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REGIONAL COASTLINE CHANGES AND FUTURE PREDICTED SCENARIO ON SOUTHERN BRAZIL.

CAMBIOS REGIONALES EN LA COSTA Y ESCENARIO FUTURO PREVISTO EN EL SUR DE BRASIL.

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ABSTRACT

The Rio Grande do Sul (RS) coastline consists of a 615 km long sandy barrier, with a NE-SW orientation. The genesis of this geographical area is related to Quaternary sea-level changes, with a complex Lagoon-barrier system. This study presents a compilation of decades of studies about short-term monitoring and long-term projections conducted by the two local main research centers on the subject. Trends in shoreline behavior between 2002 to 2013 were analyzed. The specific causes of these variations are not yet fully understood. However, some factors are likely to be responsible for coastline behavior in the long and short term. The main erosive hotspots found along the RS coastline are influenced by wave energy due to the refraction caused by the bathymetric features and coastline orientation. The Cassino Beach sector, however, has a pronounced progradation which in the long term can be mainly related to its orientation, and more recently due to jetties built at the Patos Lagoon inlet, which provided more sediment retention of the prevailing net longshore drift to the northeast. This research also offers a review about shoreline changes along the four existing inlets. Coastal vulnerability to sea-level rise (SLR) analyzed through coastline recession rates in long-term scenarios (2030 and 2100) indicated that the most vulnerable sectors are those located along embayments, which coincide with low gradient shorefaces.

Keywords: Coastal erosion, sediment budget, morphodynamic processes, projected coastline changes.

RESUMEN

El litoral de Rio Grande do Sul (RS) consta de una barrera arenosa de 615 km de longitud, con orientación NE-SW. La génesis de esta área geográfica está relacionada con los cambios del nivel del mar en el Cuaternario, con un complejo sistema de laguna-barrera. Este estudio presenta una recopilación de décadas de investigaciones y hace proyecciones a largo plazo. Se analizaron las tendencias en el comportamiento de la costa entre 2002 y 2013. Las causas específicas de estas variaciones aún no se comprenden completamente. Sin embargo, es probable que algunos factores sean preponderantes en el comportamiento de la línea costera a largo y corto plazo. Los tres principales hotspots erosivos que se encuentran a lo largo de la costa del RS están influenciados por la energía del oleaje debido a la refracción causada por las características batimétricas y la orientación de la costa. El sector de la playa Cassino, tiene una progradación pronunciada que, a largo plazo, puede estar relacionada con su orientación y, más recientemente, debido a los muelles construidos en la ensenada de la laguna de Patos, que proporcionaron una mayor retención de sedimentos del transporte longitudinal predominante a la costa. También se ofrece una revisión sobre los cambios en la costa a lo largo de las cuatro ensenadas existentes. La vulnerabilidad costera al aumento del nivel del mar (SLR) analizada a través de las tasas de recesión de la línea costera en escenarios de largo plazo (2030 y 2100) indicó que los sectores más vulnerables son aquellos ubicados a lo largo de las ensenadas, que coinciden con las costas de baja pendiente.

Keywords: Erosión Costera, balance sedimentario, procesos morfodinámicos, proyecciones de línea de costa.

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INTRODUCTION

Variations in the coastline positions are part of a natural cycle of continental adjustment to sea-level fluctuations, regardless of their causes. Although erosion is typically seen as a problem, coastal erosion occurs unnoticed on coasts that are unoccupied by human communities, where the shoreline displacement cannot be seen by untrained eyes. This phenomenon is considered natural and has no adverse effects on social communities. Coastal erosion becomes a problem only when a receding coastline affects or is affected by human actions. Erosion then becomes a risk factor and raises economic and social concerns.

According to Muehe (2006), fluctuations in coastline positions occur largely due to a lack of sediments, caused by a depletion of the sediment source, usually the continental shelf. Depletion occurs when sediments are carried to dune fields farther inland or through human action, particularly the building of dams or other infrastructure that retains sediment and prevents its flow along the coast (Komar, 2018).

The coast of Brazil has a physical and environmental diversity regarding its morphology and hydrodynamic components. In general, there is increasing energy of incident waves from north to south, with a reverse trend occurring in tides – south to north - (Muehe and Nicolodi, 2008; Pianca *et al.* 2010; Rodriguez *et al.* 2016). In Brazil, coastal erosion exceeds shoreline progradation, being significant on beaches, cliffs, and estuaries (Rodriguez *et al.,* 2016; Muehe, 2018). Some of the most important studies on this topic in Brazil can be seen in Calliari and Speranski, 2001; Esteves *et al.,* 2002; Souza-Filho and Paradella, 2003; Krause and Soares, 2004; Williams and Esteves, 2005; Angulo *et al.*, 2006; Bittencourt *et al*., 2006; Dillenburg *et al*., 2004; Dominguez *et al.*, 2006; El Robrini *et al*., 2006;; Horn, 2006; Klein *et al.* 2006; Manso *et al*., 2006; Neves *et al*., 2006; Toldo *et al.*, 2006; Vital *et al.*, 2006; Muehe and Neves, 2008; Alves, 2009; Muehe, 2010; Souza and Nicolodi, 2016; Martelo and Nicolodi, 2018; Oliveira *et al.,* 2019; Figueiredo *et al*. 2020. An update of the general situation of coastal erosion in Brazil was organized and published by Muehe (2018).

The present article aims to put forward a compilation of studies conducted by the Geological Oceanography Laboratory at the Federal University of Rio Grande (FURG) and by the Center for Coastal Geology Studies at the Federal University of Rio Grande do Sul (UFRGS), which focused on historical coastline changes and projected changes due to sea level rise effects along the Rio Grande do Sul (RS) coastline. These studies identified trends of coastline changes along the 615 km of this coast, the causes and consequences for these variations, and implications for short- and long-term coastal management.

STUDY AREA

The study area, the Rio Grande do Sul coast, comprises part of a sandy barrier that is considered as the most continuous barrier in the world (Dillenburg and Barboza, 2004). This Holocene barrier located along the southern coast of Brazil extends for 760 km (from the south of Santa Catarina state to northern Uruguay). The RS state coastline extends for 615 km almost evenly with a northeast to southwest orientation (Figure 1). This continuous pattern presents only six discontinuities, which are narrow lagoons and river mouths (Dillenburg *et al.,* 2009). Even though the coastline direction varies little, some segments vary slightly presenting subtle concavity or convexity. This alternation extends from the northern rocky promontories at Torres to the Chuí outlet its southern limit, at the Uruguayan border.

