

How important are sediment-budget estimates for shoreline protection under sea-level rise?

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Abstract

Sediment-budget (SB) estimates are critical for shoreline conservation because sea-level rise (SLR) alone does not dictate coastal recession; sediment deficits or surpluses can amplify or buffer its impacts. The interaction between SB, shoreface morphology, and SLR controls shoreline evolution across multiple timescales. This study evaluates how annual, decadal, and millennial-scale SB estimates influence shoreline response along the southern-central coast of Rio Grande do Sul, Brazil, using the probabilistic Random Shoreface Translation Model (RanSTM). The wave-dominated coast was subdivided into four SB-control coastal cells: Cell I (Albardão–Verga), Cell II (Verga–Sarita), Cell III (Cassino), and Cell IV (Mar Grosso), which differ in sedimentary behavior and shoreface morphology. SB estimates were derived from remotely piloted aircraft surveys (2023–2024), satellite imagery (2010–2024), and stratigraphic records and combined with SSP5–8.5 SLR projections for 2040, 2050, 2075, and 2125. Annual observations showed larger shoreline displacements than decadal records. Cell I exhibited short-term erosion and medium-term accretion, Cells II and IV were accretionary at both scales, and Cell III remained stable in the short term and accreted over the decadal period. Future projections showed the greatest retreat in Cell I, while all cells shifted toward retreat at longer horizons as SLR intensified. Overall, SB exerted stronger control over short- to medium-term shoreline behavior, whereas SLR became increasingly dominant toward centennial horizons, with shoreface morphology modulating the magnitude of the response. Integrating multitemporal SB estimates with morphological differences provides a physical basis for understanding coastal change and supports targeted monitoring, conservation strategies, and long-term climate adaptation planning.

1. Introduction

Shoreline change represents a growing challenge for coastal conservation, protection, and management, particularly along sandy coasts where erosion can affect beach–dune systems, infrastructure, and the space available for natural coastal adjustment (Athanasίου et al. 2020; Hein et al. 2019; Nicholls and Cazenave 2010; Ranasinghe 2016; Stive et al. 2002; Vousdoukas et al. 2020). Approximately 24% of the world's sandy and gravel shorelines retreated at rates exceeding 0.5 m/yr between 1984 and 2016 (Luijendijk et al. 2018), and this challenge is expected to increase as sea-level rise (SLR) accelerates under future climate scenarios. Identifying the processes that control shoreline response is therefore important for defining monitoring priorities and supporting conservation, coastal protection, and adaptation planning.

Sediment budget (SB) is a primary control on contemporary shoreline change and can strongly influence whether a coastal sector erodes, remains stable, or accretes under present conditions (Anthony and Aagaard 2020; Athanasίου et al. 2020; Cowell and Kinsela 2018). SLR, in contrast, acts as a longer-term forcing whose influence is expected to increase as rates accelerate (Figueiredo et al. 2018; López-Olmedilla et al. 2022). The relative importance of these controls therefore changes through time: sediment deficits or surpluses may exert stronger control over shorter periods, whereas SLR becomes increasingly important over longer projection horizons. Understanding this interaction is particularly

relevant in open, wave-dominated sandy coasts, where sediment exchanges among different sources, transport pathways, and sinks influence shoreline position and long-term coastal evolution (Goodwin et al. 2020; Komar 1976; Lima et al. 2001; Oliver et al. 2020). Estimating SB nevertheless remains challenging because these exchanges occur across multiple spatial and temporal scales (Dillenburg et al. 2000; Goodwin et al. 2020; Oliver et al. 2020; Rosati 2005).

In southern Brazil, negative SB at local and regional scales has been associated with shoreline erosion, whereas positive SB has promoted coastal accretion (Bose et al. 2020; Carvalho et al. 2026; Dillenburg et al. 2000; Esteves et al. 2006a, b; Figueiredo 2011; Forgiarini et al. 2019). However, available estimates differ considerably in temporal extent, spatial resolution, and methodological basis. In highly dynamic sandy systems, shoreline changes observed over short periods may reflect storms, seasonal variability, post-storm recovery, or sediment redistribution rather than a persistent change in the longer-term sedimentary trajectory (Castelle et al. 2018; Harley et al. 2017; Tamura et al. 2019; Woodroffe et al. 2022). The temporal scale used to estimate SB may therefore affect both the magnitude of future shoreline projections and whether a coastal sector is interpreted as erosional, stable, or accretionary. Integrating observations across multiple timescales can help distinguish recent variability from longer-term sedimentary behavior.

Morphological response to SLR also depends on the geometry of the active coastal profile. Shoreface adjustment toward a new state of dynamic equilibrium may result in beach narrowing, shoreline retreat, and increased saltwater intrusion into coastal water bodies (Bruun 1962; Roy et al. 1994; Cowell et al. 1999; Nicholls et al. 1998; Ashton and Lorenzo-Trueba 2018; Athanasiou et al. 2020). The magnitude of this response varies with shoreface slope and extent, onshore morphology, sediment supply, local sea-level variability, and wave exposure (Figueiredo 2013; Kinsela et al. 2016; Oliver et al. 2020). Wider shorefaces may require larger sediment volumes to accommodate profile adjustment under SLR, so similar sediment budgets can produce different shoreline responses depending on local morphology (Cowell and Kinsela 2018; Figueiredo et al. 2020).

Low-gradient coastal environments are particularly sensitive to SLR, which can promote shoreline retreat, habitat degradation, loss of natural ecosystems, and damage to infrastructure. Their response depends partly on sediment availability, since rising sea levels create accommodation space that must be filled to maintain coastal adjustment (Forgiarini et al. 2019; Germani et al. 2020; Nicholls and Cazenave 2010; Roy et al. 1994). Beach–dune systems are also influenced by sediment supply, storm-wave erosion, sea-level fluctuations, and human disturbance, which can affect dune stability and landward migration (Figueiredo and Hesp 2026). Coastal development may further restrict the space available for this adjustment, potentially intensifying coastal squeeze (Lansu et al. 2024). Maintaining sediment availability, dune integrity, and accommodation space is therefore relevant for conservation and adaptation under extreme events and longer-term SLR (Davidson-Arnott et al. 2024).

Spatial variability in SB adds complexity to coastal planning because sediment transport and availability are not uniform alongshore, reflecting connections among sediment sources, transport pathways, and

sinks (Cowell et al. 2003a, b; Rosati 2005; Kinsela et al. 2017). Sediment cells provide a framework for capturing this organization and, together with local morphological differences, can support the definition of monitoring and management priorities among sectors (Carvalho and Woodroffe 2023). This heterogeneity is also relevant to shoreline projections, which are increasingly used in adaptation planning but depend on how uncertainty and coastal variability are represented. Probabilistic approaches provide a range of potential shoreline responses rather than a single deterministic position, allowing uncertainty and different levels of risk tolerance to be considered in decision-making (Cowell et al. 2006; Thiéblemont et al. 2021; Ranasinghe et al. 2023).

Morphodynamic models have been widely applied to investigate coastal responses to SLR and SB variability over medium- to long-term timescales ($10\text{--}10^2$ years) (Bruun 1962; Cowell et al. 1992, 1995, 2006; Klein et al. 2016; Stolper et al. 2005). Within this context, the present study evaluates the response of an open-ocean sandy coast to projected SLR using SB estimates derived from multiple temporal scales. Specifically, we assess how annual, decadal, and large-scale SB estimates, together with spatial differences in shoreface morphology, influence future shoreline projections. We further examine how the relative influence of SB and SLR changes with projection horizon and discuss the implications of these spatial and temporal differences for coastal monitoring, conservation, protection, risk-informed planning, and management.

2. Study Area

The coast of Rio Grande do Sul is characterized by a wide, low-gradient continental shelf with abundant sediments of predominantly clastic origin (Dominguez 2009) and wave-dominated conditions (Dillenburg et al. 2000, 2004). The interaction between wave energy and glacio-eustatic sea-level fluctuations throughout the Quaternary produced substantial lateral shoreline displacements across the coastal plain (Tomazelli et al. 2000), resulting in a complex barrier–lagoon system (Villwock and Tomazelli 1995). Four barrier–lagoon systems developed through the superposition of sedimentary deposits derived from the Sul-Riograndense Rock Shield and are preserved landward of the present shoreline (Villwock et al. 1986). Three of these systems are attributed to the Pleistocene, whereas the youngest, Barrier IV, formed during the most recent Holocene marine transgression.

