Low to medium risk classes predominated in GCR and Palhoça. In addition, there were no significant changes in sectors between T10 and T50: the hotspots increased only on the Tijucas and Armação beaches. However, a considerable number of segments showed an increase to a high flooding risk level in the municipalities of Florianópolis and Gov. Celso Ramos in T50.

Hotspots from exposed and semi-sheltered stretches presented different characteristics: the exposed ones were characterized by dune heights ranging from 0 to 2 m, mostly with TWL values above the average (4.2 m) and short to medium beach width (22 m average), including consolidated and slightly urbanized shores. The semi-sheltered sectors presented lower TWL (usually lower than 1.3 m); however, their backshore characteristics hinders the dissipation of storms. These sectors presented higher exposure rates combined with a short beach width (13 m average) and the absence of natural protection (dune height ranging from 0 to 1 m). Moreover, the semi-sheltered sectors classified as critical included urbanized fringes.
4.2 Storm-induced erosion risk assessment

Values of storm-induced shoreline retreat varied from 0.12 to 4.87 m in the T10 scenario and from 12.76 to 206.8 m in the T50 scenario. The highest scores were found in the Florianópolis and Tijucas municipalities, which also had the largest retraction average in the studied area (Table 5).

Considering the erosion indicator under the T50 scenario, approximately 58% of the sectors lies within classes of null to low hazards. Classes 4 and 5 represented 21.5% of the analysed sectors for T10 and 29.4% for T50. The highlighted erosion-prone sectors comprised the following beaches: Tijucas, Ingleses, Barra da Lagoa, Galheta, Joaquina, Campeche, Armação, Matadeiro, and Lagoinha do Leste (Figs. 6A and 7A). The very high classes were concentrated in the municipalities of Tijucas and Florianópolis, indicating that these locations were more susceptible to erosion. The least susceptible district was Palhoça, in which greater than 75% of sectors had null and very low classes in both scenarios.

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**Table 5** Computed values of storm-induced shoreline retreat in the different municipalities of Santa Catarina Central Coast. Values for the entire analyzed sector are highlighted in bold

| Municipalities with exposed sectors | Rt T10 (m) | | Rt T50 (m) | |
|---|---|---|---|---|
| | Max | Min | Mean | Max | Min | Mean |
| Tijucas | 4.8 | 1.2 | 3.0 | 181.2 | 91.0 | 121.6 |
| Gov. Celso Ramos | 0.7 | 0.2 | 0.4 | 67.5 | 26.3 | 45.2 |
| Florianópolis | 3.4 | 0.1 | 1.0 | 206.8 | 12.7 | 72.5 |
| Palhoça | 0.9 | 0.1 | 0.4 | 68.6 | 14.3 | 38.7 |
| **Whole Central Coast** | **4.8** | **0.1** | **1.0** | **206.8** | **12.7** | **69.3** |

**Fig. 5** Flood Coastal Index for T10 (A) and T50 (B) scenarios
Fig. 6 Alongshore distribution of the storm-induced erosion (A) and exposure (B, C) indicators for T10

Fig. 7 Alongshore distribution of the storm-induced erosion (A) and exposure (B, C) indicators for T50
Moreover, urban or slightly urbanized coastal segments represented approximately 66% of the highest scoring sectors in T50. Most of them were characterized by the absence of frontal dunes and steeper beach face slopes.

With regard to exposures to erosion impact (Figs. 6B and 7B), the land use indicator was mostly characterized by the medium class, which represented 43.1% of the analysed sectors in the T50 scenario. The very high category represented up to 19.6% of the analysed stretches and was concentrated in the municipalities of Gov. Celso Ramos and Florianópolis. Notably, the average beach width of these sectors was 16.5 m, with a predominantly absent dune class. High exposure values may be related to the proximity of man-made infrastructure to the shore.

The very low-exposure class was predominant when assessing the Social Vulnerability Indicator in both scenarios. The second most frequent class observed was the high-exposure class, which represented 23.5% of the sectors in T50. The very-high-exposure class was observed exclusively in the municipality of Tijucas and Florianopolis. Very high exposure rates were specifically related to the ‘per capita income’ and the ‘number of residents per household’.