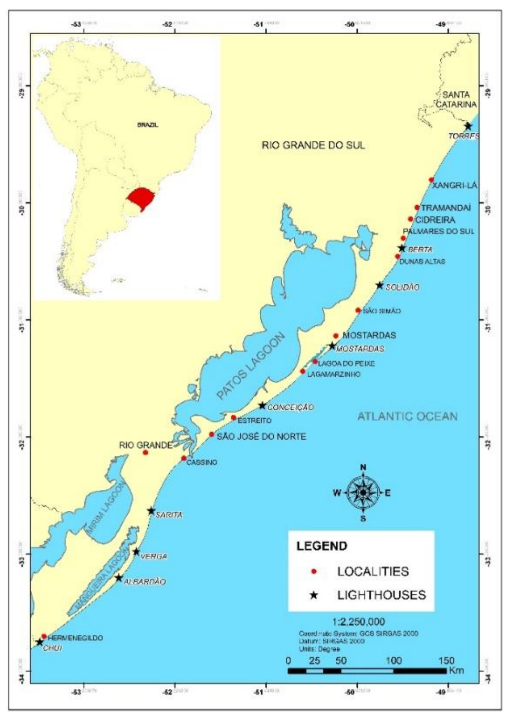

Figure 1: The Rio Grande do Sul coast and its principal landmarks. Self-elaborated.

The dominance of coastal sandy barriers in the Quaternary geological record along Brazil's southern coast is the result of an abundance of sediments (particularly sand), a gently sloping continental shelf, and the incidence of moderate- to high-energy waves and microtides (Tomazelli *et al*, 2000; Dillenburg and Barboza, 2004). The combination of this region's continental shelf morphology, mean significant wave height (around 1.4 m), and its microtidal environment (about 0.30 m) presents an ideal example of a wave-dominated coast, made even more uniform by the low number of coastal inlets (Calliari *et al.* 1998). The coastal plain is composed of unconsolidated Quaternary deposits that currently do not receive sand particles since all river-transported sediments are retained by coastal water bodies such as the Patos and Mirim lagoons. Both lagoons extend 13,750 km^2, which is approximately one-third of the state's coastal plain (Tomazelli and Villwock, 1992; 1996; Rosa *et al*, 2011).

The local wave climate is formed by sea waves (low period), swell waves (long period), and storm waves. The swell is characterized by regular waves often originating several hundred kilometers off the coast, coming mostly from the SE, with significant heights between 1.5 m and 2.0 m and a period of 8 to 10 seconds. The sea waves, which result from the action of local winds, come from the NE and E, which makes this also the dominant direction of waves in the region. This type of wave has a period of between 6 and 8 seconds, and a significant height of between 0.5 and 1.5 m (Tomazelli and Vilwock, 1992; Almeida *et al*., 1999; Toldo *et al*. 2006; Romeu *et al*., 2015; Rodriguez *et al*, 2016; Casagrande *et al*., 2018). The storm waves, although less frequent, correspond to higher energy waves. They result from the action of strong winds linked to storms that occur near the coastal region. As a rule, these waves are usually related to significant sea-level rises during storms ("storm surges"), and have high impact on the coast with intense erosion, and large movement of sedimentary material along the beach (Tomazelli and Vilwock, 1996; Barletta and Calliari, 2001; Calliari *et al*., 2003; Saraiva *et al*. 2013; Machado *et al.* 2010; Guimarães *et al*. 2015).

The beaches in the study area are formed by fine, well-selected quartz sand, (Calliari and Klein, 1993; Weschenfelder *et al.,* 1997; Nicolodi *et al.,* 2002; Oliveira and Nicolodi, 2016; Calliari and Toldo, 2016). Changes in this general pattern in certain sections of the coast are due to grain size variations such as detritus of beach rock fragments and shelly gravel, and coarse to medium quartz sand that comes from the foreshore. Two beach sections 45 km and 30 km long, south of Albardão Lighthouse and near Estreito (Figure 1), respectively, present characteristics of reflective and intermediate beaches (Short, 1984). The beaches in these regions have a pronounced slope (4° on average), erosion scarping in the swash zone and backshore, and well-developed cusp-shaped berms (Pereira *et al.,* 2009). Along the RS coast, areas affected by the relevant coastal erosion are concentrated in regions with moderate to no urbanization, as the cases of Hermenegildo Beach and the Conceição Lighthouse areas (Figure 2).

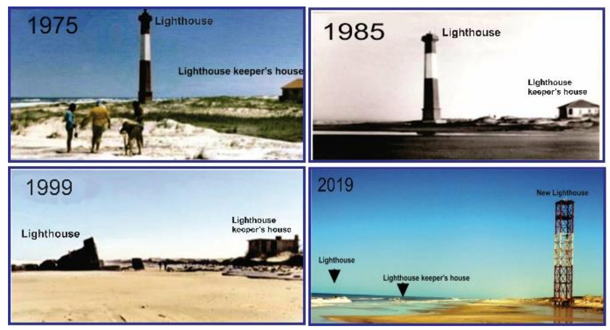

Figure 2: Conceição Lighthouse, central coast. Note that the original lighthouse collapsed in the surf zone and the new structure is exposed to the same erosive process on the beach. Source: Geological Oceanography Laboratory Database (FURG) and Bruno Moller. Self-elaborated.

The coastal area of RS is approximately 43,000 km^2 and includes 46 cities, but the large urban centers in the state are not concentrated on the coast. In the summer, however, the population of coastal cities increases significantly (Strohaecker, 2008). This coast can be divided into three sectors: north, central, and south.

The main area of urban development is concentrated on the northern coast, spanning approximately 120 km (from Torres to Palmares do Sul). In this area, there are no persistent stretches of erosion, although there are points where the coast has retreated or is currently retreating, which may be critical for coastal management in the future (Silva and Tagliani, 2012; Koerner *et al*, 2013). The other area of intense urban development is Cassino Beach, located in the southern part of the state very close to the Rio Grande Port.

METHODS

Two main methodologies were used in this study for the analysis of coastline changes in the Rio Grande do Sul State: coastline monitoring, and long-term coastline projections.

