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Wave Attenuation and Shoreline Protection by a Fringing Reef System

Atenuação de Ondas e Proteção à Linha de Costa por um Sistema de Recife em Franja

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Resumo

Conhecimento sobre dinâmica costeira é essencial para tomadas de decisão baseadas em evidências, no entanto esse tipo de informação ainda é escasso, particularmente em áreas com recifes de coral e outros ecossistemas complexos. O objetivo deste estudo foi contribuir para o entendimento de atenuação de ondas e proteção costeira em momentos distintos por um sistema de recife em franja em um arquipélago do Atlântico Sudoeste. As direções predominantes de ondas offshore foram ESE, SE, E and SSE. Os recifes de coral mostraram alta eficiência em reduzir a altura de ondas incidentes mesmo em condições energéticas durante marés altas. Focos de erosão ao longo do arquipélago foram associadas a correntes de retorno, que eram muito débeis ou até ausentes durante as marés baixas. A conservação dos recifes de coral é essencial para manter a proteção à linha de costa e informação sobre a geomorfologia dos recifes deveria ser incluída em protocolos de monitoramento.
Palavras-chave: clima de ondas; recifes de coral; atenuação de ondas; SMC-Brasil

Abstract

While knowledge on coastal dynamics is essential to guarantee well-informed decision making, information is still scarce, particularly regarding areas with the presence of coral reefs and other complex ecosystems. The objective of the present study was to contribute towards the understanding of wave attenuation and shoreline protection at different tide moments by a fringing reef system located in a Southwestern Atlantic archipelago. The predominant directions of offshore waves adjacent to the archipelago were ESE, SE, E and SSE. Coral reefs demonstrated high efficiency in wave height attenuation even under higher energy conditions during high tides. Erosion hot-spots along the archipelago were associated with rip currents, which were greatly reduced or absent during low tides. Coral reef conservation is essential to maintain shoreline protection and information on reef geomorphology should be included in reef status protocols to help advance this field of knowledge.
Keywords: wave climate; coral reefs; wave attenuation; SMC-Brasil

1 Introduction

The coastal zone is a highly dynamic environment molded by the action of waves, tides, winds, and also sediment grain size, beach slope, storm surges, presence of geologic features, among others. Coral reefs are an example of a geologic feature that can affect incoming waves and are frequently responsible for the ecosystem service of shoreline protection. However, current literature still lacks comparisons on the capacity of wave energy and wave height attenuation by different reef morphologies (Elliff & Silva, 2017). As indicated by Quataert *et al*. (2015), while some correlations can be made between different morphologies, the biological community, geology and hydrodynamic conditions are extremely variable.

Beaches fronted by coral reefs commonly present more complex topography, which results in wave transformation processes that are also complex, making the role of reef systems unclear regarding coastal morphology (Costa *et al*., 2016). Moreover, as stated by Monismith (2007), since the geometry of reef systems are unlike those of beaches, for example, which are more commonly studied ecosystems, investigations on coral reefs are expected to generate novel insights on coastal dynamics from a more general perspective. Thus, to ensure a reliable assessment of the potential of shoreline protection provided by coral reefs, local studies are necessary especially within an ecosystem-based management framework.

However, high-quality long-term data for coastal dynamics characterization are not always available. In fact, decision-makers and stakeholders of most coastal zones of the world have difficulties in proposing adequate management strategies due to lack of local information (Fernandino *et al*., 2018a). Moreover, with most coral reefs located in developing nations, the study of this ecosystem can become more difficult due to socioeconomic challenges. Thus, the objective of the present study was to contribute towards the understanding of wave attenuation and shoreline protection at different tide moments by a fringing reef system.

2 Materials and Methods

2.1 Study Area

The coastal Archipelago of Tinharé-Boipeba was used as a case study to better understand the role of the existing fringing reef system in coastal dynamics and shoreline protection. This Southwestern Atlantic archipelago is located in the state of Bahia, Brazil, along a stretch of coastline known as Costa do Dendê (Figure 1). The archipelago is inserted within a mosaic of environmental protected areas and is classified as a sustainable use conservation unit.