The Holocene barrier exhibits spatially variable behavior along the Rio Grande do Sul coast. Following the coastal-barrier typology proposed by Roy et al. (1994), Dillenburg et al. (2000) classified these sectors as retrogradational (transgressive), progradational (regressive), or stationary. Retrogradational barriers generally occur along coastal protrusions, where sediment supply is limited and the shoreface tends to be steeper, whereas progradational barriers develop mainly within embayed sectors characterized by positive sediment budgets and gentler shoreface gradients (Dillenburg et al. 2000, 2005; Martinho et al. 2009). The emerged portion of the study area consists predominantly of extensive sandy beaches bordered by foredune ridges, while transgressive dune fields dominate parts of the coastal landscape (Villwock and Tomazelli 1995).

The region is subjected to a microtidal semidiurnal regime, with an average tidal range of approximately 0.47 m (Möller et al. 2001). Consequently, sediment transport and deposition along the coast are predominantly wave-driven (Lima et al. 2001). Locally generated wind waves, mainly associated with NE winds, commonly reach significant wave heights of approximately 2 m and peak periods of approximately 12 s. Swell waves predominantly arrive from the SE and are characterized by longer periods, lower steepness, and greater sediment-transport capacity, with significant heights of approximately 2.8 m and periods of approximately 15 s (Pianca et al. 2010; Romeu et al. 2015). High-energy events associated with low-pressure systems and extratropical cyclones can generate energetic waves, storm surges, and erosional episodes along the coast (Parise et al. 2009; Maia et al. 2016; Machado and Calliari 2016).

Net longshore transport of sandy sediments occurs predominantly from SW to NE. This transport direction is supported by the migration of ephemeral stream channels (*washouts*) along the beach (Pereira da Silva 1998; Figueiredo et al. 2007; Calliari et al. 2010) and by the orientation and morphological response of lagoonal and fluvial inlets along the coast (Tomazelli and Villwock 1992; Lélis and Calliari 2006).

The study encompasses approximately 150 km of the southern-central coast of Rio Grande do Sul, extending from the vicinity of Albardão Lighthouse in the south to the northern limit of Cell IV, located approximately 8 km south of Estreito Lighthouse. The coastline has a predominantly SW–NE orientation and includes sectors with contrasting Holocene evolutionary behavior, from stationary or aggradational barriers in the south to strongly progradational sectors associated with the Cassino embayment and the Patos Lagoon inlet (Fig. 1).

The study area was subdivided into four coastal cells based on the sediment-cell concept (Bowen and Inman 1966; Davies 1958) and the coastal-tract framework proposed by Cowell et al. (2003a, b). Coastal cells represent morphological units within which sediment sources, transport pathways, and sinks can be considered within a common sediment-control volume. The delimitation adopted here was further guided by changes in shoreline orientation, coastal-barrier evolutionary type, historical shoreline behavior, and bathymetric characteristics, all of which may influence sediment-budget patterns and coastal response (Cowell et al. 2003a, b; Daley 2005; Kinsela et al. 2016; Rosati 2005). Within each cell, representative coastal sectors were selected for short-term RPA monitoring, satellite-based shoreline analysis, and topobathymetric characterization, as described in the Methods.

Cell I extends from the vicinity of Albardão Lighthouse in the south to Verga Lighthouse in the north. This coastal sector has been described as stationary or aggradational (Dillenburg et al. 2000; Martinho et al. 2009; Caron 2014). Such barriers are characterized by limited large-scale progradation over the late Holocene and by the development of complex foredune systems (Roy et al. 1994).

Cell II extends from Verga Lighthouse to Sarita Lighthouse, along the southern portion of the Cassino embayment. This sector is predominantly progradational and includes transgressive dunes immediately landward of the present shoreline (Dillenburg et al. 2000). Its geological evolution is also associated with

an incised valley containing a paleofluvial channel that extends toward the inner continental shelf, indicating the presence of an inherited topographic depression (Barboza et al. 2021).

Cells III and IV, located immediately south and north of the Patos Lagoon inlet, respectively, encompass the Cassino and Mar Grosso coastal sectors. Both cells exhibit a well-established progradational trend documented by geological, geomorphological, and stratigraphic studies (Dillenburg et al. 2000, 2009, 2017; Barboza et al. 2018; Bitencourt et al. 2020). Cell III corresponds to the Cassino sector south of the inlet, where the Holocene barrier records extensive progradation. Cell IV extends northward from the inlet to approximately 8 km south of Estreito Lighthouse, where the progradational barrier transitions toward a retrogradational sector (Barboza et al. 2018). At Estreito, entirely retrogradational sequences have been identified from GPR records, marking a clear change in Holocene barrier behavior along the coast (Bitencourt et al. 2020).

3. Materials and Methods

The methodological framework comprised three main steps. First, sediment-budget (SB) estimates were obtained at annual and decadal scales by calibrating RanSTM in deterministic mode against observed shoreline displacements derived from RPA surveys and satellite imagery. Large-scale SB estimates were independently derived from previously published stratigraphic and geological reconstructions. Second, these multitemporal SB estimates were incorporated into stochastic RanSTM simulations together with projected sea-level rise (SLR) to estimate future shoreline positions for 2040, 2050, 2075, and 2125. Finally, additional simulations were conducted to isolate the relative contributions of SB and SLR to projected shoreline change.

3.1 The RanSTM model

This study employed the RanSTM (Random Shoreface Translation Model) (Cowell et al. 2006), a stochastic extension of the STM (Shoreface Translation Model) (Cowell et al. 1992). RanSTM is a morphological-behaviour model designed to simulate coastal evolution in response to external forcings such as sea-level rise and sediment budget variations, and internal controls (inherited coastal profile shape). According to Roy et al. (1994), the main factors controlling the evolution of sandy barriers on wave-dominated coasts are substrate slope, sediment budget, and sea-level fluctuations (Cowell et al. 1995, 2003a, b). Therefore, these are key variables that constitute the model inputs.

The stochastic capability of RanSTM allows each input parameter (e.g. sea level, sediment budget) to assume up to three values, derived from available data and their associated uncertainties (min, mode, max) (Cowell et al. 2006). Model inputs include sea-level variation, sediment budget, and substrate geometry and texture (e.g., sand, mud, or rock), represented as probability density functions (PDFs) and randomly sampled in each Monte Carlo simulation (Cowell et al. 2006; Figueiredo et al. 2020; Kinsela et al. 2016). This probabilistic framework enables the assessment of a wide range of potential shoreline change scenarios, from 0.01% to 100%, thus providing a risk-based perspective of potential impacts

(Adlam 2008; Carvalho et al. 2026; Figueiredo 2011, 2020; Forgiarini et al. 2019; Germani et al. 2020; López-Olmedilla et al. 2022).

To construct the input dataset, three key elements are required: topobathymetric characterization (onshore and offshore morphology, including active morphodynamic limits), sediment budget, and sea-level variation. Shoreline projections generated by RanSTM present a range of potential outcomes, each associated with its respective probability (Cowell et al. 2006).

Shoreline change (R) is determined in the model through the horizontal and vertical translation of the shoreface, driven by sea-level variation through time (S), substrate geometry and texture (P), and sediment budget changes (V), as expressed in the equation below:

$$R = f(dS/dt, dP/dt, dV/dt) \quad (1)$$

3.2 Inputs

3.2.1 Topobathymetric Profile and Shoreface Geometry

The characterization of the shoreface and the subaerial coastal zone was derived from the substrate input represented by the topobathymetric profile. Given the wide spatial extent of the study area and its morphological variability, the area was subdivided into four cells following the coastal-tract methodology proposed by Cowell et al. (2003).

Bathymetric data were obtained from the Nautical Chart of the Brazilian Navy and historical surveys conducted by the Geological Oceanography group at FURG. Coastal topographic data were collected using a Kolida RTK GPS. Profiles were surveyed from the base of the foredune to approximately 1.5 km landward, at the following locations: Verga Lighthouse, Sarita Lighthouse, Cassino Beach, and Mar Grosso Beach (Fig. 2). These data were subsequently processed in ArcGIS Pro following the methodology proposed by Daley (2005), with the aim of constructing a representative profile for each cell.

Conceptually, the shoreface was divided by Cowell et al. (1999) into two units: the upper shoreface and the lower shoreface. The spatial extent of the active limits of these units is primarily controlled by wave action and sediment transport and therefore responds differently depending on the temporal scale considered (Nicholls et al. 1998). The upper shoreface, being more directly exposed to wave action, responds rapidly to changes in external forcing, whereas the lower shoreface adjusts much more slowly, potentially taking centuries or even millennia to achieve a new state of dynamic equilibrium (Cowell et al. 1999; Niedoroda et al. 1985).