COASTLINE MONITORING

The coastline has been monitored by field measurements using a GPS (post-processed) in a vehicle along the coastline from Torres to Chuí. The measured limits of the swash zone are compared using Geographic Information Systems (GIS). Coastline monitoring has been conducted since 1997 (Toldo *et al*., 1999), and the data used in the present research refers to the period between 2002 and 2013.

Depending on the circumstances, water motion from waves, tides, storm surges, and near-shore currents combine and interact with the coastal land, which in turn has considerable inherent variability (Komar, 2018). To understand the processes that act on the coastline it is necessary to understand the behavior of the subaqueous topography. Processes that act on the surf zone and are reflected on the coastline are dependent on bathymetry. In relation to Rio Grande do Sul, some authors discuss this topic in a specific way (Gruber *et al.* 2003; 2006; Barboza *et al.* 2011; Goulart and Calliari 2013; Dillenburg *et al.* 2017).

Boak and Turner (2005) developed a detailed study of shoreline indicators. They consider them as a feature that is used as a proxy to represent the "true" shoreline position. Individual shoreline indicators generally fall into one of three categories: a) a visually discernible coastal feature, b) based on a specific tidal datum, c) based on the application of image-processing techniques to extract proxy shoreline features from digital coastal images that are not necessarily visible to the human eye. The most used coastline indicator is the "high water line" (HWL). Generally, it is determined visually as a change in tone left by the highest tide level. Due to its wide application, however, the definition and interpretation of the HWL has received considerable attention in the literature.

The HWL is used in this study, and the field measurement is determined by the average swash zone. For beaches in Rio Grande do Sul, the width of the swash zone is approximately 16 m (Toldo and Almeida, 2003), taking into consideration features such as wave height and wavelength in deep waters, as well as the slope of the beach face. The main errors that occur in coastline and waterline surveys are associated to the amplitude of the astronomical and meteorological tides, wave run-up, and the slope of the beach face (Toldo and Almeida, 2003). These parameters were monitored before and after the surveys to minimize errors (Table 1).

Table 1: Control parameters for coastline monitoring used to identify the waterline. Adapted from Toldo and Almeida, 2003. Self-elaborated.

Parameter	Control
Amplitude of astronomical tide	With an average value of 0.30 m it can create up to 9 m of displacement in the horizontal plane when the survey is performed over a beach-face with an average slope of 1/30 over a period of 10 hours. The error had maximum and minimum values of the tide amplitude of the order of 0.32 and 0.20 m, respectively, during the field survey. This factor can be monitored using field instruments or by consulting weather forecasts that contain astronomical tide conditions.
Amplitude of meteorological tide	With an average value of 1.2 m this parameter can generate an error greater than 35 m in the horizontal plane, with a beach-face slope of 1/30. However, this factor can be monitored using information on the entrance of cold fronts and storms to the southern coast using weather models before collecting data in the field.

Wave run-up	For beaches on the RS coast, wave run up was 0.55 m. This parameter is associated with the slope of the beach-face as the wave broke and spread out to an average distance of 16 m. This error is associated to variations in wave height during coastline surveys. It can be monitored using measured wave data or through weather models.
Slope of the beach-face	With average variations between 1/20 and 1/40, induced by seasonal factors or by local fluctuations in the energy of incident waves, this factor is difficult to monitor in areas that extend hundreds of kilometers, as is the case of the beaches in Rio Grande do Sul.

Since storm surge is responsible for the increase or decrease in sea level of predicted astronomical tides, wave and wind data was monitored previous to field work in order to avoid such conditions. This phenomenon usually involves the intrusion of seawater into low-lying areas, causing flooding (Rodriguez *et al*., 2016).

In addition, astronomical tide data was monitored to avoid the combination of positive storm surge with the wave setup, which can result in extreme values of run-up (maximum vertical excursion of swash on the shoreline). This can result in inundation, especially when these storms coincide with an astronomical spring tide (Rodriguez et al. 2016).

According to Albuquerque *et al.* (2013), the use of GPS for mapping coastlines is one of the most accurate methods, compared to other techniques, such as photointerpretation. Coastline indicators are characterized by their continuity throughout the area to be mapped, and their position can be consistently reproduced by different individuals (Morton and Speed, 1998; Pajak and Leatherman, 2002).

Previous studies (Morton *et al.* 1993, List and Farris 1999, Toldo Jr. *et al*. 1999 and Esteves *et al*. 2001) have demonstrated that this method is effective for mapping regions of 100 km or more in length, as long as a control for error is inserted in the results. Ruggiero *et al.* (1999) and Huang *et al*. (2002) indicate that detailed maps with GPS are also recommended for areas of only a few kilometers in extension (Albuquerque *et al.*, 2013).

In the present study, two measured water lines were compared for the period between 2002 and 2013. Measurements consisted of data acquired from a Pathfinder Trimble® Pro-XRS GPS, with 10 to 30 cm precision in navigation mode in both the vertical and horizontal directions. In the field, the GPS receiver was installed on a traction vehicle that moved along the water line at a velocity of 50 km/h. The stationary GPS antenna was installed by the Geodetic Department at the Geosciences Institute of UFRGS, as an integral part of a network of IBGE antennae that covers a radius of 500 km, with its center in Porto Alegre. Data generated from this stationary antenna was used to correct data from the field. The sample time for both pieces of equipment was 3 s. Files for post-processing were created with submetric resolution.

After a coastline vector was created, a common line was generated using routines avaiable by the Erdas Imagine® Modeler software. Erosion and accretion rates for each polygon were applied using the change polygon method (Smith and Cromley, 2012). Using this method, it is possible to extract variations between the previously digitized coastlines through the addition and subtraction of polygons. Therefore, changes in the area can be calculated by breaking a complex polygon down into a series of simple sub-polygons (Albuquerque *et al.*, 2013).

THE LONG-TERM COASTLINE PROJECTIONS

The concept of risk in this work was established by Nicolodi and Pettermann (2010) and is associated with an event that may or may not happen. The real risk occurs when there are material or immaterial assets, for there is no risk if the perception of losing something does not exist. The notion of “possible loss”, intrinsic to risk, can be broken down into several components (Castro *et al.* 2005). In this research, the component of natural risk is addressed, according to Egler (1996).

Long-term coastline projections were performed through the application of a morphokinematic coastal model, the shoreface translation model (STM), and in its stochastic version, the random shoreface translation model (RanSTM) (Cowell *et al.,* 1992). Simulations aimed to project the coastline position considering projected sea-level rise (SLR) scenarios for the years 2030 and 2100, exploiting the uncertainty associated to such estimates. The application of the RanSTM aimed to quantify regional variability to SLR through the analysis of projected coastal recession distance outputs.