Infrastructure exposures (Transport System and Business) were the least representative in the erosion impact extent. The transport network indicator is characterized by low exposure in 47% of the sectors in the T50 scenario. The stretches that are represented by very high exposure, are distributed along Florianópolis, Tijucas and Gov. Celso Ramos municipalities. The Business indicator was also mostly represented by very low exposure in both return periods, T10 and T50. Up to 7.8% of the sectors are classified with high and very high $i_{\text{exp}, BU}$, which points to beaches in the municipalities of Florianópolis and Gov. Celso Ramos.

Among the exposed sectors, the overall exposure index ($i_{\text{exp}}$) is mostly described by very low and low-exposure classes in T10 and T50, respectively. The high- and very-high-exposure classes represented 19.5% of the total sectors for T10 and 41.1% for T50. Florianópolis showed the highest exposure indices to storm-induced erosion, comprising up to 66.6% of the sectors of high and very high classes. This municipality was followed by Gov. Celso Ramos, which was characterized by beaches with reduced backshore at and a representative part of its structures very close to the coastline. The very-high-exposure classes included the following sectors: Tijucas, Palmas, Ingleses, Barra da Lagoa, Campeche, Morro das Pedras, Armação, Pântano do Sul, and Pinheira (Ponta do Papagaio) (Figs. 6C and 7C).

In the study area, sectors with medium erosion risk (category 3) predominated for T10 and T50 return periods (Fig. 8), with a CI average of up to 2.3. The very high class represents approximately 27% of the exposed segments in the T50 scenario. The analysis identified seven critical sectors for the T10 and 14 for the T50, corresponding, respectively, to 13.7% and 27.4% of the investigated stretches. The hotspots were specifically located on the following beaches: Tijucas, Palmas, Ingleses, Barra da Lagoa, Joaquina, Campeche, Armação, Matadeiro, Pantano do Sul, and Pinheira (Ponta do Papagaio) (Fig. 8B).

The results indicate that Florianópolis is the most susceptible and vulnerable municipality to erosion in the study area. Considering T50, middle risk and critical sectors predominates in this city (72%). Tijucas presents the second highest risk caused by erosion. With a CI average of 3.4, the risk varies from medium to critical; in the municipality of Gov. Celso Ramos, the low and medium classes predominate, while Palhoça is mainly represented by the null to low-risk categories. Moreover, there was a large increase of hotspots for T50 and the highlighted changes were mainly represented in the municipalities of Tijucas and Florianópolis.
The high CI rates were driven by high values of exposure indicators, such as land use and transport systems, combined with medium to high values of hazard indicators. Morphologically, the critical sectors are mostly characterized by the absence of frontal dunes (78%) and a short beach width (average: 20 m). As expected, most of the hotspots are localized on Santa Catarina Island (71% in the higher return period scenario), which present geographically higher exposure to hydro-meteorological events and an important urban development near the coast.

4.3 Critical areas for storm-induced erosion and flooding risk

In the area, the hotspots that included simultaneously erosion and flooding hazards in the longer return period scenario were Tijucas, Palmas, Ingleses, Barra da Lagoa, Campeche, Armação, and Pinheira (Fig. 9). The highest CI values were found in the municipalities of Florianópolis and Tijucas, suggesting that they are the most susceptible and vulnerable sectors to storm-induced impacts.

5 Discussion

Integration of existing data, empirical models, and spatial analysis allowed us to perform a flood and erosion risk assessment, which provided additional information concerning the area of interest. The chosen approach proved to be efficiently adaptable to data-poor areas, especially the hazard assessment module of the framework.
The high flood CI rates essentially reflected the rank of the flood impact indicators and the spatial distribution of specific exposure descriptors, such as land use and transport systems. The higher values of the flood impact indicators can be justified by the interaction between the morphological and hydrodynamic characteristics of each sector: in general, these segments are exposed to a higher incidence of waves, with poorly developed or non-existent dunes and TWL values above the average calculated for the whole area (4.2 m). Thus, the distribution of critical sectors is mainly controlled by their geographic position, geological heritage and/or by changes linked to anthropic interference that usually is related to the removal of natural barriers (i.e. primary foredune), favouring hinterland exposure.