Closure depths, which define the active morphodynamic boundaries of the shoreface, are strongly influenced by wave processes. These processes control sediment exchange between the shoreface and the adjacent beach and drive the ongoing redistribution of sediments that shapes the shoreface profile, typically resulting in a concave-up morphology (Cowell et al. 1999; Niedoroda and Swift 1991).

The shoreface geometry of each coastal cell was parameterized by fitting power-law functions to the observed topobathymetric profiles, following the general curve-fitting approach described by Kinsela et al. (2017). The upper and lower shoreface segments were represented by their respective shape parameters (m_c and m_i). Different combinations of upper (h_c) and lower (h_i) shoreface closure depths were tested, and a modeled shoreface profile was generated for each combination. The modeled profiles were then compared with the corresponding observed topobathymetric profiles, and goodness of fit was quantified using the root mean square error (RMSE). For each coastal cell, the combination of h_c and h_i that produced the lowest RMSE was selected as the best-fit shoreface configuration.

Table 1 summarizes the geometric characterization of the shoreface adopted for each cell analyzed in this study. The closure depths of the upper (h_c) and lower (h_i) shoreface, which define the boundaries of sediment exchange, exhibited little variation among cells. In contrast, the upper-shoreface shape parameter (m_c) varied among cells, highlighting morphological differences, whereas the lower-shoreface shape parameter (m_i) remained relatively constant.

Table 1
Parameters defining shoreface geometry for each cell, including upper (h_c) and lower (h_i) shoreface closure depths, distances to the upper (L_c) and lower (L_i) shoreface, and slope coefficients for the upper (m_c) and lower (m_i) limits.

Cell	h_c (m)	L_c (m)	m_c (°)	h_i (m)	m_i (°)	L_i (m)	Slope (°)
I	-5	541.3	0.98	-20	0.32	22335.9	0.06
II	-8	2316.8	0.79	-18	0.36	19885.4	0.05
III	-7	1941.1	0.69	-20	0.39	22799.6	0.04
IV	-7	1061.8	0.83	-19	0.29	16348.5	0.05

The distances between the shoreline position and the closure depths of the shoreface, both upper (h_c) and lower (h_i), show significant variations among the different cells, highlighting morphological heterogeneity across the study area, as shown in Fig. 2. The figure displays the topobathymetric profiles corresponding to the four cells, divided into two sections: onshore (a) and offshore (b).

3.2.2 Short- and Medium-Term Estimates of Sediment Budget—Deterministic RanSTM Design

The RanSTM model (Cowell et al. 2006) allows the input of a range of values for the sediment budget (SB) variable, enabling its representation across different temporal and spatial observation scales. To capture the variability of SB in each cell, estimates were conducted at two distinct scales: annual, based on RPA monitoring (2023–2024), and decadal, based on satellite imagery (2010–2024).

SB was estimated through the application of the model in its deterministic form. In these simulations, input parameters (minimum, mean, and maximum) were held constant, and sea-level rise was assumed to be zero. The adjustment of SB was carried out using a trial-and-error approach until the simulated shoreline displacements reproduced the observed shoreline behavior over each time interval (Bose et al. 2020; Figueiredo et al. 2018).

The morphological indicator used to monitor shoreline change was the foredune toe, which was identified both in satellite images and in orthomosaics generated from RPA surveys. The satellite dataset used corresponds to the RapidEye series provided by the Planet® platform, with a spatial resolution ranging from 3 to 5 m/pixel and covering a temporal span of 14 years (2010–2024), sampling a 5 km coastal segment.

For the annual shoreline monitoring, four field campaigns were conducted in each of the four previously defined sites, aiming to collect topographic data and shoreline position. High-resolution aerial imagery was obtained using a DJI Phantom 4® RPA, while geographic coordinates (latitude, longitude, ellipsoidal elevation) of control points distributed across the surveyed area (approximately 400 m², covering the beach and foredune field) were measured with a Real-Time Kinematic (RTK) GPS. The combination of RPA imagery and RTK control points enabled the generation of high-resolution orthomosaics (2 cm/pixel).

The SB estimates derived from these deterministic simulations were subsequently used as baseline inputs for the stochastic scenarios projected for the years 2040, 2050, 2075, and 2125, assuming a constant rate of sediment gain or loss over time for each cell.

3.2.3 Large-Scale Estimates of Sediment Budget

The large-scale sediment budget was estimated based on stratigraphic and geophysical evidence reported in previous studies. For Cells I and II, values were derived from Caron (2014), who conducted geophysical surveys with Ground Penetrating Radar (GPR) in the Verga Lighthouse and Sarita Lighthouse regions. Additionally, the Cell II assessment was supported by Barboza et al. (2021), who reconstructed the coastal plain evolution since the Pleistocene through sediment core analyses, providing estimates of Holocene sediment package thickness.

In Cell III, the sediment volume estimate was based on Dillenburg et al. (2017), who analyzed the morphological evolution of the Holocene barrier at Cassino Beach. In this sector, the barrier prograded approximately 18 km from the mid-Holocene to the present, with an estimated sediment package thickness of about 12 m.

For Cell IV, the sediment budget was derived from RanSTM simulations performed by Dillenburg et al. (2000), who reconstructed shoreline evolution along the Rio Grande do Sul coast since the Holocene using the STM framework. Based on this model, it was possible to estimate the sediment volume required for the current barrier configuration.

The sediment volumes adopted in this study’s simulations are summarized in Table 2, which compiles the large-scale sediment budget estimates based on the Holocene sedimentary package preserved.

Table 2
Large-scale sediment budget estimates, based on preserved
Holocene sediment volumes accumulated over ~ 5 kyr.

Cell	SB - LE (m³/m/ano)	Data source
I	7	Caron (2014)
II	18	Barboza et al. (2021) e Caron (2014)
III	40	Dillenburg et al. (2017)
IV	16	Dillenburg et al. (2000)

3.2.4 Sea-Level Rise Projections

In this study, the Shared Socioeconomic Pathways 8.5 (SSP5-8.5) scenario from the Intergovernmental Panel on Climate Change (IPCC) was adopted, considering regional sea-level-rise projections for the years 2040, 2050, 2075, and 2125. The estimates were obtained using the Sea Level Projection Tool developed by the National Aeronautics and Space Administration (NASA) (available at: <https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool>), based on the IPCC Sixth Assessment Report (AR6; IPCC 2022) for the city of La Paloma, Rocha, Uruguay. The projections were adjusted based on the current sea level, as shown in Table 3.

Table 3
Values of regional sea-level rise (minimum, medium,
and maximum) for 2024, 2040, 2050, 2075, and 2125,
based on the IPCC SSP5-8.5 scenario projections.

SSP5-8.5	2024	2040	2050	2075	2125
max (m)	0.08	0.09	0.18	0.38	1.23
mode (m)	0.06	0.06	0.13	0.23	0.88
min (m)	0.03	0.05	0.09	0.27	0.67

3.3 Future Shoreline Position Simulation Design

The modelling experiments were organized to evaluate the combined effects of SB and SLR and subsequently isolate their individual contributions to shoreline response.

For the combined-forcing experiments, 16 stochastic simulations were performed, corresponding to four coastal cells and four projection horizons (2040, 2050, 2075, and 2125). For each experiment, 1,000 Monte Carlo realizations were performed by randomly sampling the probability distributions assigned to

the uncertain model inputs. The SB distribution incorporated information from the annual RPA-derived estimate, the decadal satellite-derived estimate, and the large-scale estimate, while shoreface geometry was defined according to the representative configuration of each cell (Table 1) and SLR forcing corresponded to the respective projection horizon (Table 3). The ensemble of 1,000 realizations generated probability-of-exceedance curves describing the range of possible shoreline responses.

Projected shoreline-change rates were extracted at the 50% and 10% probabilities of exceedance. These levels represent contrasting positions within the distribution of modelled shoreline responses and were used to compare cells and projection horizons.

To examine the relative contributions of SB and SLR, two additional groups of experiments were conducted for each cell and projection horizon. In the SB-only experiments, SLR was set to zero, isolating shoreline response associated with sediment-budget conditions. In the SLR-only experiments, SB was set to equilibrium, isolating shoreline response associated with projected sea-level change. These experiments were compared with the combined SB + SLR simulations to assess how the relative influence of both drivers changes with projection horizon.

Across the four cells and four projection horizons, the experimental design comprised 16 combined SB + SLR experiments and 32 isolated-driver experiments (16 SB-only and 16 SLR-only), resulting in 48 modelling experiments.