RanSTM deals with parameter uncertainty by simulating coastal changes, represented by the constituents in Equation 1. It generates a number of recession value estimates, from which risk probabilities are compiled. Each input parameter can be inserted in the model through a range of values (minimum, mean, and maximum), considering the associated uncertainty for each parameter. The retreat value may be represented in terms of its risk curve, in which the recession distance or shoreline transgression is the magnitude of the impact. The key advantage in stochastic simulation is transforming qualitative uncertainty into quantified risk by the assignment of a probability density function (PDF) to each of the input parameters to generate forecasts*.*

Therefore, the risk curve originated from Equation 1 represents the probability that a given recession distance will be exceeded:

$$R(t) = \bar{R}_v(t) + \bar{R}_{SL}(t)$$

where $R(t)$ is the total recession distance; $\bar{R}_v(t)$ is the mean-trend recession due to littoral sediment budget imbalance; $\bar{R}_{SL}(t)$ is the mean-trend recession due to accelerated sea level rise.

The concepts underpinning the coastal-tract delineation approach adopted in this study for defining coastal sectors are fundamental to the meaningful application of the profile-based numerical model by which coastal response to both internal and external forcing is evaluated here. Within the numerical model, an aggregated terrain data model (topography and bathymetry) is subject to internal forcing from morphokinematic shoreface adjustments combined with external forcing from inherited substrate geomorphology, sediment budget imbalances, and the climate-driven effects of sea level rise.

Alongshore sediment transport is directly influenced by coastline configuration in plan form as it defines the degree of exposure to incident waves. Regional alongshore variations in shoreline orientation are likely to affect the intensity of littoral currents generating transport gradients which produce variable sediment budgets. Along the Rio Grande do Sul coast, as the shoreline gently undulates, the littoral-transport differentials oscillate accordingly, resulting in areas with negative budgets where erosion rates are high, alternating with areas characterized by long term progradation (Dillenburg *et al*. 2000; Alves, 2009; Martinho *et al*., 2009).

Therefore, the coastline of RS was subdivided into nine compartments considering those factors described in previous studies (Dillenburg *et al*., 2000; Lima *et al*., 2001; Dillenburg *et al*., 2005; Toldo *et al.,* 2006; Absalonsen and Toldo, 2007; Alves, 2009; Dillenburg *et al*., 2009). Coastal compartments or cells analyzed in the present study are C1- Chuí to Albardão Lighthouse; C2- Albardão Lighthouse to Sarita Lighthouse; C3- Sarita Lighthouse to Rio Grande jetties; C4- Rio Grande jetties to Conceição Lighthouse; C5- Conceição Lighthouse to Mostardas Lighthouse; C6- Mostardas Lighthouse to Solidão Lighthouse; C7- Solidão Lighthouse to Xangri-lá; C8- Xangri-lá to Arroio do Sal; C9- Arroio do Sal to Torres (detailed description can be found in Figueiredo, 2013).

Model input parameters and model output results are presented in the form of a range of feasible impact projections (stochastic model), instead of a single estimate (deterministic model). The definition of the sediment budget input parameters involves compiled data from the field or previous studies, such as in the case of sediment budget data, estimated from alongshore-transport analysis and shoreline historical behavior.

Sea-level rise rates predicted in climate models are also presented in the form of probability intervals as estimated by the Intergovernmental Panel on Climate Change (IPCC). For the present study, the chosen probability interval for the coastal response to sea-level rise for the year 2100 includes values between 0.18 m, corresponding to the lower limit presented by Bindoff *et al.* (2007); and 1.1 m, corresponding to the upper limit (RPC8.5 – higher scenario), relative to 1986-2005, for the Mar del Plata region in Argentina. An intermediate value of 0.89 m corresponds to the Bindoff *et al.'s* (2007) upper limit (0.59 m), plus the acceleration of melting glaciers (0.20 m), and the highest sea-level elevation in the South Atlantic (0.10 m). Proportional recession values relative to those presented for the year 2100 were calculated for 2030.

Coastal response model results were presented in the form of probability or risk, where each projected coastline has a probability (0 to 100%) of being surpassed in a given time span in the future (e.g., from present day until 2100). Probabilistic approaches allow for greater transparency in coastal management decisions revealing the consequences if quantitative estimates are wrong (Cowell *et al.,* 2001; 2006).

RESULTS

Overall, the analysis of the coastline changes between 2002 and 2013 indicated stability on 43,5% of the coastline, moderate erosion on 41%, moderate progradation on 9%, pronounced progradation on 3%, and pronounced erosion on 3,5% of the coastline (Table 2). The specific causes of coastline variation cannot be completely determined but include geological inheritance, shoreline orientation, and wave energy focus (as a result of wave refraction due to local bathymetric features). Those factors combined can explain the occurrence of erosional hotspots along the RS coast such as Conceição Lighthouse and Hermenegildo Beach (Calliari and Speranski, 2006, Maia *et al,* 2016). Cassino Beach, however, presented pronounced progradation, which was in part due to the construction of jetties at the inlet of Patos Lagoon in 1901, that altered the sediment transport patterns, causing sediment transpor to the northeast (Goulart and Calliari, 2013; Pereira and Calliari, 2005). The results are displayed in Figure 3 and Table 2. Regions were classified into five categories, using the same class ranges (Toldo *et al.* 1999).

Table 2: Categories of Rio Grande do Sul coastline variation, their limits, and lengths. Self-elaborated.

