COMPUTATIONAL SIMULATION OF EROSION AT COPACABANA BEACH – RJ - BRAZIL, UNDER THE INFLUENCE OF STORM WAVES: COASTAL PROTECTION STRATEGIES

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This study investigates the morphodynamic behavior of Copacabana Beach, Rio de Janeiro, during a significant storm event from August 10 to August 25, 2017, using the SisBaHiA® model. The storm generated southeast waves up to 3.8 meters in height, causing intense erosion, particularly in the southern region between lifeguard stations 5 and 6. During this period, cross-shore sediment transport was calculated, showing sediment displacement offshore, leading to shoreline retreat and increased vulnerability of local infrastructure. A proposed solution involving sand nourishment and the construction of a retaining structure was simulated to assess its impact on stabilizing the area. The results showed reduced erosion rates and improved sediment retention in the southern region, minimizing shoreline retreat and protecting the coastal infrastructure. This study demonstrates the potential of combining nourishment and structural interventions to enhance the beach's stability during extreme storm events.

Keywords: Morphodynamics model; Sediment transport; Coastal erosion.

INTRODUCTION

Coastal morphodynamics involves the processes that govern the configuration and evolution of beaches. The interaction between waves, currents, and sediments, as well as the resulting cycles of erosion, transport, and deposition, plays a fundamental role in determining the response of beaches to environmental changes. These responses can manifest as either erosive or depositional characteristics. Waves significantly influence sediment transport and redistribution along the coastal profile, with the degree of beach exposure to the local wave climate being a key factor (Muehe, 2001).

The understanding of these processes not only contributes to the preservation of coastal ecosystems but also plays a vital role in protecting coastal infrastructure and resident communities. However, coastal erosion is driven by the interaction between wave action, natural factors, and improper coastal occupation. Disorganized urban expansion, natural resource exploitation, and climate change are just some of the factors that intensify shoreline retreat.

The cross-shore sediment transport constitutes a fundamental aspect in comprehending coastal dynamics under the influence of storm wave action. This phenomenon not only influences the flow of sand around coastal structures but also impacts seasonal variations in shoreline position. During transient erosive episodes, such as storms, a significant alteration in the beach profile is observed due to cross-shore transport. Sediments are displaced to deeper areas, leading to the formation of sandbanks, causing wave breaking to occur farther from the shoreline (U.S. ARMY, 2002).

Copacabana Beach, located in Rio de Janeiro, Brazil (Figure 1), is an important socio-economic region. In the early 1970s, a project was initiated to replenish the sand stock, expand the beach area, and create the boardwalk (Velho, 1999). 3.5 million m^3 of sand were used for the nourishment of Copacabana beach, reaching about 90 meters wide after all stages of the project (Vera-Cruz, 1972).

The region between lifeguard stations 5 and 6 is the most vulnerable area of Copacabana Beach, particularly susceptible to storm waves coming from the southeast. This section of the beach experiences the highest erosion rates, which have caused significant damage to coastal infrastructure, including buildings, kiosks, and sidewalks.

In response to this issue, the present study examines a proposed solution involving the construction of a sediment retention structure and the nourishment of sand stocks in the affected region between lifeguard stations 5 and 6. The primary objective of this intervention is to create a more stable physiographic unit in the southern part of the beach. This would not only help mitigate erosion but also enhance the dynamic range of the beach, thereby offering greater protection to the coastline and the infrastructure along it.

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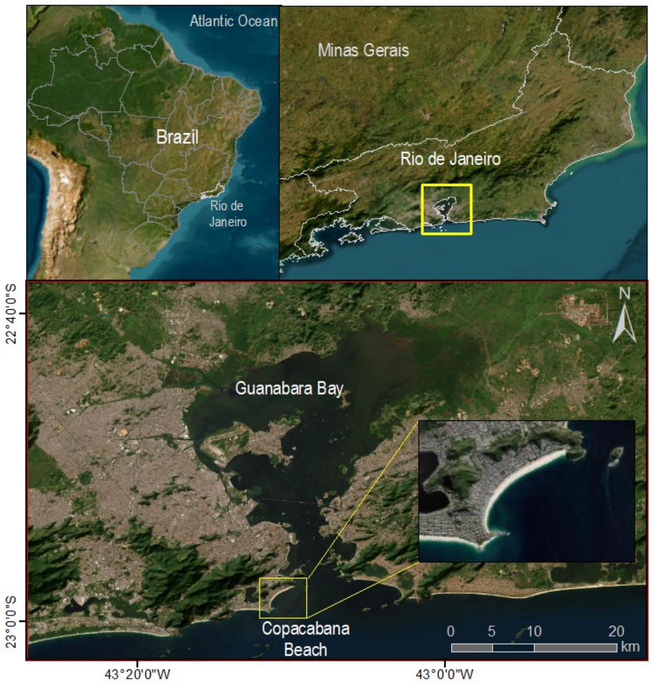