4. Results

The following sections present the sediment-budget estimates obtained at different observational timescales, followed by the projected shoreline responses under combined sediment-budget and sea-level-rise forcing and the simulations isolating the effects of each driver.

4.1 Short- and Medium-Term Sediment Budget Estimates

Sediment-budget estimates derived from the deterministic simulations differed substantially among coastal cells and observational timescales (Table 4). These values represent the sediment-volume changes required by RanSTM to reproduce the observed shoreline displacements under stable sea-level conditions.

Table 4

Shoreline displacement in each study cell for the periods 2023–2024 and 2010–2024, comparing shoreline position and sediment-budget estimates required to generate the observed changes obtained from the RanSTM model in deterministic simulations. SB, sediment budget; RPA, remotely piloted aircraft-derived estimate; SAT, satellite-derived estimate.

Cell	Shoreline displacement (m) (2023–2024)	SB–RPA (m ³ /m/yr)	Shoreline displacement (m) (2010–2024)	SB - SAT (m ³ /m/yr)
I	-8	-180	47	78
II	7	120	24	27
III	0	0	47	85
IV	8	130	36	42

Cell I showed a retreat of 8 m between 2023 and 2024, corresponding to a shoreline-change rate of – 8 m/yr and an estimated SB of – 180 m³/m/yr. In contrast, between 2010 and 2024, the shoreline advanced 47 m, corresponding to 3.3 m/yr and an estimated SB of 78 m³/m/yr.

Cell II showed shoreline advance at both timescales. The shoreline advanced 7 m between 2023 and 2024, corresponding to 7 m/yr and an estimated SB of 120 m³/m/yr. Over the 2010–2024 period, shoreline advance reached 24 m, corresponding to 1.7 m/yr and an estimated SB of 27 m³/m/yr.

Cell III remained approximately stable between 2023 and 2024, with no net shoreline displacement and an estimated SB of 0 m³/m/yr. Over the 14-year satellite record, however, the shoreline advanced 47 m, corresponding to 3.3 m/yr and an estimated SB of 85 m³/m/yr.

Finally, Cell IV showed shoreline advance at both observational scales. Between 2023 and 2024, the shoreline advanced 8 m, corresponding to 8 m/yr and an estimated SB of 130 m³/m/yr. Between 2010 and 2024, shoreline advance reached 36 m, corresponding to 2.5 m/yr and an estimated SB of 42 m³/m/yr.

The annual and decadal estimates were subsequently combined with the large-scale SB values presented in Table 2 to characterize the range of sediment-budget conditions for each coastal cell. The resulting SB input distributions are shown in the right panels of Fig. 3. Cell I was the only sector whose distribution incorporated both negative and positive SB estimates, whereas the distributions for Cells II and IV were entirely positive. Cell III included a zero annual estimate and positive decadal and large-scale estimates.

4.2 Future Shoreline Position

Projected shoreline responses under combined SB and SLR forcing are shown in Fig. 3 for 2040, 2050, 2075, and 2125. The probability-of-exceedance curves indicate progressively greater shoreline retreat toward the longer projection horizons, although the magnitude and timing of the response differed among cells.

Historical and current values correspond to observed shoreline changes and are therefore not associated with exceedance probabilities, whereas future rates correspond to the 50% and 10% probabilities of exceedance obtained from the stochastic simulations. Historical, current, and projected shoreline-change rates for all four cells are summarized in Table 5.

Table 5
Historical and current annual shoreline-change rates (m/yr) for the periods 2010–2024 and 2023–2024, and projected shoreline-change rates for 2040, 2050, 2075, and 2125. Projected values correspond to the 50% and 10% probabilities of exceedance obtained from stochastic simulations combining sediment-budget estimates calculated from observed shoreline variation with sea-level-rise projections. Historical and current rates are observed values and are not associated with exceedance probabilities.

Sector/ Scenario	Cell 1		Cell 2		Cell 3		Cell 4	
2010–2024 (m/yr)	3.3		1.7		3.3		2.5	
2023–2024 (m/yr)	-8		7		0		8	
Prob. of exceedance	50%	10%	50%	10%	50%	10%	50%	10%
2040 (m/yr)	-3.4	-7.0	0.8	-1.7	-0.9	-2.8	1.2	-0.8
2050 (m/yr)	-3.8	-7.1	0.5	-1.4	-1.3	-3.4	0.8	-1.4
2075 (m/yr)	-4.0	-7.3	-0.9	-3.0	-1.8	-3.9	0.4	-2.1
2125 (m/yr)	-5.7	-8.8	-2.4	-5.8	-3.6	-6.5	-1.2	-4.4

Cell I showed the greatest projected retreat throughout the simulation period. At the 50% probability of exceedance, projected shoreline-change rates were – 3.4 m/yr in 2040, – 3.8 m/yr in 2050, – 4.0 m/yr in 2075, and – 5.7 m/yr in 2125. At the 10% probability of exceedance, projected retreat ranged from – 7.0 m/yr in 2040 to – 8.8 m/yr in 2125.

Cell II remained slightly accretionary at the 50% probability of exceedance during the earlier projection horizons, with rates of 0.8 m/yr in 2040 and 0.5 m/yr in 2050. The projected response shifted to retreat by 2075 (– 0.9 m/yr) and reached – 2.4 m/yr by 2125. At the 10% probability of exceedance, retreat was projected for all four horizons, ranging from – 1.7 m/yr in 2040 to – 5.8 m/yr in 2125.

In Cell III, projected retreat occurred at both exceedance levels from the earliest projection horizon. At the 50% probability of exceedance, rates ranged from – 0.9 m/yr in 2040 to – 3.6 m/yr in 2125. At the 10% probability of exceedance, projected retreat increased from – 2.8 to – 6.5 m/yr over the same period.

Finally, Cell IV showed the smallest projected shoreline changes among the four sectors. At the 50% probability of exceedance, the cell remained accretionary through 2075, with projected rates of 1.2 m/yr in 2040, 0.8 m/yr in 2050, and 0.4 m/yr in 2075. By 2125, the projected rate shifted to – 1.2 m/yr. At the 10% probability of exceedance, retreat was projected throughout the simulation period, increasing from – 0.8 m/yr in 2040 to – 4.4 m/yr in 2125.

Across all cells, projected retreat became more pronounced toward 2125. At the 50% probability of exceedance, all four cells exhibited negative shoreline-change rates by the final projection horizon, ranging from – 1.2 m/yr in Cell IV to – 5.7 m/yr in Cell I. At the 10% probability of exceedance, all cells showed retreat throughout the projection period, with 2125 rates ranging from – 4.4 m/yr in Cell IV to – 8.8 m/yr in Cell I.

The spatial expression of the 2125 projections is shown in Fig. 4, where the current shoreline is compared with the projected positions corresponding to the 50% and 10% probabilities of exceedance.

4.3 Influence of Sediment Budget and Sea-Level Rise on Shoreline Projections

Additional simulations were used to compare the isolated effects of SB and SLR with the combined SB + SLR projections (Fig. 5). The relative contribution of the two drivers varied among coastal cells and projection horizons.

In Cell I, the SB-only simulations produced predominantly negative shoreline-change rates, whereas the SLR-only simulations also resulted in retreat that increased toward the longer projection horizons. The combined SB + SLR simulations consequently produced retreat throughout the full projection period, with the largest values occurring in 2125.

In Cells II and III, the SB-only simulations produced positive shoreline responses, while the SLR-only simulations produced increasing retreat toward the longer projection horizons. In the combined simulations, the positive contribution associated with SB reduced the magnitude of the projected recession relative to the SLR-only response, particularly at the earlier projection horizons. Nevertheless, the combined response became increasingly negative toward 2075 and 2125.

In Cell IV, the SB-only simulations also produced positive shoreline change, whereas SLR-only simulations showed progressively greater retreat with time. The combined simulations remained close to equilibrium or slightly accretionary at the 50% probability of exceedance through 2075 before shifting to retreat by 2125.

Overall, the isolated-driver experiments showed contrasting shoreline responses to SB and SLR. Positive SB conditions produced accretionary responses in Cells II–IV, whereas projected SLR produced retreat in all cells. In the combined simulations, the relative contribution of SLR became progressively more evident toward the longer projection horizons.

5. Discussion

5.1 Sediment-Budget Estimates Across Different Monitoring Timescales

In this study, SB was derived from two shoreline-monitoring datasets: satellite imagery (2010–2024) and RPA surveys (2023–2024). Although these represent the longest available records for each monitoring approach, the results reinforce the importance of long-term shoreline monitoring for the interpretation of SB variability (Luijendijk et al. 2018).