Category	**Limits (m)**	**Length (km)**	**Percentage**
Stable	Without significant variations during the time period analyzed	268	43,5%
Moderate Erosion	< 30	256	41%
Pronounced Erosion	> 30	22	3,5 %
Moderate Progradation	<30	52	9%
Pronounced Progradation	>30	17	3%

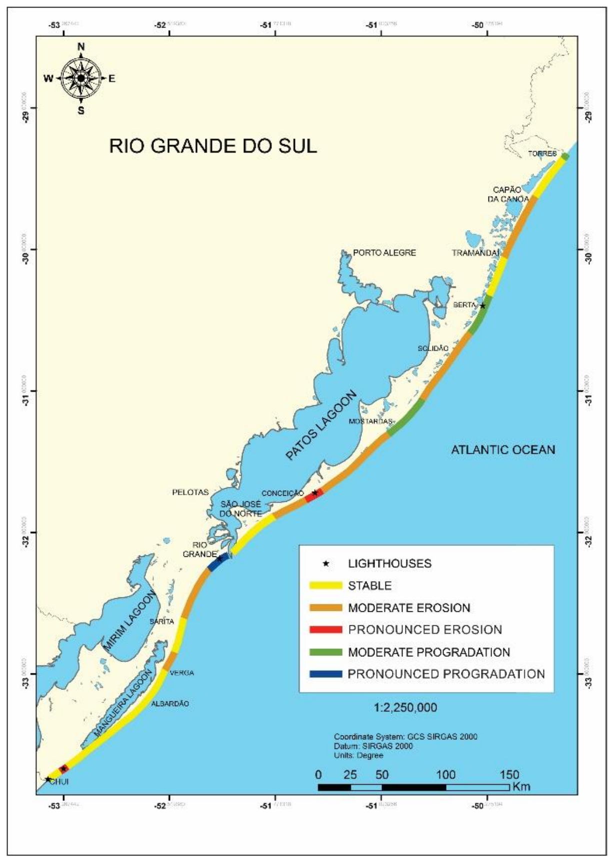

Figure 3: Coastline variations in RS from 2002 to 2013, where: Stability = without significant variations, Moderate Erosion = < 30 m during the period analyzed, Pronounced Erosion = > 30m, Moderate Progradation = <30 m, and Pronounced Progradation = >30m. Self-elaborated.

Cassino Beach had the highest rates of progradation (Dillenburg *et al.,* 2017). Goulart and Calliari (2013) monitored the Cassino Beach coastline using video data (ARGUS) and confirmed that the average rate of progradation in the area is about 9 m/yr. Albuquerque *et al.* (2013) analyzed the causes of coastline variation and erosion at Hermenegildo Beach and calculated a recession rate of 6.29 m/yr from 1996 to 2000 and a rate of 5.25 m/yr from 2005 to 2006.

At the Conceição Lighthouse Beach sector, the Geological Oceanography Laboratory (LOG-FURG) has been systematically monitoring the beach profile (since 1996), identifying an intense loss of sediment (Pereira *et al*., 2007). The rate of shoreline retreat reached 4.37 m/yr, summing 70 m of coastline retreat and a total sediment volume loss of 181.02 m^3/m of beach sediments (1996-2012) (Machado and Calliari, 2016).

Casagrande *et al.* (2018) identified stable or progradational sectors on the north coast (Cidreira Beach) by comparing high resolution satellite images between 2004 and 2015. This behavior contradicts what was previously presented (Toldo *et al.* 1999 and Esteves *et al.* 2006). This coastal behavior may be associated to changes in wind and wave patterns in the region during the analyzed period or over a longer time-scale, for the transgressive behavior of the coast (Barboza *et al*., 2011, and Dillenburg and Barboza, 2014).

Considering the long-term coastline projections, the RanSTM model results showed the highest rates of retrogradation in coastal embayments, characterized by gently sloping shorefaces (Figueiredo 2013). The section from Sarita Lighthouse to the Rio Grande jetties (C3), which includes Cassino Beach, is characterized by the lowest general shoreface slope (0.032° to 0.027°) (Dillenburg *et al.*, 2000) and the highest historical rates of progradation (1947-2000) of 3.22 $m.yr^{-1}$, based on the limit of maximum swash along the entire RS coast. Projected coastline positions from the RanSTM modeling in the present study indicate an average retreat of about 695 m (50%), resulting in coastline retrogradation rates of about 8.1 $m.yr^{-1}$ by 2100. Average projected rates of coastline retreat for 2030 are even higher (11 $m.yr^{-1}$) with a projected coastline position located 166 m (50%) from present day dune toe position (Figure 4).

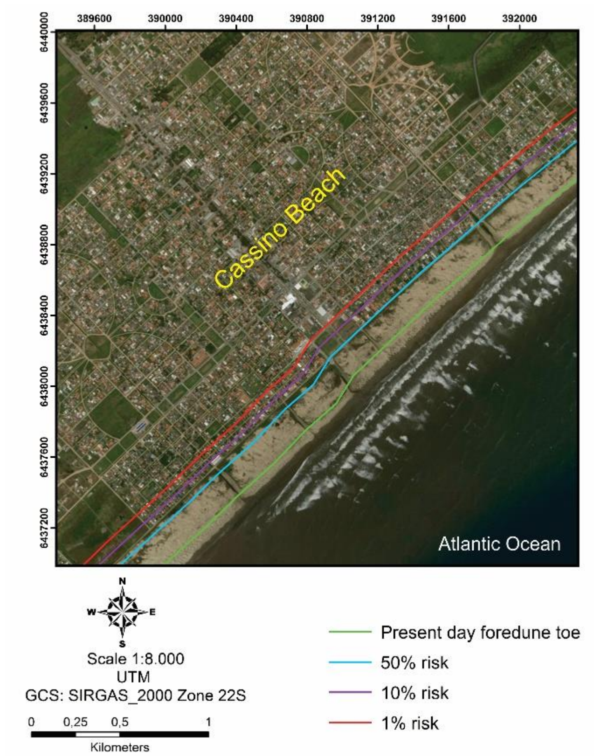

Figure 4. Projected coastlines for 2030 with different risks (50, 10, and 1%). Cassino Beach sector, with focus on the urbanized area of Cassino Beach. Self-elaborated.

DISCUSSION

According to Tomazelli *et al*. (2006) and Da Motta *et al* (2015), the main factors that influence coastline variation in RS are sediment budget, wave energy, wave refraction, and estuarine morphodynamics.

Da Motta *et al.* (2015) analyzed the sediment budget for the middle of the RS coast from 1998 to 2009 by tracing cells on Landsat 7 images. The sediment budget was calculated for each predefined coastal cell by analyzing longshore transport from both the southwest and the northeast. The results showed an alternation between erosional and depositional trends in the same cells depending on the season, especially in cells located between the two most prominent inflections of the coast: Mostardas, and Dunas Altas beaches (Toldo *et al,* 2006). These results show that the regional sediment budget is controlled by wave seasonality and an annual net drift to the northeast is markedly present in all cells. However, a net littoral drift reversal occurs frequently in the southern stretch of the middle coast, generating a sediment supply for this region from erosion of the beaches located to the north (Motta et al. 2015).