However, with increasing pressure from the growing tourism industry and poor coastal management, the archipelago experiences several environmental conflicts, such as the presence of oil residue on beaches, marine litter, decline of coral reefs and coastal erosion. Silva *et al*. (2009) evaluated the environmental sensitivity of the beaches of the archipelago towards coastal erosion and identified that most of the shoreline of both Tinharé and Boipeba islands are highly sensitive to erosion, a concerning situation for a community that deeply relies on coastal tourism for revenue. Dominguez & Corrêa-Gomes (2011) also identified important erosion hot-spots, particularly in the most populated areas of the islands.

The coastline of the whole region in which the archipelago of Tinharé-Boipeba is inserted is highly indented. Silva *et al*. (2009) explain that the current configuration of the region is related to the geological inheritance of the Camamu Basin, through the Mesozoic sedimentary rocks of the area, and to the marine regression and transgression events that occurred during the Quaternary, which formed Holocene and Pleistocene marine terraces. Cliffs, which measure between 5 and 80 m in height, are formed by the outcropping of sandstones and limestones of the Camamu Basin itself and are mostly undergoing a retreat process, leading to the formation of small coves and pocket beaches (Silva *et al*., 2009). Marine regression and transgression events also defined the archipelago's characteristically truncated coral reef tops, which were formed during the last of these regression events and led to the formation of channels and tide pools.