The analysis of shoreline displacement revealed marked differences between monitoring scales: annual RPA surveys generally showed larger shoreline-change rates than those derived from satellite imagery over the 14-year period. This contrast was particularly evident in Cell I, where the annual record showed 8 m of shoreline retreat (-8 m/yr), associated with an estimated SB of -180 m³/m/yr, whereas the 2010–2024 record showed 47 m of shoreline advance and a positive SB of 78 m³/m/yr. Short-term beach and nearshore variability has previously been documented in the study area (Goulart 2014; Pereira et al. 2012), whereas the longer-term evolution of this sector has been described as stationary or aggradational (Dillenburg et al. 2000; Dillenburg and Hesp 2009; Martinho et al. 2009; Caron 2014).

Along the Rio Grande do Sul coast, frontal systems and extratropical cyclones can generate extreme winds, energetic waves, storm surges, and substantial beach erosion (Parise et al. 2009; Machado and Calliari 2016). Substantial shoreline changes associated with extratropical cyclones have also been documented elsewhere, while storm response and recovery may vary according to local morphology (Harley et al. 2017; Burvingt and Castelle 2023). Alternating phases of erosion and accretion over longer monitoring periods further demonstrate that short-term shoreline behaviour may not represent the longer-term trajectory of a coastal sector (Castelle et al. 2018). Accordingly, an annual record may capture event-scale erosion or incomplete recovery, whereas a decadal record integrates a broader range of coastal conditions (Harley et al. 2017; Castelle et al. 2018; Burvingt and Castelle 2023).

The recent behaviour observed in Cell I may also be influenced by local anthropogenic activity, as the beach is used as a roadway by trucks and tractors transporting timber from forestry plantations (Caron 2014). However, the contribution of this activity to the measured shoreline change was not quantified in the present study and cannot be separated from hydrodynamic variability.

Cells II, III, and IV showed greater consistency with their established longer-term progradational behaviour. Cells II and IV advanced at both annual and decadal scales, whereas Cell III remained approximately stable during the annual interval and advanced 47 m between 2010 and 2024. These patterns agree with previous studies describing the progradation of the Cassino embayment and sectors adjacent to the Patos Lagoon inlet (Dillenburg et al. 2000, 2009, 2017; Barboza et al. 2018; Bitencourt et al. 2020). The Cassino barrier, including Cell III, has prograded approximately 18 km since the mid-Holocene, forming an extensive Holocene progradational coastal plain. For comparison, the Holocene

progradation of the Moruya barrier in southeastern Australia reached approximately 5 km (Roy et al. 1994; Kinsela et al. 2016; Oliver et al. 2020).

At the decadal scale, Cells I and III both recorded 47 m of shoreline advance. However, Cell III required a larger SB ($85 \text{ m}^3/\text{m}/\text{yr}$) than Cell I ($78 \text{ m}^3/\text{m}/\text{yr}$) to reproduce this displacement. This difference reflects the influence of shoreface morphology: Cell III has a wider and gentler shoreface, requiring a greater sediment volume to produce a comparable horizontal shoreline advance (Cowell et al. 1995, 1999; Cowell and Kinsela 2018). The comparison demonstrates that SB magnitude cannot be interpreted independently of the morphology of the active coastal profile.

5.2 Sediment Budget, Shoreface Morphology, and Future Shoreline Response

Future shoreline projections along the analyzed sectors indicate that shoreline behavior over the shorter projection horizons (2040–2050) is mainly influenced by SB. At longer timescales (2075 and 2125), however, SLR exerts progressively greater control on shoreline recession, leading to retreat even in sectors with positive SB. This pattern is consistent with previous studies showing that sediment supply can reduce or delay shoreline recession, whereas the influence of SLR becomes increasingly important over longer projection horizons (Bose et al. 2020; Carvalho et al. 2026; Figueiredo et al. 2018; Forgiarini et al. 2019; López-Olmedilla et al. 2022).

Southern South America was identified by Voudoukas et al. (2020) as a region with substantial projected sandy-coast erosion under a high-emission scenario. A mean retreat rate of approximately $-2.5 \text{ m}/\text{yr}$ was projected for this region, lower than the rates estimated here for Cells I and III by 2125. At the 50% probability of exceedance, Cell I reached $-5.7 \text{ m}/\text{yr}$ and Cell III $-3.6 \text{ m}/\text{yr}$. Comparable recession rates have also been obtained using RanSTM along the northwestern Portuguese coast, where López-Olmedilla et al. (2022) projected rates of approximately $-5.9 \text{ m}/\text{yr}$ by 2100.

These differences in projected retreat are also related to the inherited shoreface morphology of each coastal cell: wider and gentler shorefaces require larger sediment volumes to fill the accommodation space created by SLR and maintain profile adjustment (Roy et al. 1994; Dillenburg et al. 2000; Cowell et al. 1995, 1999; Cowell and Kinsela 2018; Figueiredo et al. 2020). This effect is particularly evident in Cell III, where retreat was projected from the earliest horizon despite stable annual conditions and positive decadal and large-scale SB estimates. Its shoreface geometry increases the sediment demand associated with adjustment under rising sea level. In areas with gentler substrate slopes, barrier translation may also be enhanced during periods of rapid SLR (Bitencourt et al. 2020; Rosa et al. 2017).

In contrast, Cell IV showed the lowest projected retreat among the analyzed sectors. Its narrower shoreface and positive SB reduce the sediment volume required for profile adjustment and delay the transition toward shoreline recession. The combined influence of shoreface morphology and sediment availability on shoreline response to SLR is consistent with previous applications of RanSTM and related approaches (Figueiredo 2011; Carvalho et al. 2026; López-Olmedilla et al. 2022). Although barrier

evolution depends on several interacting factors (Hesp and Short 1999; Cowell et al. 2003a, b; Dillenburg and Hesp 2009), this interaction has also been important in the Holocene evolution of the Rio Grande do Sul coastal barrier.

The onshore morphology appears to exert a smaller influence on projected retreat than the shoreface at centennial timescales (Fig. 2). Cell I has the highest onshore elevations among the analyzed profiles but also shows the greatest projected shoreline recession, whereas Cell IV has a lower topographic profile and the lowest projected retreat. This pattern is consistent with previous studies indicating that the long-term response of barrier systems is strongly influenced by the geometry and spatial scale of the active profile (Kinsela 2007; Figueiredo et al. 2020; Forgiarini et al. 2019). The lower shoreface extends over a spatial scale of approximately 10^3 m and can act as a long-term sediment sink as accommodation space increases under SLR, whereas subaerial coastal features generally occur over smaller spatial scales of approximately 10^2 m (Cowell et al. 1999; Cowell and Kinsela 2018; Figueiredo et al. 2020).

5.3 Implications for Coastal Conservation, Planning, and Management

The contrast between annual and decadal shoreline behaviour in Cell I illustrates why the monitoring interval matters for coastal planning, since the same sector appears erosional at the recent annual scale but accretionary at the decadal scale, potentially leading to different interpretations of future shoreline behaviour. Projected shoreline positions are increasingly used to identify sectors susceptible to shoreline retreat, assess potential exposure, and support adaptation decisions, but their management value depends on whether the observational record adequately represents the processes relevant to the planning horizon (Cowell et al. 2006; Klein et al. 2016; Thiéblemont et al. 2021; Ranasinghe et al. 2023; Durap and Balas 2024).

Different observation periods capture different components of shoreline behaviour, with RPA surveys resolving recent and localized changes, satellite records integrating longer-term variability, and stratigraphic data providing the broader evolutionary context of the coastal barrier (Dillenburg et al. 2000, 2017; Luijendijk et al. 2018; Oliver et al. 2020; Woodroffe et al. 2022). These records should therefore be interpreted as complementary rather than equivalent, since combining them places recent changes within their longer-term sedimentary context and reduces dependence on a single monitoring interval (Thiéblemont et al. 2021; Carvalho and Woodroffe 2023).

Sediment cells provide a useful spatial framework for interpreting alongshore differences in sediment availability and morphodynamic response because they represent sectors connected through sediment sources, transport pathways, and sinks (Cowell et al. 2003a, b; Rosati 2005; Kinsela et al. 2017). The contrasting responses of Cells I–IV show that neighbouring sectors may require different monitoring and management priorities and should not be treated as a morphologically uniform coastline (Carvalho and Woodroffe 2023).