Toldo et al. (2006) and Lopes et al. (2008) observed through coastline mapping and estimates of longshore transport that the center coast had high rates of erosion, especially on beaches located south of Mostardas Beach. These authors concluded that sediments removed from these locations were transported to north, and deposited on the Mostardas and Dunas Altas beaches, due to little changes in shoreline alignments and therefore, in the potential alongshore sediment transport in these two localities. This area naturally widens the beach by obstructing longshore transport. These beach deposits are an important sediment source for the local dune fields (Nicolodi *et al,* 2003). On the north coast, Lopes *et al.* (2008) identified a moderate coastline erosion between Tramandaí and Capão da Canoa.

The main causes of erosion along the open coast are related to abrupt changes in coastline direction, the presence of inlets, and the anthropic influence, like human-made structures in the coastal zone (Muehe, 2006). The erosive processes are probably connected to complex three-dimensional bathymetry both parallel and perpendicular to the coast. This is the case of the two erosional hotspots, where the inner continental shelf and the shoreface are characterized by linear shoals, marine terraces, outcrops of beach rocks, and distributed both linearly and randomly (Calliari and Speransky, 2006 and Figueiredo *et al.,* 2018).

Bathymetric features during storm waves produce local wave patterns and currents which are responsible for concentration of wave energy, and therefore for the erosional hot spots. Complex bathymetry leads to lateral gradients in the wave field. The concept of focal wave points was suggested by Glushkov in 1935 (apud Zenkovitch, 1967). This suggests that certain sections of the coast may be subject to high-energy waves and this action may cause localized erosion. The focus of storm waves is relatively fixed in a certain coastal sector depending on the angle of incidence and the period of the waves (Calliari and Speransky, 2006).

An attempt was made to classify the RS coastline based on the wave refraction pattern and its relationship with coastal processes of erosion and accretion (Calliari and Speransky, 2006). Long-period waves greater than 9 s were mainly considered. Refraction diagrams constructed with wave period and direction increments of 1s and 10 degrees respectively, revealed four main patterns: convergent or focus, variable, divergent, and without focus and divergence. All of them demonstrated definitive stability in relation to changeable wave period and direction from deep water. As a result, from wave incidence from the southern quadrant, a strong relation was found between the location of wave focus spots and localities with beach erosion. Such evidence is related to the Conceição Lighthouse area and Hermenegildo Beach, located in the middle and at the extreme southern littoral coastline, respectively (Figure 5).

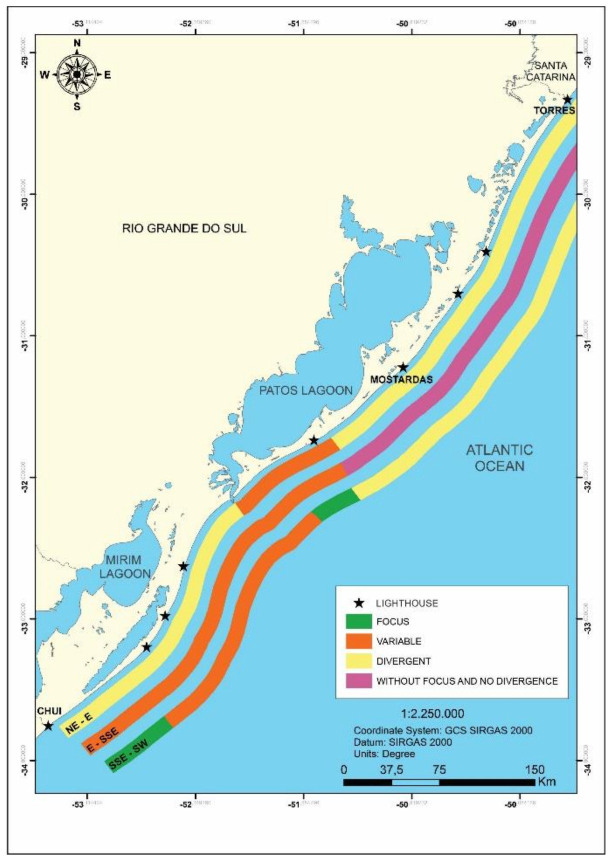

Figure 5. Wave focus along the Rio Grande do Sul coastline. Adapted from Calliari and Speranski (2006). Self-elaborated.

The effects of the propagation of waves on the inner continental shelf can be considered as one of the causes of coastal erosion. Silva *et al.* (2014) analyzed this propagation between Torres and Mostardas on the northern coast. The authors used REF/DIF, a wave propagation model based on a parabolic approximation of a gentle slope that simulates irregular wave behavior, considering the effects of shoaling, refraction, diffraction, and energy dissipation. Its capacity to simulate the effects of wave refraction combined with those of diffraction make it an appropriate model to study wave propagation in this region, and even to other areas of rugged terrain as only a few simpler studies have been performed using a wave-ray method. The inner continental shelf and the shoreface along the northern and middle RS coast between Torres and Mostardas beaches present bathymetric subparallel isobaths, but varying in width and slope. In the northern sector, between Torres and Cidreira, the inner shelf is wider, while the width of the foreshore is narrower.

Da Vara (2012) modeled refraction patterns between Sarita Lighthouse and Chuí Stream aiming to verify possible relationships between local erosion and phenomena associated to wave energy. Based on the regional wave climate, several wave situations were simulated, beginning from deep waters using the TMA energy spectrum and the Borgman directional spectrum. The behavior of waves with periods of 10, 12, and 16 s was analyzed with significant wave heights of 2, 4, and 4.8 m, respectively, and south, south-southeast, southeast, east-southeast, and east incidences. The same wave focus pattern was found by Calliari and Speransky (2006).

Goulart (2010), and Goulart and Calliari (2011) applied a REF/DIF spectral model to investigate the influence of the shoreface and the inner shelf on the RS coast. Specifically in the region near Estreito, on the middle coast, the authors simulated five modal cases, with Hs = 1.5m and Tp = 10s, to try to understand what influences the transformation of incident waves in common conditions at Capela submarine bank. Additionally, extreme weather events were simulated. Extreme events were selected for their effect on the monitored coastline, quantified by the period in which they occurred, and by situations that had verified high rates of erosion in the region. The events were characterized by the wave heights and periods, of 4.65 m, 11 s; 6.2 m, 14 s; and 9.22 m, 13.6 s, respectively, all coming from the southeast.