Figure 1: Study area.

METHODS

The morphological evolution of Copacabana Beach was carried out through simulations using models from SisBaHiA® - Environmental Hydrodynamics Base System (Figure 2). The hydro-sedimentological morphodynamic model was developed considering the action of waves and currents, performed by coupling the hydrodynamic model, a sediment transport model, and a wave propagation model. It is possible to analyze the morphodynamic evolution of the beach based on the coupled models (Rosman, 2024).

Silva (2019) incorporated into SisBaHiA® a cross-shore sediment transport model based on Kriebel & Dean (1984) formula:

$$Q_T = K\left(\alpha D - D^*\right) \qquad (1)$$

Where Qt represents the magnitude of sediment transport transverse to the coast, *K* is an adjustable constant, *D* is the energy dissipation rate of waves per unit volume in the surf zone, D^* is the same rate for the situation where the beach profile is in equilibrium (Dean, 1977), and α is the energy dissipation coefficient introduced by Silva (2019) in the formula for improved results in calculating transverse transport within the model.

Sistema de Modelagem Computacional - SisBaHiA®

Figure 2: SisBaHiA Initial Screen.

METOCEAN DATA

The bathymetric data were digitized from nautical charts provided by the CHM – Brazilian Navy Hydrography Center (*Nautical Charts | Hydrography Center of the Navy*). Nautical Chart 1501 of Guanabara Bay and Nautical Chart 1511 of the Barra of Rio de Janeiro were used, with the latter providing greater detail of the bathymetry in the Copacabana Beach region. The bathymetric elevations are referenced to the Chart Datum (CD) of the CHM's Nautical Chart 1511.

The altimetric data used in the modeling of the dry portion of the beach were derived from field studies conducted by Silva and Lins-de-Barros (2018) during the year 2017. These studies involved monitoring campaigns in different seasons. Additionally, cross-shore profiles were analyzed at 19 specific points along the beach, conducted in 2019, as documented by Hoogendoorn (2021).

The granulometric data of the sediments from Copacabana Beach considered in the modeling were obtained from Costa (2020), based on surveys conducted at three locations on the beach between 2017 and 2018. At Point 1, located near Forte de Copacabana, the D50 value is 0.28 mm. At Point 2, near Copacabana Palace, the D50 is 0.37 mm. Finally, at Point 3, located near Pedra do Leme, the D50 value is 0.33 mm.

The sea level in the region of interest varies primarily due to the astronomical tide, which is deterministic and predictable, causing oscillatory variations in levels and currents with typical periods of around 12 hours. Additionally, the meteorological tide, generally caused by the propagation of waves over the continental shelf, generates variable mean sea levels (MSL) in both space and time, as well as drift currents not related to astronomical tides.

The set of 33 harmonic constants obtained from the Finite Element Solution (FES) was used to calculate the astronomical tides (Lyard et al., 2014). The non-astronomical sea level variations were obtained from reanalysis in the South Atlantic through the Hybrid Coordinate Ocean Model (HYCOM) (Figure 3).