Probabilistic shoreline projections further allow this variability to be incorporated into planning by representing a range of modelled responses rather than a single future shoreline position (Cowell et al. 2006; Figueiredo and Cowell 2016; Thiéblemont et al. 2021; Ranasinghe et al. 2023). The 50% and 10% exceedance levels represent different probabilities within this range and can support risk-informed decisions in which the level of precaution depends on the consequences, lifetime, and acceptable risk associated with a particular intervention (Cowell et al. 2006; Kinsela et al. 2017; Ranasinghe et al. 2023).

For sandy beach–dune systems, future adjustment also depends on sediment availability, sediment connectivity, and the space available for landward migration (Defeo et al. 2009, 2021; McLachlan et al. 2013; Davidson-Arnott et al. 2024). Infrastructure and intensive coastal occupation may restrict this space and intensify coastal squeeze (Lansu et al. 2024), while human use can affect dune-forming processes and vegetation establishment (Davidson-Arnott et al. 2024; van Rosmalen et al. 2025). Coastal protection planning should therefore consider not only projected retreat but also whether interventions constrain landward migration or disrupt sediment connectivity, particularly where natural beach–dune adjustment remains possible.

Greater physical retreat, however, does not necessarily imply greater overall coastal risk, which also depends on the exposure and vulnerability of populations, infrastructure, ecosystems, and other valued assets (Kinsela et al. 2017; Durap and Balas 2024). These components were not quantified here, so the lower physical retreat projected for Cell IV should not be interpreted as evidence of lower ecological or socioeconomic vulnerability. The value of the present projections lies instead in identifying where physical responses differ along the coast and where monitoring, conservation, protection, and adaptation priorities may need to be spatially differentiated, rather than in prescribing specific measures (Carvalho and Woodroffe 2023; Ranasinghe et al. 2023; Durap and Balas 2024).

5.4 Uncertainty, Limitations, and Interpretation of the Projections

The probabilistic approach used here incorporates SB variability derived from annual RPA, decadal satellite, and millennial-scale geological estimates into the projected shoreline responses (Cowell et al. 2006; Figueiredo and Cowell 2016; de Carvalho et al. 2026). However, these sources cover different temporal windows and do not represent the full range of conditions that may occur in the future. Changes in sediment supply, wave climate, alongshore transport, inlet dynamics, and human interventions may therefore lead to shoreline responses beyond those captured by the present SB inputs.

Episodic storm impacts were not explicitly parameterized and are included only when their effects are already reflected in the shoreline observations used to estimate SB. This is particularly relevant along the Rio Grande do Sul coast, where frontal systems and extratropical cyclones can produce substantial erosion (Parise et al. 2009; Machado and Calliari 2016). RanSTM also uses an aggregated morphological representation and does not explicitly resolve individual events, three-dimensional sediment transport, or detailed alongshore variability. The projections are additionally sensitive to shoreface geometry and closure-depth assumptions (Nicholls et al. 1998; Cowell et al. 2006; Figueiredo et al. 2020) and were

developed only for the regional SSP5–8.5 scenario. The exceedance probabilities should therefore be interpreted as possible physical shoreline responses under the adopted model structure and forcing conditions, rather than as deterministic forecasts or complete coastal-risk assessments..

6. Conclusions

This study highlights the complex interaction between sediment budget, shoreface morphology, and sea-level rise in the evolution of a sandy barrier coast. Although the long-term behaviour of the southern-central coast of Rio Grande do Sul indicates predominantly progradational or stable conditions, shoreline change varied according to the observation scale. Annual RPA monitoring generally showed larger shoreline displacements than the decadal satellite record. Cell I exhibited short-term erosion and medium-term accretion, whereas Cells II and IV were accretionary at both scales and Cell III remained stable in the short term and accreted over the medium term.

Future projections showed the greatest retreat in Cell I, associated with its negative short-term sediment budget and low-gradient shoreface. Despite positive sediment budgets, Cells II, III, and IV also shifted toward retreat at longer projection horizons as the influence of SLR increased. Overall, sediment budget exerted a stronger influence on shoreline behaviour over shorter timescales, whereas SLR became increasingly dominant toward centennial horizons, with shoreface morphology modulating the magnitude of the response. The probabilistic approach captures part of the variability associated with sediment-budget estimates, although episodic storm impacts and future changes in sediment supply remain relevant sources of uncertainty. These results provide a physical basis for supporting coastal monitoring, conservation, and adaptation planning along morphologically heterogeneous coastlines.

Declarations

Author Contribution

J.S.S.: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft. S.A.F.: Conceptualization, Methodology, Supervision, Writing – review and editing. E.S.G.: Conceptualization, Methodology, Supervision, Writing – review and editing. N.D.C.: Investigation, Data curation, Formal analysis, review and editing. A.M.C.: Investigation, Data curation. All authors reviewed and approved the final manuscript.

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Data Availability

The datasets generated and analysed during the current study are available in a public research data repository. Repository details have been omitted during peer review to preserve author anonymity and will be provided upon acceptance.

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Figures

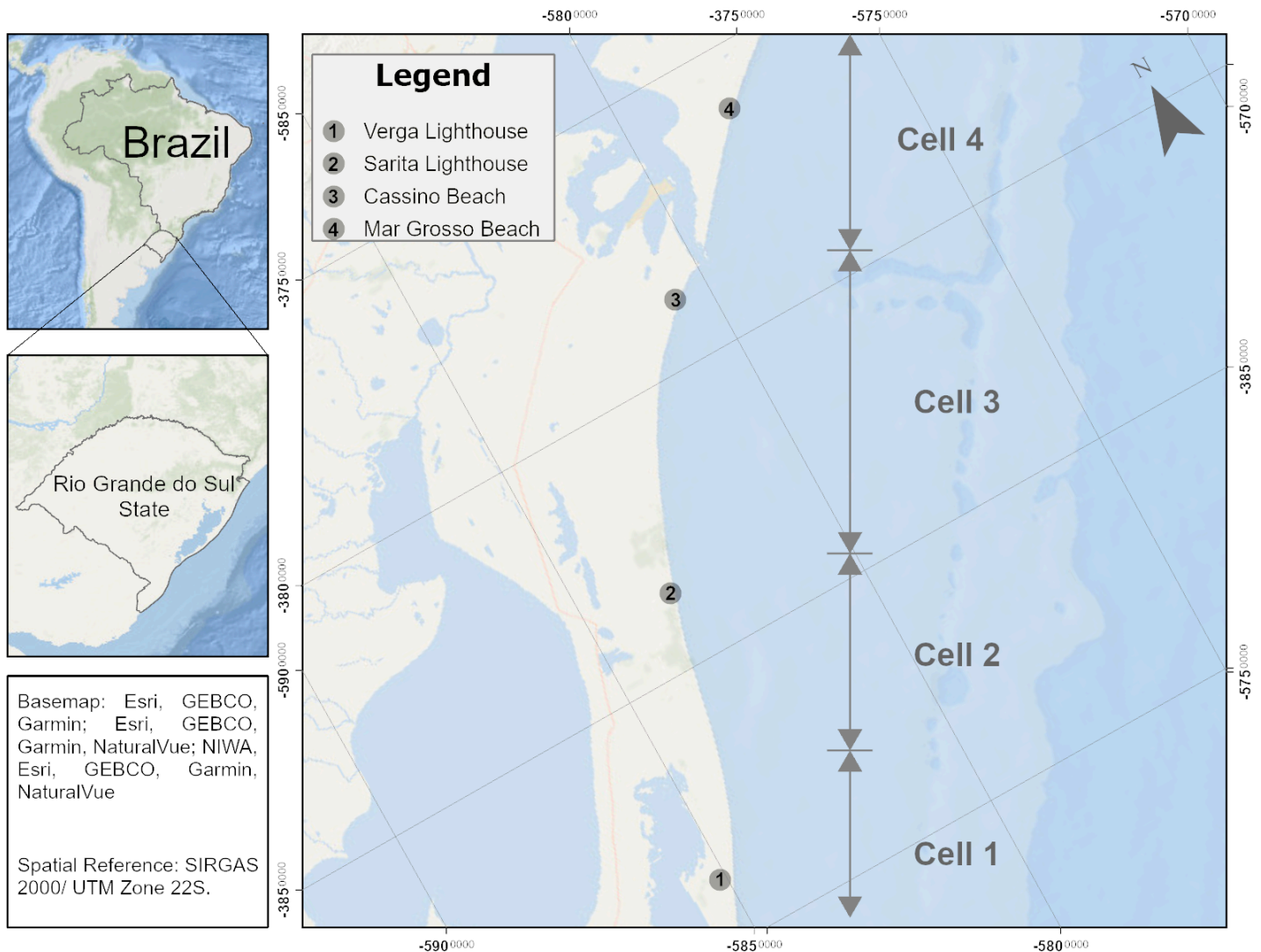


Figure 1

Location of the study area along the coast of Rio Grande do Sul, southern Brazil. The main map shows the four sediment-budget control coastal cells and the reference locations used in the analysis: (1) Verga Lighthouse, (2) Sarita Lighthouse, (3) Cassino Beach, and (4) Mar Grosso Beach.