Note that during very extreme events, waves can enhance flooding and erosion, however here for semi-sheltered sectors we assume that this effect is not as relevant as it is the storm surge level. This assumption allowed us to use the simplifications necessary for the assessment but can also minimize the recognition of the hazard effect in these areas.

The degrees of exposure reflected the distinct patterns of urbanization and socio-economic activities in the different municipalities. Gov. Celso Ramos and Florianópolis show a higher density of urban industries and infrastructure networks close to the shore, which is why a greater number of elements are exposed to the scenario proposed here. In the case of Tijucas, the most exposed sectors are essentially linked to the social vulnerability index,
because it has a low-income population settled near the coastline, which is an exception in the area.

Some identified hotspots, such as the beaches of Barra da Lagoa and Armação in the municipality of Florianópolis (Fig. 5B), have been highlighted previously to be under flooding and erosion threat (Bonetti et al. 2013; Klein et al. 2016b). Other examples are the beaches of Canasvieiras, Ponta das Canas, Ingleses, and Campeche, which were among the most affected areas during the storms observed from 1991 to 2001 (Simó and Horn Filho 2004). A study carried out on a smaller scale by Klein et al. (2016a) also points to the Barra da Lagoa and Ingleses beaches under an inundation regime and to Ponta das Canas, Canasvieiras, Jurerê, and Daniela under an overwash regime for T50 (according to the scale of flooding regime proposed by Sallenger 2000). Furthermore, note that Tijucas is, in fact, particularly susceptible to the occurrence of extensive flood episodes (Santos and Bonetti 2018), because a relatively well-developed low-lying chenier coastal plain is established on its hinterland (FitzGerald et al. 2007).

Considering the analysis of the distinct probabilistic distribution, there were no major changes between scenarios. As the hazard extent was probably limited by the morphological characteristics in the study area, the exposures presented a slight increase in the higher values as well.

The superior CI rates presented in the erosion risk assessment were mostly driven by high values of exposure indicators combined with medium to high hazard categories. The exposure assessment reflected essentially the land use and the transport system descriptors, as did the flood exposure analysis. Concerning the erosion assessment, it was observed that very high retraction rates were related to very low dune height classes and short beach widths. The variables used to characterize beach morphology had the greatest influence on the results, showing the importance of using higher resolution topographic and bathymetric data to apply this approach. Moreover, the selected model to obtain wave parameters does not include wave refraction phenomena, which may increases the error. In this line, note that this work focused on the capability of detecting hotspots using CRAF1 methodology despite the scarce available dataset, and not on obtaining trustworthy numerical flooding and erosion estimations. We intend to show that these results can be useful on hotspot identification, although the accuracy on erosion and flooding estimates cannot be proved. Still, note that the results of the hazard assessment followed the general pattern of the study area, with a retraction average for the whole area of 69.3 m for the T50 return period (Table 5).

Although the maximum values are higher than observed (up to 49 m along the coast of Santa Catarina Island; Leal et al. 2020), they highlight some of the exposed beaches that have historically greater erosion problems: some critical sectors in Florianópolis, such as Ingleses, Barra da Lagoa, Joaquina, Campeche, Armação, Matadeiro, and Pantano do Sul (Fig. 8B), are well-known areas where erosive process linked to different causes have already been described (Abreu de Castilhos et al. 1995; Castilhos and Gré 1997; Torronteguy 2002; Simó and Horn Filho 2004; Faraco et al. 2006; Mazzer et al. 2008; Oliveira et al. 2008; Mazzer and Dillenburg 2009; Rudorff and Bonetti 2010; Bonetti et al. 2013; Klein et al. 2016b; Dalbosco et al. 2019; Leal et al. 2020).