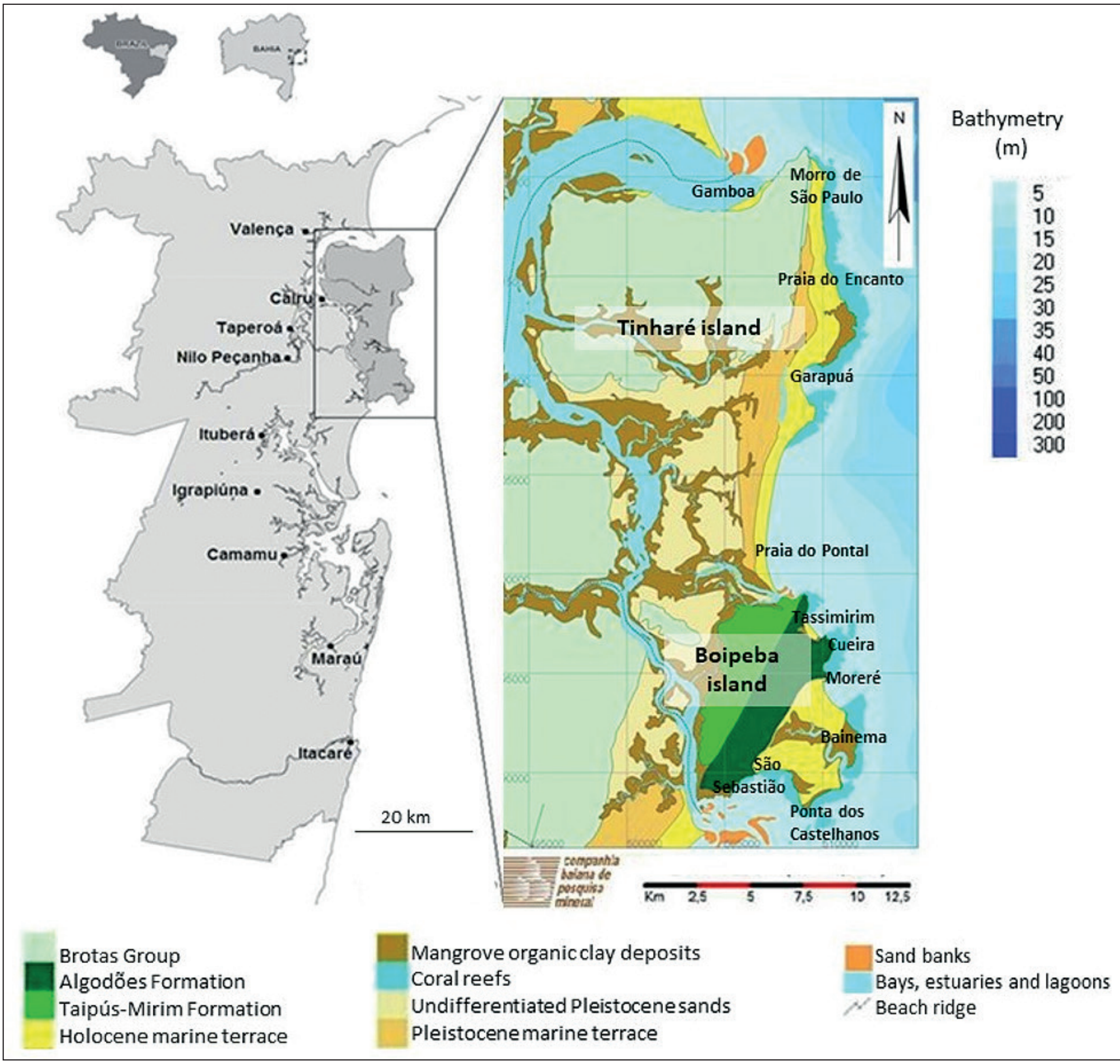

Figure 1 Location and geology of the Archipelago of Tinharé-Boipeba (modified from Dominguez & Corrêa-Gomes (2011)). Located on the coast of the state of Bahia, the municipality of Cairu encompasses this coastal archipelago. The islands contain high geodiversity and are located on the narrowest part of the Brazilian continental shelf. Fringing coral reefs border most of the two largest islands, Tinharé and Boipeba. This coastal area is an important tourist destination, with the main visited sandy beaches named on the right.

Although the coral reefs of the Camamu Bay, which encompasses the Archipelago of Tinharé-Boipeba, were the first Brazilian coral reefs to be reported in the literature, the region remains one of the least studied areas in the state of Bahia (Leão *et al*., 2003). The coral reefs of the Archipelago of Tinharé-Boipeba are mainly fringing reefs that border the shoreline, with occasional shallow banks and deeper reef banks. The fringing reefs and the adjacent isolated banks are found emerged during low tides, forming natural pools (Elliff & Kikuchi, 2017).

2.2 Coastal Dynamics

Almeida *et al*. (2015) detail how the scarcity of coastal hydrodynamic data has led to the creation of models that can meet this demand, particularly in Brazil with the Brazilian Coastal Modeling System, SMC-Brasil (Sistema de Modelagem Costeira – Brasil). In the present study, coastal dynamics were modelled using SMC-Brasil, which comprises a suite of software and methodologies. As presented by González *et al*. (2016), this free system is the product of a partnership between the Brazilian Ministry for the Environment and the Environmental Hydraulics Institute of the Universidad de Cantabria (IHCantabria), Spain, which sought to provide Brazilian researchers and environmental planners with an instrument to improve coastal zone management, including in face of climate change. SMC-Brasil includes a database for marine hydrodynamics (waves, sea level, bathymetry and coastline) that allows behavioral reanalyses of waves and tides over a 60-year period (1948-2008), with temporal resolution of one hour and grid of 1 km² (González *et al*., 2016).

SMC-Brasil methodology consists on selecting a series of representative cases from the available data on wave climate and propagate the cases from deep water to the point of interest near the coast by means of the maximum dissimilarity (MaxDiss) technique (Camus *et al*., 2011). A detailed description of the tool's framework and functionality can be found in the user's manual, available at <http://smcbrasil.ihcantabria.com/downloads/>.

2.3 Bathymetry

The bathymetry available for the study area in the SMC-Brasil database is a digitized version of Nautical Chart No. 1100 of the Brazilian Navy. To improve resolution, the bathymetric shapefile available from the study conducted by Dominguez & Corrêa-Gomes (2011) was added and bathymetry was also manually corrected to consider the presence and morphology of all major reef banks and fringing reef structures along the studied area. To do so, aerial images from Google Earth Pro were used combined with the coral reef shapefile also made available by Dominguez & Corrêa-Gomes (2011). Mean depth of 0.5 m was attributed to all reefs that are found to be emerged during low tides.

2.4 Wave Climate Analysis

The SMC-Brasil wave database was composed following three steps. The first regarded a global reanalysis, called Global Ocean Waves (GOW), which was carried out for the C3A project (Project on Coastal Climate Change Impacts in Latin America and the Caribbean) of the United Nations Economic Commission for Latin America and the Caribbean (CEPAL). The second step was to perform the downscaling of the GOW data for the Brazilian coast. This was carried out by applying the Simulating Waves Nearshore (SWAN) model, adding more detailed bathymetry (nautical charts) and regional wind data. The reconstructed wave series generated through this methodology were named Downscaled Ocean Waves (DOW) (Camus *et al*., 2013). These two steps are embedded within the SMC-Brasil framework, but to apply them to a given study area, they must be transferred to the coast with greater spatial resolution.