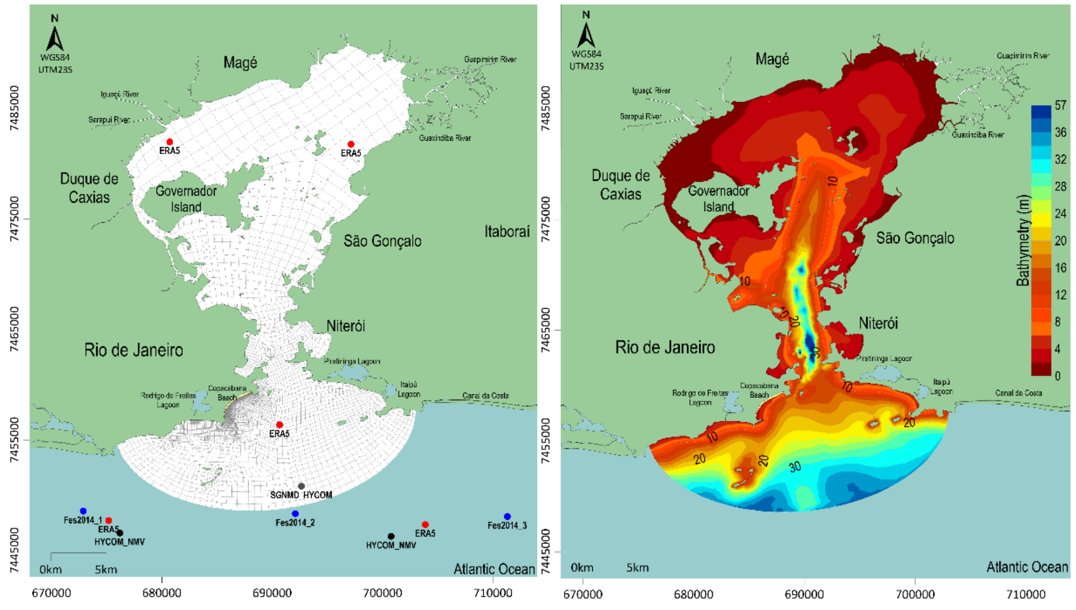

Figure 3: Biquadratic finite element mesh used for the domain discretization, with the location of the stations (left) and bathymetry in meters relative to local chart datum (right).

The wind data used in the model were reanalysis data obtained from the ERA5 website - ECMWF (European Centre for Medium-Range Weather Forecasts). The data have a three-hour time interval for the entire simulation period. The series for each station were interpolated to the nodes of the hydrodynamic model's mesh, generating the wind field for the entire modeling domain.

Two stations were selected within Guanabara Bay, one station on the shallow continental shelf off Copacabana Beach, and two other stations located farther offshore. Figure 4 shows the hourly wind speed and direction at the station near Copacabana Beach between August 10 and 25, 2017.

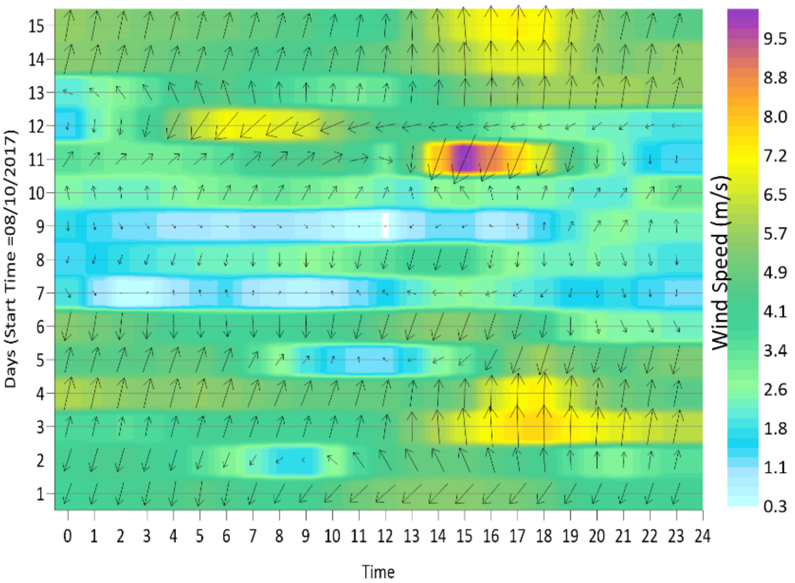

Figure 4: Hourly wind speed and direction from August 10 to August 25.

The deep-water wave climate used in the wave propagation model is based on reanalysis data obtained from ERA5 of ECMWF (European Centre for Medium-Range Weather Forecasts). The wave time series for 2017 corresponds to the location at the UTM coordinates (700444 E; 7347694 S). The station is located at a depth of approximately 200 meters.