Another factor that influences RS coastline variation is the morphodynamics of inlets, which can be reduced to four specific cases (Figure 1): Mampituba River (in Torres), Tramandaí Lagoon, Patos Lagoon, and the Chuí Stream (on the Uruguayan border).

The Tramandaí and Imbé beaches, located south and north of the Tramandaí Lagoon inlet, respectively, showed homogeneous erosional tendencies along the analyzed sectors. This tendency contradicts predicted patterns from stratigraphic studies (Dillenburg *et al*., 2002) and refraction diagrams (Calliari and Speranski, 2001). Coastline configuration and continental shelf morphology indicate that the area should be stable. The erosional tendencies detected may reflect remobilization of sand from foredunes and the backshore during urbanization as discussed by Esteves *et al*., (2001) and Dillenburg *et al*., (2002). Watanabe *et al.* (2019) analyzed the opposite behavior between two regions of the Holocene barrier, comprising the interval between Xangri-lá and Dunas Altas, where two sedimentary processes of an antagonistic nature occurred at the same time. A portion of the Holocene barrier exerts retrogradational behavior with a transgressive coastline, represented by the coastal projection morphology located at the northern end of the central coast, and another portion with progradation characteristics with a regressive coastline, represented by the northern embayment. Higher frequency behavior variations are present even within coastal segments whose morphology would indicate uniform behavior. The delimitation of the regressive, transgressive, and transitional segments presented in a transitional sector indicates variations in the processes involved locally and regionally, composing a behavior of alternating records as a fractal of the coast as a whole (Dillemburg and Barboza, 2009; Watanabe *et al*, 2019).

The estuarine mouth of Patos Lagoon has undergone both natural and anthropic transformations. Natural factors include the precipitation regime, the wave incidence, and sediment transport. However, after the left margin of the inlet was fixed with jetties, stopping the migration of the inlet to the northeast, a transverse section was fixed and there are no records of silting recorded at the estuary mouth.

In the case of the Mampituba River, in the northern part of the state, changes in beach width were observed in two different patterns: intense accretion from 1974 to 1989, followed by a stable period from 1989 to 2000. Different from other areas, this region has a certain degree of protection because neighboring sectors to the south and north are anchored by a rocky headland and the western jetty. Jetty construction was the principal cause of intense accretion rates from 1974 to 1989. The stable period after 1989 most likely represented a morphological coastline adjustment to stabilization of the inlet.

North of the Mampituba River, Passo de Torres Beach presents unique behavior: accretional sections close to the eastern jetty, and erosional intervals further to the north. Unfortunately, the lack of field data such as beach profiles makes this pattern difficult to explain. Aerial photographs showed the sealing of a washout as it reached the ocean and the formation of a small lake due to urbanization projects. The presence of the washout during that time was responsible for the discontinuity in coastal foredunes and sand transport from dunes to the surf zone. The recovery of sandy deposits near the jetty can also be attributed to a shadow zone formed by storms arriving from the south toward the eastern jetty. Additionally, sand from an ebb flow delta in the Mampituba River may be transported and deposited north of the eastern jetty, as long as the jetties are relatively short and permit sand transport across the inlet. The erosional pattern farther north may be a result of the partial retention of sediments updrift from the inlet. Evidence of this erosional pattern can be observed in foredune scarping at the field site (Lelis and Calliari, 2006).

Despite the scarcity of field data and beach dynamics, two reference features represented by the average high tide line and the base of the foredunes at significant time intervals between aerial images enabled the identification of evolutionary patterns for the studied sections. Although the rates of shoreline migration represent an approximation of reality, both have similar trends. Accretional sections were areas that interrupted longshore drift due to the jetties (Cassino and Torres). Erosional sections show a deficit of sediment retention upstream of the same structures (Lelis and Calliari, 2006; Schossler *et al*. 2017; Silva *et al,* 2017).

High rates of accretion in sections south of the Patos Lagoon inlet coincide with mud deposition on the beach profile, indicating anthropic influence. High rates of accretion versus low rates of erosion to the south and north of the Patos Lagoon inlet and Mampituba River are strongly supported by the fact that the RS longshore current is bidirectional. However, accretion rates south of the structures corroborate that net transport is to the northeast, as previously described (Motta, 1969; Tomazelli and Villwock, 1992; Calliari and Speranski, 2001). Structures that are not long enough to cross the surf zone do not provide these indications, as is the case with the mouth of Tramandaí and the Chuí stream in the extreme south.

In addition to hydrodynamic controls along the RS coastline, beaches adjacent to inlets are subject to additional controls. Engineered structures impose the same dynamic controls with implicit morphodynamics adjustments. Changes in bathymetry, reduction in the degree of exposure, alterations in wave patterns, and interference in the longshore current are the main factors leading to variations of the coastline. In this way, human influences, such as urbanization, port construction, and the stabilization of inlets can induce considerable changes (Beck and Wang, 2019).

IMPLICATIONS FOR COASTAL MANAGEMENT IN THE SHORT- AND LONG-TERM

Coastline variations bring inherent challenges and difficulties to coastal management processes when considering the principal geomorphological features that make up beaches and surrounding environments, as much from a spatial point of view as functional. These management challenges are magnified when considering current climate change scenarios.

Comparatively, average projected rates of retreat for 2100 for the Conceição Lighthouse and Mostardas Lighthouse sector, a region characterized by a higher slope of 0.070 to 0.104°, is in the order of 3.7 m.yr^{-1}. Average rates of retrogradation for this region are smaller compared to the previous sector, even though the Conceição Lighthouse area has historical erosive tendencies (Pereira *et al.*, 2007). This fact highlights the dominant control the shoreface slope has over coastal response to accelerated rising sea-level, corroborating previous findings (Roy *et al*., 1994; Muehe 2001; Muehe 2010). Roy *et al*. (1994) demonstrated that during rapid marine transgression, changes in coastline configuration were dominated by shoreface slope variations and that the sediment budget had minimal influence on coastline retreat rates. When the rates of sea level rise are slower, the effects of the sediment budget become more noticeable and during stable coastal conditions, they dominate coastal evolutionary processes.

On this theme, the current coastline configuration and historical or long-term progradational and retrogradational tendencies (in the last 6 ka) reflect stable sea level conditions where the sediment budget dominated the evolutionary scenario (Dillenburg *et al.* 2000). With accelerated rates of sea-level rise, as predicted by the IPCC, it is highly likely that regional coastal changes will once again be dominated by substrate slope. In this context, reversals in the rates of retrogradation and progradation in adjacent sectors are likely to occur in the future due to small variations in the morphology of local substrates.