Step three of this methodology regards this aspect and is case-specific, since wave transference is greatly influenced by the local characteristics of each area, particularly bathymetry (Camus *et al*., 2013). As described by Almeida *et al*. (2015), for this analysis of wave climate in a given study area, a DOW point located preferably beyond the continental shelf should be selected. The wave climate characteristics of this DOW point analysis are used to create a set of representative cases of mean and more energetic conditions. The parameters of each case were wave height (Hs), peak period (Tp), mean direction (θm), peak enhancement factor (γ), and angular dispersion (σ). Based on these values, the cases were then used to establish grids for the transference of wave propagation to the shoreline, according to the most frequent wave directions observed. Wave propagation was conducted through the OLUCA-SP model, which is included within the SMC-Brasil framework. As described by González *et al*. (2007), OLUCA-SP is a weakly nonlinear model that combines refraction and diffraction, including the effect of shoaling, energy dissipation through bottom friction and wave breaking, and interactions between waves and currents. Cases were modelled in each grid designed for mean and more energetic conditions, considering low, mean and high tide values, to obtain coastal wave climate and wave-induced current patterns.

3 Results

3.1 Wave Climate of the Selected DOW Point

The predominant directions of offshore waves adjacent to the Archipelago of Tinharé-Boipeba were, in decreasing order, ESE, SE, E and SSE. Most waves originated from ESE (60.11%), but the most energetic sea conditions, represented by the highest values of Hs12 and Tp12 were recorded for waves originating from SSE, which are associated with cold fronts reaching the area. The months of December, January and February (austral summer) presented the greatest occurrence of waves with lower heights, while the months of June, July and August (austral winter) showed higher occurrence of larger waves.

The combined distribution of wave height and peak period (Hs-Tp) analysis showed that the mean and most frequent waves occurring in the offshore area adjacent to the archipelago measure between 1.1 m and 1.8 m and have peak periods between 6 s and 8 s. Moreover, the return period was also calculated for the offshore waves to account for episodic events. While the most probable energetic Hs12 value observed was 3.25 m, there is a chance that every 10 years the area will experience waves with up to 3.5 m in height, and that once every 25 years there could be waves measuring up to 3.8 m.

3.2 Wave Climate on the Coast

Wave climate during mean conditions and extreme conditions was similar along the coastline, with the main difference being the height and period of incoming waves. Waves from a general eastward direction suffer little diffraction along the reefs, reaching the shoreline at an almost perpendicular angle due to refraction. The coral reefs at the southernmost portion of the island of Boipeba create a protected area adjacent to São Sebastião in these conditions.

When considering waves originating from a general SE direction, the scenario changes. The southernmost area of Boipeba, that was protected from waves incoming from E, became more affected. The coral reefs in this area cause diffraction and waves reach the shoreline at an angle, leading to longshore drift. However, in this scenario, other areas become sheltered from incoming waves due to the presence of coral reefs, such as Garapuá and Moreré. Waves suffer diffraction also across the long open sandy beach stretch in the center-southern portion of Tinharé and reach the coast perpendicularly.

Wave heights reaching the shoreline were affected both by the conditions of these waves (mean or more energetic) and by the tide. As expected, waves in storm surge conditions are larger and can reach the shoreline with more energy. However, the fringing reefs bordering the archipelago form a natural storm barrier and, as the first obstacle to encounter the waves, lead to the attenuation of both wave energy and wave height. The ability to provide this ecosystem service varied according to the tide: during low tides the top of these reefs are emerged and completely block incoming waves, while during high tides reefs are less able to attenuate wave energy and height since they are completely submerged. However, even in more energetic conditions during high tides, the coral reefs of the Archipelago of Tinharé-Boipeba were able to decrease wave height from over 2.5 m to under 0.5 m (Figure 2).