In this study, the period from August 10, 2017, to August 25, 2017, was considered, during which a significant storm event took place, generating waves up to 3.8 meters in height, coming from the southeast direction (Figure 5).

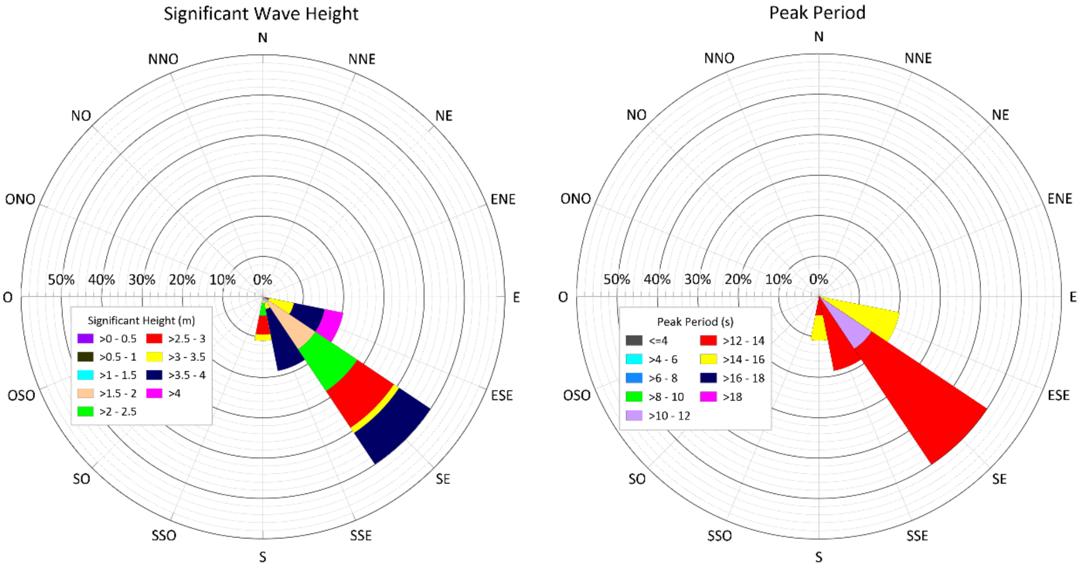

Figure 5: Wave rose for the storm period between August 10, 2017, and August 25, 2017.

RESULTS

The analysis of Copacabana Beach under the influence of storm waves from August 10th to August 25th, 2017, when the cross-shore transport module in SisBaHiA® was activated, is presented here. Pinho *et al.*, (2023) calculated the longitudinal sediment transport of Copacabana Beach for the entire year of 2017.This study aims to provide a more detailed understanding of the coastal dynamics of Copacabana Beach during storm events, when the beach profile is rapidly altered by wave action.

Figure 6 illustrates the results of beach morphodynamics during the modeled period in the Current Situation. It is observed that at the onset of modeling using the cross-shore transport module of SisBaHiA, the beach is stable. The date of August 25 was chosen because it yielded results consistent with Google Earth satellite images from the same date.

This archival image from Google Earth, dated August 25, 2017, clearly highlights the impact of erosion caused by southeast waves in the southern region of the beach. Additionally, the image reveals the presence of the sediment plume further offshore. The modeling results are consistent with observations made from satellite images and historical newspaper and magazine archives.

The image on the left shows the bathymetric variation of Copacabana Beach on August 10, 2017, for the Current Scenario. For all the following morphodynamic evolution results, the blue line represents the position of the coastline at the initial modeling time, on January 2, 2017, while the red line indicates the modeled time. It is important to emphasize that the hydrosedimentological model initially started running on January 2, 2017, and the cross-shore sediment transport module was only activated on August 10.

The image on the right shows the bathymetric variation on August 25, 2017, marking the final instant of the cross-shore sediment transport simulation for the Current Scenario. An erosive feature is highlighted in the southern region of Copacabana Beach, identified as the most susceptible point to partial or nearly total erosion of the sand strip. This occurrence, which often compromises local infrastructure, presents potential risks for both the resident population and visitors.