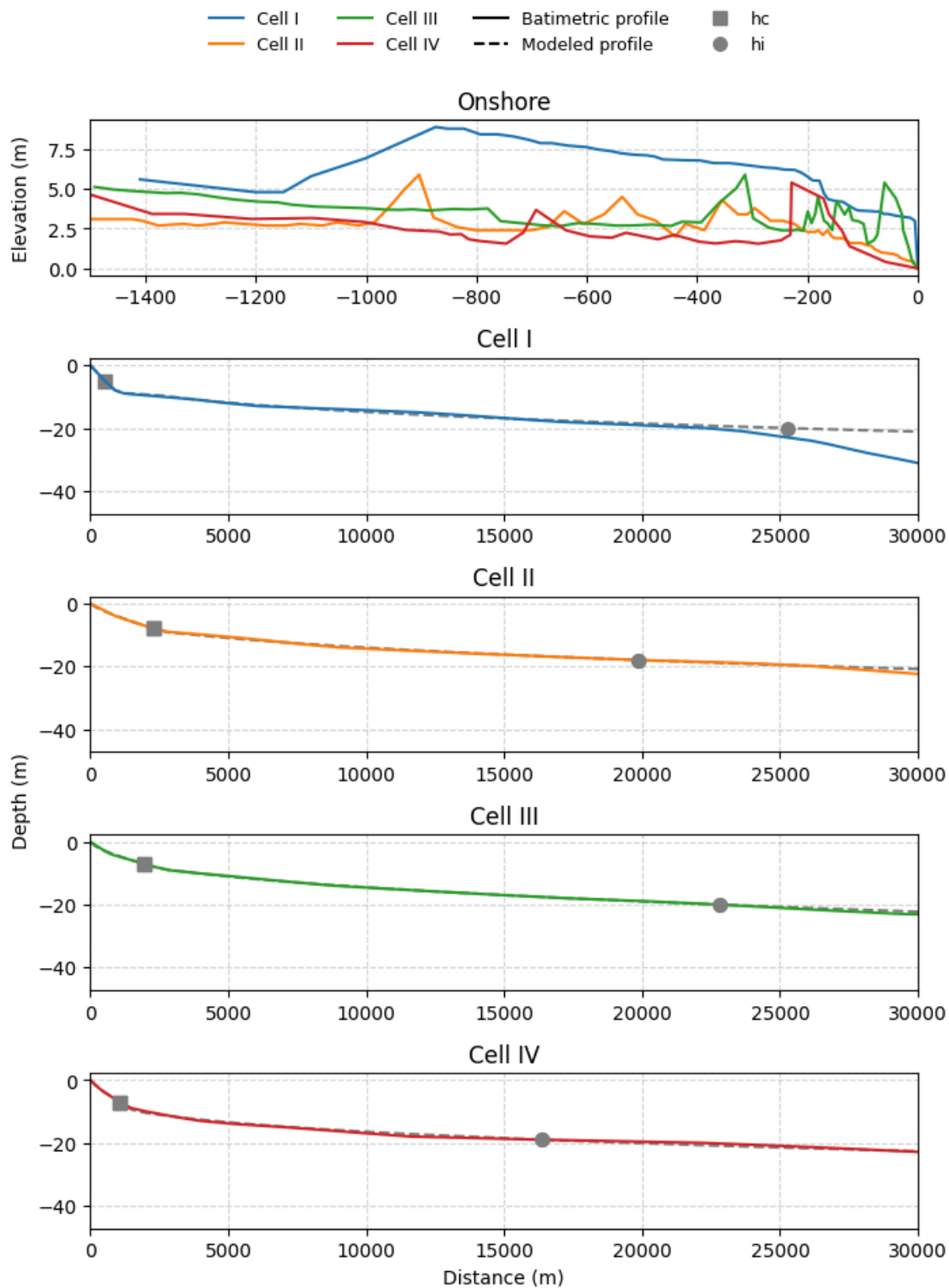


Figure 2

Topobathymetric profiles used in the study. (a) Topography and (b) bathymetry, highlighting the upper (hc) and lower (hi) closure depths in each cell.

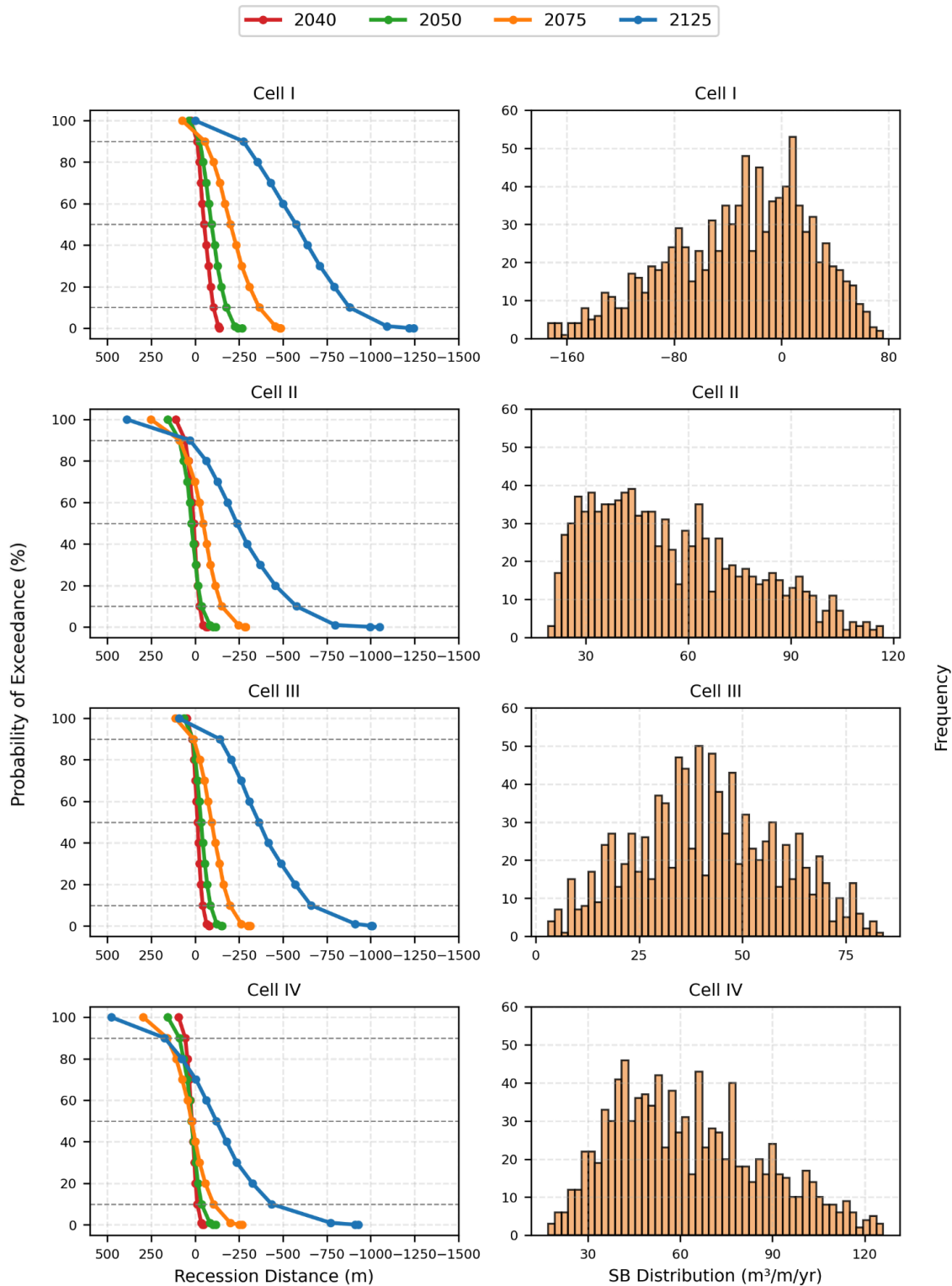


Figure 3

The left panels show probability-of-exceedance curves for each projection year: 2040 (red), 2050 (green), 2075 (orange), and 2125 (blue), associated with the shoreline retreat distances for each study cell. The right panels display the sediment-budget input PDFs ($\text{m}^3/\text{m}/\text{yr}$) for each cell.