Wave induced coastal currents were found to be stronger over areas occupied by the reefs, since wave breaking occurred in this region. Rip currents were observed particularly in areas where coral reefs were present around but not directly in front of the beach, such as in Garapuá and Moreré. However, this phenomenon was either not observed or was less significant during low tides. Currents during mean tide levels reached greater velocities when compared to high and low tides within the same case analyzed. Moreover, the strongest currents were caused by southeastern waves during storm surge conditions.

4 Discussion

The presence of a fringing reef system along the Archipelago of Tinharé-Boipeba had an important influence on the coastal dynamic processes analyzed in the area. Coral reefs were particularly relevant regarding wave height attenuation to the shoreline. Despite a broad range of empiric observations, there are still few direct scientific data regarding effective shoreline protection by coral reefs, as indicated by Reguero *et al*. (2018).

Costa *et al*. (2016) analyzed the influence of reef geometry in wave attenuation at another Brazilian reef. These authors identified that reefs located on the continental shelf could reduce up to 67% of incoming wave energy, while fringing reefs reduced up to 99.9% during low tides. Although wave attenuation was not analyzed in a quantitative manner in the present study, the results of Costa *et al*. (2016) agree with the present findings, which showed high efficiency of wave height attenuation by fringing reefs, even under more energetic conditions.

An important reef attribute for wave energy dissipation is friction over the reef flat (Quataert *et al*., 2015). While SMC-Brasil does consider friction in general, the model is not prepared to evaluate friction at the level of reef rugosity. In fact, as indicated by Hearn (2011), important developments in the field of reef hydrodynamics modelling considering measured roughness maps should become available over this decade. Thus, a more thorough quantitative analysis of shoreline protection in the area could build on the results of the present study and add information regarding reef rugosity and detailed geometry as new technologies become available for this and other study areas.

Lack of interdisciplinarity is also an issue regarding better understanding of this complex ecosystem. While important efforts to assess reef health status such as the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocols are tools used worldwide by the coral reef scientific community, they do not include the survey of geomorphological parameters such as rugosity, roughness and detailed dimensions of the reef studied. If global protocols included this type of information, reef hydrodynamic modelling would be able to advance greatly.

As previously stated, most coral reefs are located in developing nations, which poses logistic and financial difficulties for field surveys. Nevertheless, local information is necessary and "one-size-