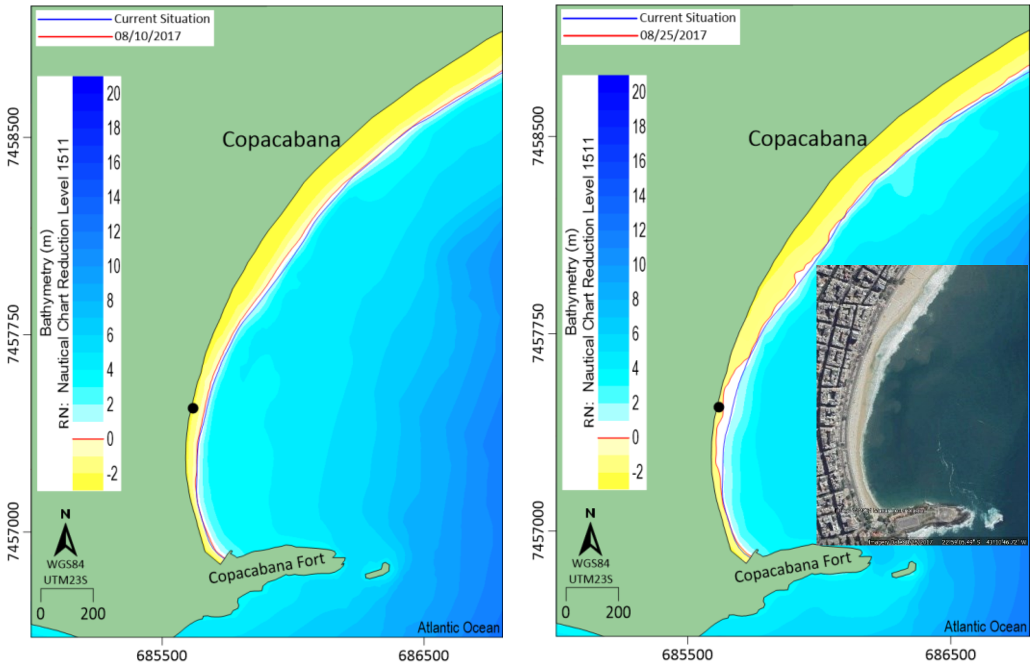

Figure 6: Bathymetric elevation maps for the Current Situation on August 10, 2017 (left) and August 25, 2017 (right). The black dot marks the location of Lifeguard Station 5. In detail, in the image on the right, a satellite image from August 25, 2017.

Figure 7 presents the variations in beach profiles for the Current Scenario for August 10, 2017 (black line) and August 25, 2017 (red line).

In SisBaHiA®, bathymetric data is represented by positive elevations, while altimetric data for the dry beach area is represented by negative values. This distinction allows for the representation of both submerged and emerged features of the beach. The beach profiles analyzed in this study were obtained from Lifeguard Post 5, located in the southern region of Copacabana Beach.

The beach profile for the Current Scenario, before the sand nourishment project and the construction of the groin, shows significant variability in bathymetric elevation. Erosion of the beach berm by approximately 1 meter and sediment deposition in deeper areas result in a reduction in the overall bathymetric elevation. These variations reflect the dynamic nature of the beach, influenced by storm events and natural sediment transport processes.

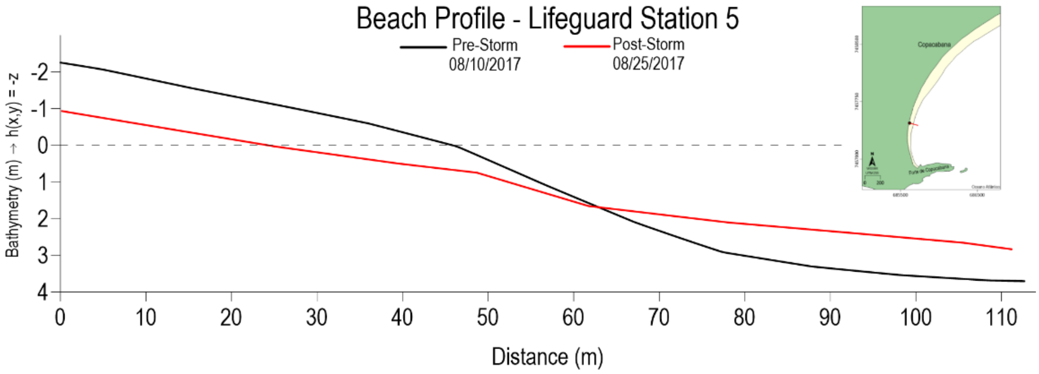

Figure 7: Beach profiles for the Current Scenario, obtained near Lifeguard Station 5.