Bonetti et al. (2018) assessed the susceptibility of sandy beaches to erosion for the entire Santa Catarina coast. The authors primarily considered environmental indicators in the analysis; thus, some results are similar to the observed pattern presented here for the erosion hazard assessment. The study pointed to the dominance of low to medium-susceptibility values in the south sector of the state, whereas an alternating distribution of susceptibility classes, tending to higher values, prevails in the Santa Catarina Island (Florianópolis). However, differences can be seen especially in the exposed beaches of Gov.
Celso Ramos and Tijucas municipalities, and they can be explained by the influence of the hydro-meteorological components on the hazard assessment. Along the Santa Catarina Coast, the inclusion of wave data has already been pointed out for having a large impact on the final result of susceptibility/vulnerability assessment (Serafim et al. 2019). Nevertheless, the primary control of the geological setting, beach orientation and proximity of man-made infrastructure over the vulnerability of the Santa Catarina coast, as previously proposed by Bonetti et al. (2018), was confirmed in our study.

The analysis of the T10 and T50 scenarios shows that the level of erosion risk tends to increase in the study area when considering a higher return period and suggests that the Santa Catarina Coast will be largely affected by coastal retreat. Furthermore, considering both hazards, the scenario tends to worsen due to the interactive relationship between the two process and the human activities on the coastal plain (Pollard et al. 2018).

In summary, the regional pattern identified for flooding and erosion risk is corroborated by the historical analysis based on the state’s Civil Defence disaster databank, presented by Rudorff et al. (2014): Florianópolis is the most affected municipality in Santa Catarina State, and the other municipalities in the central sector, excepted Tijucas, have no record of emergency situations linked to storm-induced waves and surges. The authors attributed this fact to the presence of Santa Catarina Island, which acts as a natural barrier to large wave systems, partially protecting the adjacent coast.

Tijucas is historically characterized by a low frequency of damages related to storm surges. Its coastline is located at the inner portion of a sheltered bay where wave energy is attenuated by the process of refraction and diffraction due to its morphological configuration and muddy inner shelf substrate. However, high susceptibility levels to extreme events, particularly flood, have been reported on a local scale (Santos and Bonetti 2018). These events are concentrated in a sector where a long-term retreat of the coastline was detected by these authors based on the analysis of historical images and can be explained by the presence of low-lying areas and their greater exposure to the east waves.

Our results are also partially corroborated, in a comparative way, with the analysis developed on regional scale by Serafim et al. (2019). The study highlights most of the sectors presented here as at high risk for both hazards (Fig. 9) (assigns high and very high scores to Palmas, Barra da Lagoa, Armação, Campeche, and Pinheira beaches) and points out that most of the critical stretches are related to the low adaptive capacity found in areas with high occupational density. Similarly, here the critical sectors are driven by the high exposure indices (in turn related to high occupational density) but also by the morphological configuration, which controls the segment susceptibility to the main wave direction (as also suggested by Bonetti et al. 2018; Mussi et al. 2018, using different scales). The role of the morphological configuration was also discussed by Muler and Bonetti (2014), who presented a vulnerability analysis for Santa Catarina Island based on different wave directions. The study showed that, although south and southeast waves present the greatest heights, they are associated with low exposure of buildings because most of the populated sectors are located on semi-sheltered portions of the Island.

The obtained findings also highlight the key role that dunes may play in coastal protection. Dune absence or fragmentation has been related to the very high impacts of flood and erosion. In the study area, human occupation takes place over the Holocene coastal plain, represented by unconsolidated sandy sediments that offer even less protection to storm wave action. Anthropic activities in these areas contribute to the intensification of erosive processes because of the imbalance in the sediment budget of the coast, which sometimes lead to the decrease of the beach extent and presence of natural barriers, consequently making the hinterland more vulnerable to the flood events. For example, in Ingleses beach
there is a natural input of sand from two dune fields that bring sediments from Santinho and Moçambique beaches (through sand overpassing). In the last decades, urban development in this sector was established over the dunes, interrupting sand transport and leading to a local deficit of sediments (Vieira da Silva et al. 2016).

Note that, although the erosion assessment was carried out only for the exposed sectors, many semi-sheltered beaches are characterized by lowland areas and presented an extremely low level of protection in face of a small TWL increase. Studies carried out in the Florianópolis sector show that even considering only the sea level rise, the city has little or no protection from its effects (Montanari et al. 2020). Furthermore, for sheltered and semi-sheltered sectors, the regional pattern of beach responses to extreme events can be disrupted on a local scale due to the connectivity between beach systems via physical processes, like sediment redistribution or/and headland bypassing (Burvingt et al. 2017).