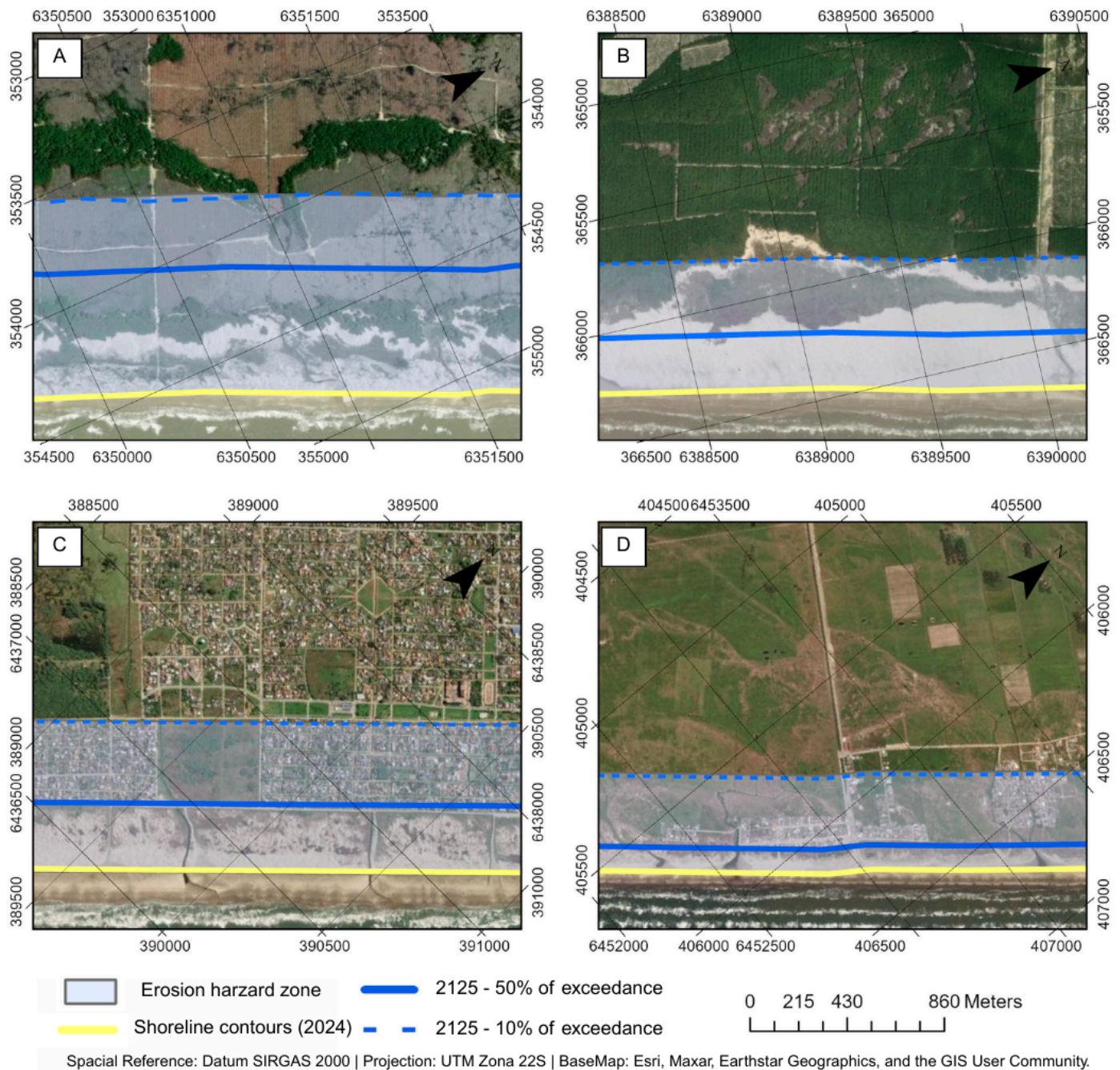


Figure 4

Shoreline projections for the year 2125. The current shoreline, represented in yellow, outlines the base of the foredune; the projections represent retreat distances with probability-of-exceedance values of 50% (solid blue line) and 10% (dashed line) for the four cells: (a) Cell I, (b) Cell II, (c) Cell III, and (d) Cell IV.

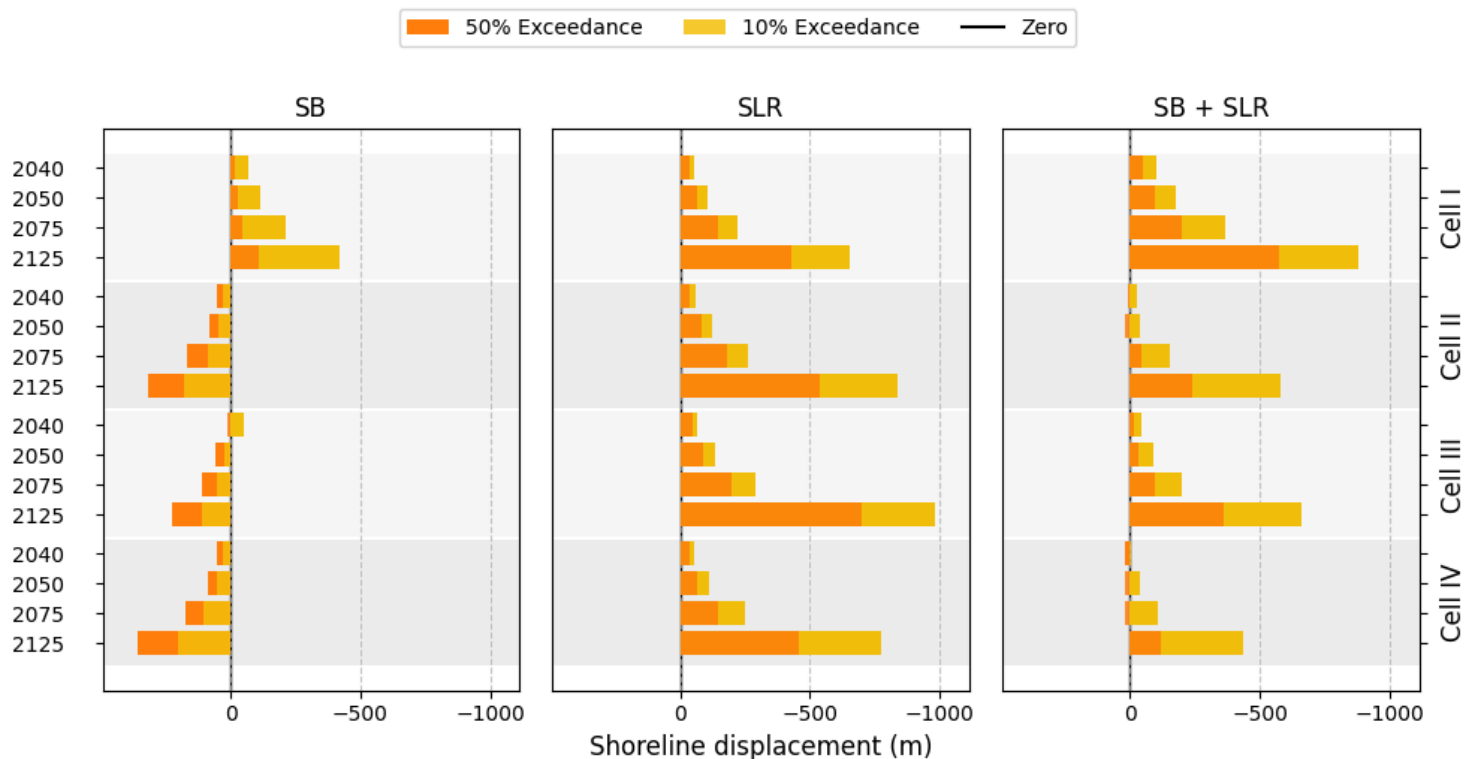


Figure 5

Projected shoreline-change rates obtained from simulations isolating sediment-budget effects (SB), sea-level-rise effects (SLR), and their combined influence (SB + SLR) for Cells I–IV and the 2040, 2050, 2075, and 2125 projection horizons. Values are shown for the 50% and 10% probabilities of exceedance. Positive values indicate accretion and negative values indicate retreat.