In the Projected Scenario, on August 10, 2017 (Figure 8, left), sedimentation is observed near the end of the groin, while erosion occurs to the north of the structure, with a coastline retreat of approximately 18 meters. It is important to note that between May and June, several storm events occurred, with wave heights reaching up to 3.5 meters, peak periods of 15 seconds, and azimuths ranging from south to southeast.

From July 18 to 22, the coastline of Rio de Janeiro also experienced significant storm wave activity, with wave heights of up to 3 meters and an average peak period of 12 seconds. Consequently, the initial bathymetry used for the cross-shore sediment transport model differs from the initial bathymetry applied in the annual simulation conducted earlier in this study.

In the Projected Scenario, on August 25, 2017 (Figure 8, right), erosive effects are observed south of the sediment retention structure, with a reduced variation in the coastline. The submerged region of the beach, between Forte de Copacabana and the groin, exhibits a tendency for sediment deposition. To the north of the groin, however, coastal erosion is evident, with the beach line retreating by approximately 25 meters. At this location, the average width of the beach is around 120 meters. The formation of submerged sandbars in the more distal areas of the coastline alters the bathymetry, consequently affecting the wave breaking zone.

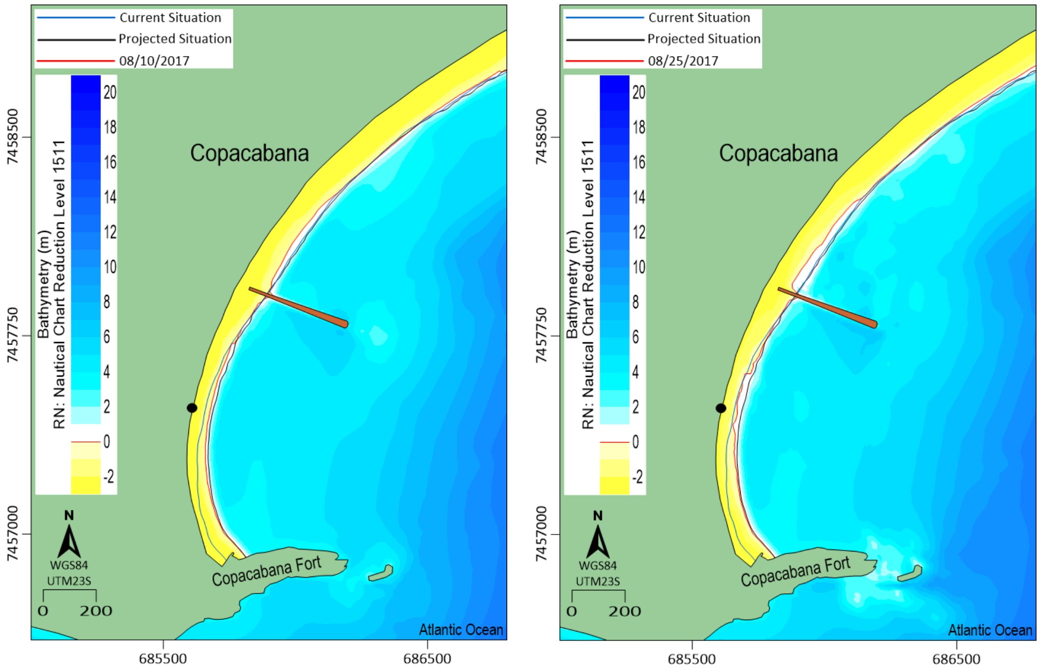

Figure 8: Bathymetric elevation maps for the Projected Situation on August 10, 2017 (left) and August 25, 2017 (right). The black dot marks the location of Lifeguard Station 5.