In regard of the main challenges pointed out in Sect. 3, although the data used to characterize the topography and bathymetry in the area present low accuracy to obtain reliable numerical values of flood and storm-induced erosion, data source resolution is homogeneous over the whole study site, affecting equally the risk estimation along the coast. Besides, using the available information allowed the identification the main hotspots of Santa Catarina Central Coast, which indicate that CRAF1 can be applied with the purpose of recognizing sensible areas where high accuracy data are not available, which is the case for almost all the Brazilian coast as well as for most of the developing and underdeveloped countries.

Even though the need to apply some alternatives for the treatment of the predicted variables in CRAF1, the tool proved to be flexible enough to be used in conditions of greater data scarcity. It has already been pointed out that, specifically for hazard assessment, the type of data required make it difficult to evaluate some coastal stretches at regional levels (Narra et al. 2019); however, in this study, we showed that the tool can be implemented with simplifications by using some alternatives. Here, several parameters were simplified due to the low resolution of the input data; nevertheless, the general pattern was respected, corroborating the well-known areas and providing important information, especially in qualitative terms, for the Santa Catarina Central Coast.

### 6 Conclusions

This study applied the CRAF1 framework in a data scarcity condition, focusing on the Santa Catarina Central Coast, to identify storm-induced hotspots of flood and erosion. The approach proved to be efficient and adaptable to sites where high-resolution data are usually unavailable. Despite the need to adopt some assumptions and simplifications, the method generated useful results for the identification of critical risk areas.

The integration of indicators through risk maps allowed the identification of 18 critical segments for T10 and 20 for T50 concerning flood risk. Likewise, in respect to erosion risk, seven critical stretches were identified for T10 and 14 for T50. In both cases, the sectors under very high risk to storm-induced impacts include the municipalities of Florianópolis and Tijucas, which correspond to the areas with the highest number of registered warning recurrences due to storm events. Among the exposed sectors, nine simultaneously presented the risk caused by erosion and flooding in the longer return period scenario. This result was related to the anthropic occupation of lowland areas, which are naturally more vulnerable to wave impacts.
The risk analysis in probabilistic terms allowed the identification of the main hazard in the study area, showing that the storm-induced erosion process tended to be more severe along the years when compared with the flooding process. However, often these hazards are strongly related, and when considering a large return period, a major impact can reach a greater number of stretches, as the hinterland becomes more susceptible.

Some simplifications were necessary when applying the methodology, for example, to obtain geomorphological and hydraulic parameters, as well for the data used in the exposure analysis. The risk assessment also took into account the maximum hazard extent in each sector and did not consider important parameters related to overwashing processes, obstacles, soil infiltration, and the presence of river basins, which may influence the regional vulnerability pattern. Nevertheless, it was possible to identify the most critical areas, which coincide with those where damage was registered during extreme events and also with some hotspots highlighted in previous works.

Although many previous studies have been developed in the area, future sea-level rise scenarios were not considered in those analyses, a factor that can be of great importance for management purposes. In this way, the results obtained here can be used as the basis for future research by indicating the areas that deserve more attention and more detailed analysis in the perspective of potential risk. Also, given the data scarcity in the study area, it was not possible to do a comparison of the results obtained here with the results obtained by applying the same approach with good quality data. Such analysis would complement the qualitative assessment provided here and is highly recommended for future researches.

It is important to highlight that the low resolution in our input data and the simplified models applied here may not allow to obtain accurate flooding and erosion values. Nevertheless, it was possible to identify the main hotspots of Santa Catarina Central Coast using CRAF1 methodology in spite of the data scarcity and simplifications in empirical formulas applied here.

This study proposed some alternatives that allow the implementation of the CRAF1 tool conditions of data scarcity. With this, it is expected to inspire similar analyses in countries that do not have a structured spatial data infrastructure, expanding the scope of the original methodology applied in Europe.

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**Declarations**

**Conflict of interest** The authors have not disclosed any competing interests.
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