These scenarios indicate that even with a relative degree of uncertainty, coastal communities must adapt to climate change. It should also be noted that Rio Grande do Sul has large extensions of coastline that are not urbanized, allowing for superior efficiency in the application of environmental management tools and planning that already exist, such as the Ecological and Economic Coastal Zoning (ZEEC) (Nicolodi *et al.*, 2018). In this context, risk and vulnerability assessments of communities and ecosystems are crucial to the decision-making process of regional coastal managers and planners (Nicolodi and Pettermann, 2010).

One of the most important tools in environmental assessments with a vulnerability approach is the application of indicators, which organize, quantify, and simplify information without compromising the veracity of the analysis. Among environmental indicators, geo-indicators are those whose purpose is to estimate geological processes and phenomena on or near the Earth's surface, and which vary significantly during less than 100 years. One commonly used geo-indicator is coastal erosion.

In Rio Grande do Sul, few initiatives have been developed in this sense (Nicolodi and Toldo (2003), Redchen (2005), Tabajara *et al.* (2005), Portz (2015), Tabajara *et al.* (2012), Barboza and Rosa (2014), and Souza and Nicolodi (2016)). In this context, it is crucial to understand that variations in the average position of the coastline are part of a natural cycle of continental adjustment to sea level rise, independent of their causes. Even though coastal erosion is always treated as a 'problem', it often occurs unnoticed in society and on unoccupied coasts, where the movement of the beach profile is rarely perceived by those unaccustomed to looking for it. In those cases, coastline erosion is treated as a natural process without great consequences for society.

Coastal erosion becomes a problem when coastline retreat influences or is influenced by human actions and becomes a social or economic risk (Portz *et al.,* 2010; Forgiarini *et al.* 2019). Relatively simple methods such as prohibiting building in defined locations to preserve areas of open sediment transport can bring effective results, especially in the long term, contributing to the development of a more equilibrated coastal zone.

CONCLUSIONS

The 615 km of sandy beaches along the Rio Grande do Sul coast have complex hydro and sedimentary dynamics due in part to their genesis, linked to sea level variations that occurred during the Holocene, and to modern physical processes and anthropic action. In general, the RS coastline had a period of stability from 2002 to 2013 on 31% of the coast, moderate erosion on 45%, moderate progradation on 17%, pronounced progradation on 3%, and pronounced erosion on 4%.

Specific causes of variations cannot be completely defined but some of them are coastline direction, geological inheritance, and wave energy refraction caused by local bathymetry. Some of these factors are responsible for erosional sections, with a focus on two erosive hotspots: Conceição Lighthouse and Hermenegildo Beach. The other extreme, Cassino Beach, has pronounced progradation due to the construction of jetties at the mouth of Patos Lagoon, which retain sediment from the longshore current to the northeast and alters sedimentation patterns.

Alongshore transport estimates indicate that variations in the identified coastlines on the mid-RS coast are correlated to sediment removal from those locations and deposition of that sediment in zones of the coast that protrude more than others. One example is the sector between Mostardas and Dunas Altas beaches, where the beach naturally widens by interrupting longshore transport. These beach deposits are an important source of sediment to dune fields.

Regarding the concentration of wave energy, specifically due to refraction caused by local bathymetry, the following points can be made:

1. Two concave bathymetric portions were found on the inner RS continental shelf. Groups of sand bars and sand ridges at depths between 25 and 15 m function as bathymetric lenses.

2. Local bathymetric lenses can focus wave energy with wave periods greater than 9 s and incidence from the southern quadrant.

3. In both erosional areas, the positions of migratory wave focus points coincide with erosional areas on the beach. The specific erosional mechanism can act on the surf zone and move the focus point.

Considering data obtained so far, the convergent pattern (focus) associated with the complex geomorphology and geology of the internal continental shelf is the factor responsible for permanent natural erosion in large areas (tens of kilometers). Geomorphological evidence of erosion supports these affirmations. Additional factors related to geology and geomorphology of the shoreface and continental shelf, such as the presence of rocky steps, amplify local erosional problems due to their difficulties in returning sand to the beach after storms. Other predominant patterns along the coast that lack geomorphological evidence of erosion indicate that most of the coast is in a stable state (hundreds of kilometers). Some sectors have erosive trends (hundreds of meters) for which no plausible explanation was found.

The classification shown in the present study encompasses only situations with long-period waves (> 9 s). Stable focal points were not detected for short-period waves. Short-period waves also seem to undergo little refraction and create irregular wave patterns. Future studies in greater detail may be able to elucidate their role in coastal morphodynamics.

It should be noted that natural causes are not the only ones responsible for the variation in the coastline, especially on beaches near inlets. Engineering structures impose dynamic structural controls with implications in morphodynamic adjustments. Changes in bathymetry, reduction of the degree of exposure, alterations in wave patterns, and interference in longshore transport are the principal factors that induce coastline reorientation.

Human actions along the coast, including urbanization as well as works on ports and the stabilization of inlets, can induce considerable changes. Results from the present study show that in the long term, estimated distances of retreat must be established for coastal areas especially urban areas located near inlets.

Large-scale coastal modeling results for sea-level rise impacts indicate that the southern sector of the RS coast has the largest retreat rates for all risk levels and all time compared to sectors on the central and north coast. Coastal sectors that have historically prograded can become more vulnerable under conditions of sea level rise in the long term.

The results enable better quantification of erosive tendencies regarding risk by providing management alternatives. It is suggested that conservative risk limits be used in coastal management, especially in areas that have little urbanization and areas with high vulnerability due to low substrate slopes, to avoid substantial coastline loss and large adaptive expenses. A better understanding of coastline variation, their causes, and consequences allows for improvement in mapping vulnerable areas and communities, improving ecosystem-based managements (Asmus *et al*, 2019).

As a recommendation, it is suggested to draft a law that restricts construction or urban development (and propose natural reserves) in specific areas in the coastal zone that are underdeveloped or uninhabited. Though implementation of such a law would be politically and methodologically difficult, being that the coastal zone has a wide range of uses, the present authors support a national emphasis on a law that aims to above all preserve the sediment budget on beaches, and consequently, in ecosystems and communities.

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