Figure 9 illustrates the variation in the beach profile near Lifeguard Post 5, located in the southern part of Copacabana Beach, for the Projected Scenario on two different dates: August 10 and August 25, 2017. When comparing the profiles from these two dates, it is evident that there were no significant changes in the beach profile between August 10 and August 25. The profile shows a relatively stable coastline, with minimal variations in bathymetric elevation. This suggests that the coastal interventions, such as the sediment retention structure and sand nourishment, have been effective in maintaining the stability of the beach profile over this short period.

The lack of substantial changes between the two dates indicates that the implemented measures have successfully reduced the erosive processes that typically affect the beach profile after storm events. The beach remains relatively stable, with the coastline showing only minor adjustments, reflecting the protective effect of the interventions. This stability is particularly important for preventing further erosion and maintaining the integrity of the beach, which is typically subject to significant changes during storm events.

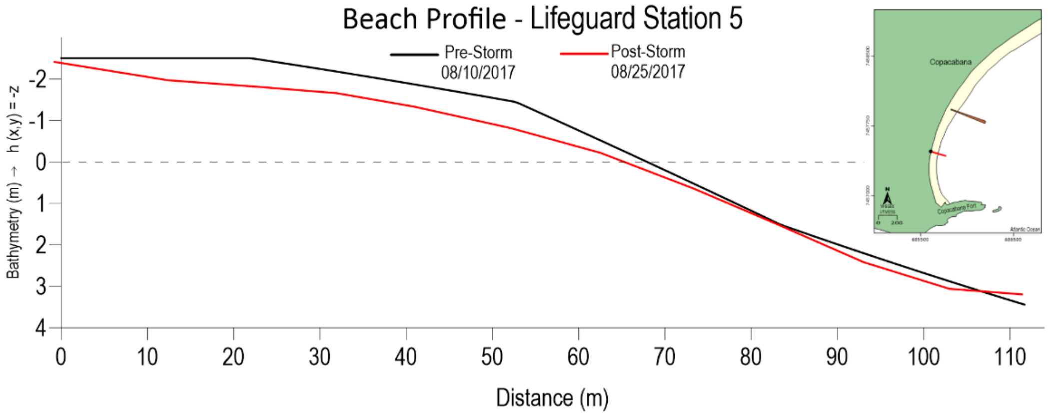

Figure 9: Beach profiles for the Projected Scenario, obtained near Lifeguard Station 5.

Figure 10 shows the overlay of bathymetric contours at 0, 2, 4, 6, and 9 meters, with the Current Scenario on the left and the Projected Scenario on the right. In the Projected Scenario, the bathymetric contours exhibit clear stability, indicating the success of the implemented interventions, such as the sediment retention structure and sand replenishment, in preserving the coastline's configuration.

The minimal variations in the bathymetric lines suggest a significant reduction in the erosive processes that are more pronounced in the Current Scenario. This stability is essential for mitigating coastal retreat, particularly in the southern region of Copacabana Beach, which has historically been vulnerable to erosion.

Conversely, the Current Scenario reveals significant erosion, particularly evident in the 0-meter contour, representing the shoreline. The retreat of the coastline, especially in the southern part of the beach, is largely driven by the persistent southeast wave action, which has exacerbated erosion in this area.

The bathymetric changes in this scenario reflect continuous sediment loss, disrupting the beach's dynamic equilibrium and threatening local infrastructure. The formation of erosive features, such as sandbars and shoreline retreat, underscores the urgent need for coastal protection measures.

These results clearly distinguish the stability observed in the Projected Scenario from the erosion in the Current Scenario, reinforcing the effectiveness of the proposed coastal management strategies. The modeling data provides valuable insights into the beach's morphodynamic behavior and demonstrates the potential benefits of protective interventions. This reinforces the importance of ongoing coastal management practices to address the long-term challenges posed by storm waves and sea-level rise.