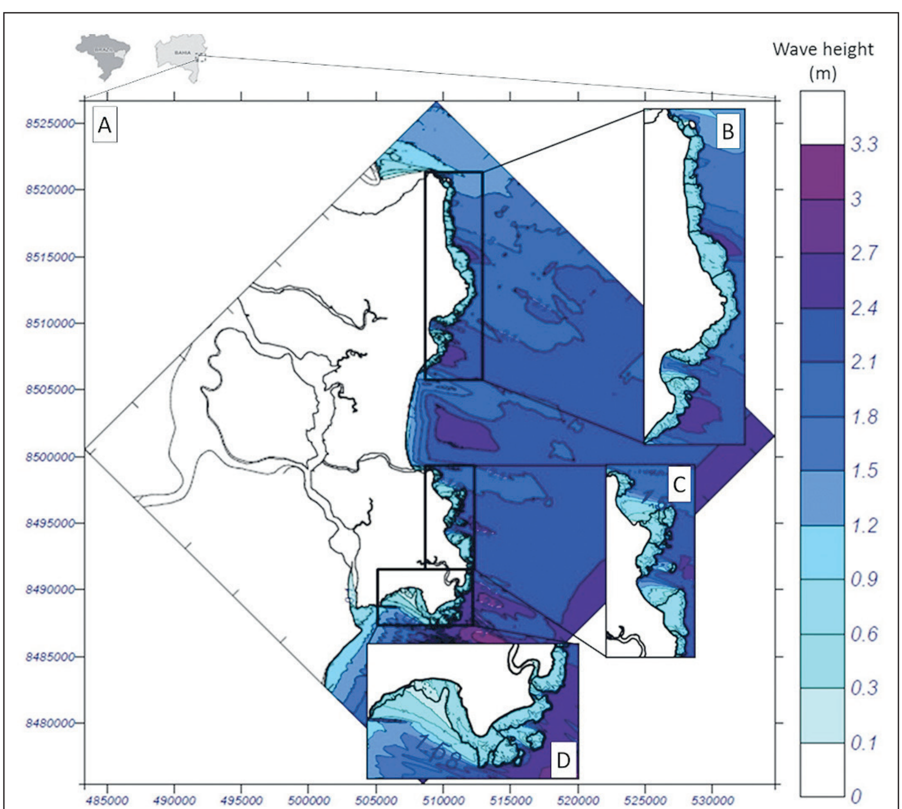

Figure 2 A. Overview of wave heights in more energetic conditions during a high tide in the Archipelago of Tinharé-Boipeba, in which coral reefs (black outline adjacent to the shoreline) promote a considerable reduction; B. Fringing coral reefs extending from the densely populated area of Morro de São Paulo until the cove of Garapuá efficiently decreasing wave height; C. The northern portion of the island of Boipeba, where most inhabitants of this island are located, is protected directly by fringing and patch coral reefs and indirectly by the shadow zones they create; D. The southernmost area of the archipelago also presents an important shadow zone created by the attenuation of wave height by the coral reefs.

fits-all" approaches should be avoided. For example, Monismith (2007) identified that most scientific efforts towards understanding colony-scale hydrodynamics, which is crucial in the study of reef rugosity, has concentrated on branching corals. However, if we consider the case study presented herein, most of the relevant reef-building coral species in the area are massive in form (e.g. *Mussismilia hispida, Siderastrea stellata, Mussismilia braziliensis*, Leão *et al*., 2003). Therefore, there are still many questions about the interaction of Brazilian coral reefs in general with hydrodynamic parameters. Moreover, as discussed by Ruckelshaus *et al*. (2015), local scientists are in fact the best equipped actors to guarantee the longevity of a study, especially one that requires frequent field visits and eventual adjustments to fit local reality. Thus, international efforts should always include training opportunities that can allow locals to take ownership over the projects developed, ultimately honing a sense of belonging and will to carry on the work that has begun.

Still regarding the dangers of generalizing information, while the fringing coral reefs of the present case study were shown to efficiently decrease wave height and wave energy, the Archipelago of Tinharé-Boipeba presents important areas under coastal erosion (Silva *et al*., 2009; Dominguez & Corrêa-Gomes, 2011). Although it may seem contradictory that a coastline bordered by coral reefs with the capacity to offer shoreline protection is under erosion, this is not an isolated finding (Fernandino *et al*., 2018b). As discussed by Costa *et al*. (2016), the combination of widespread coral reef degradation and sea-level rise can increase wave transmission over a reef system, leading to coastal erosion. Reguero *et al*. (2018) also observed that shoreline erosion increased in Grenada possibly due to coral reef degradation. The results of the present study indicated that most of the areas under erosional processes were associated with rip currents, which could be an indication that the presence of reef structures can cause an intensification of wave-induced coastal currents, increasing sediment transport. Moreover, the archipelago presents several areas of inadequate human occupation, as reported by Silva *et al*. (2009), which has led to sedimentary imbalance.

There is a clear demand for more detailed studies regarding shoreline protection delivered by coral reefs, particularly considering the relevance of this service in face of climate change scenarios (Spalding *et al*., 2014; Reguero *et al*., 2018). However, studies should also investigate the interaction among reef attributes, hydrodynamic aspects of the adjacent marine environment and the relevant benefits delivered to society. Although SMC-Brasil is not currently able to simulate all hydrodynamic processes involving reef systems, the framework allows a rapid and relatively simple qualitative evaluation of wave and current patterns in a given area, which improves access to information and can help researchers and decision-makers develop better evidence-based strategies for coastal management.

5 Conclusions

This was the first application of SMC-Brasil to assess the capacity of wave attenuation by coral reefs. Moreover, coastal modelling systems had not been used in the study site at this level of detail so far, and fringing reefs have so far been less studied regarding coastal dynamics. Generalizations and lack of interdisciplinarity were found to be limiting factors for this type of study. This issue should be addressed in other sites worldwide to improve the application of coastal modelling tools, particularly for management purposes. Identifying the potential benefits provided by natural systems has numerous advantages and can serve as a stepping stone to reach adequate ecosystem-based management strategies to deal with issues such as the coastal erosion observed in the Archipelago of Tinharé-Boipeba.

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