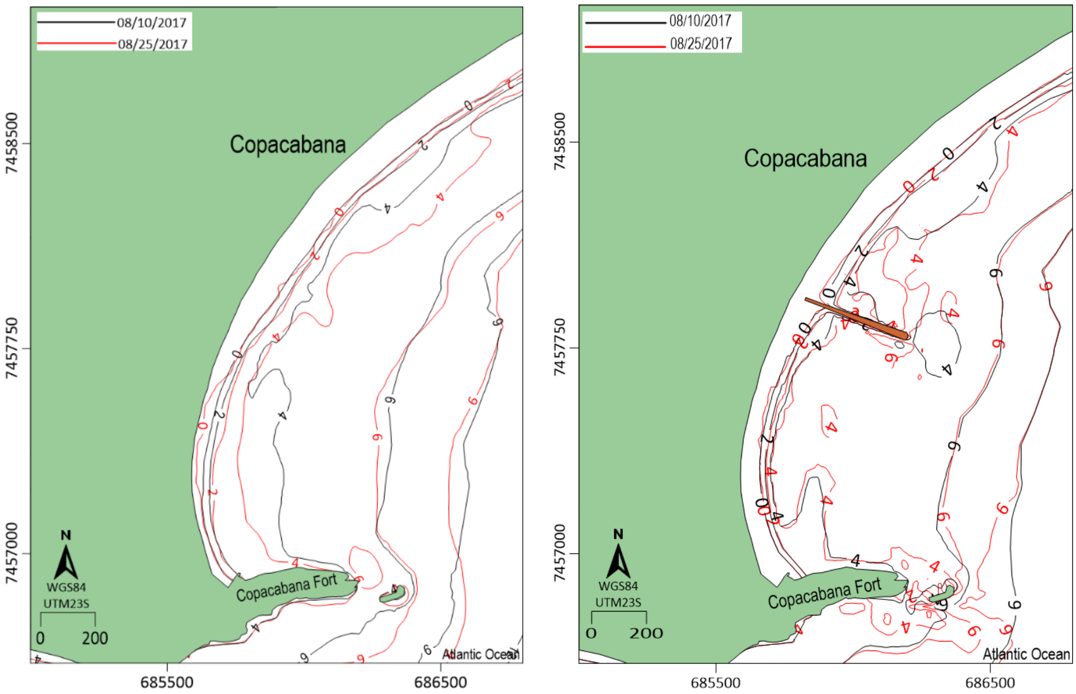

Figure 10: Overlay of bathymetric elevation maps for the Current (left) and Projected (right) Situations.

CONCLUSIONS

This study aimed to enhance the understanding of coastal morphodynamics at Copacabana Beach, focusing on the interaction between natural processes and human activities. The main objective was to analyze the morphological evolution of the beach in response to the construction of a sediment retention structure and the sand replenishment project. Simulations using the SisBaHiA® model were conducted for different scenarios to assess the impact of these interventions.

The results obtained for both the Current and Projected Scenarios provide valuable insights into the morphodynamic behavior of the beach under varying environmental conditions and human interventions. In the Current Scenario, significant coastline variations were observed, with predominant erosion in the southern region and sediment deposition in the central region, particularly after storm events.

This pattern highlights the vulnerability of the southern part of the beach to southeast wave action, resulting in substantial sand loss and presenting risks to local infrastructure and public safety. The results also indicate a long-term trend of coastline retreat in the southern area since the 1970s, contrasting with the slight widening of the central region.

In contrast, the Projected Scenario, incorporating the sediment retention structure and sand nourishment, demonstrated a significant reduction in erosion rates, particularly in the southern part of the beach, leading to coastline stabilization. The deposition of sediments between Forte de Copacabana and the groin, coupled with reduced erosion to the north, suggests that the proposed measures could effectively mitigate erosion and promote beach recovery.

These findings provide a solid basis for the development of sustainable coastal management strategies, showing that interventions such as sand replenishment can help address the erosive impacts of storms and other environmental variability.

The hydrosedimentological morphodynamic modeling methodology proved effective in supporting coastal management strategies and identifying sustainable solutions that align with natural processes. Based on the results, it is recommended to conduct systematic surveys of beach profiles along Copacabana Beach, with sedimentological characterization, at least on a seasonal basis and after major storm events. This recommendation should extend to other beaches in the city of Rio de Janeiro, as such data are essential for model calibration.

Furthermore, a detailed study of the wave conditions resulting from the groin construction is highly recommended. The area near Posto 5 at Copacabana Beach, a renowned surf spot, would benefit from an analysis of wave characteristics to assess the potential impacts on surf conditions. Correlating these characteristics with the morphodynamic model will provide valuable insights into whether the project will have favorable or unfavorable effects on surfing, ensuring that surfing and bodyboarding activities continue to be practiced safely and sustainably.

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