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High-resolution optical remote sensing geomorphological mapping of coral reef: Supporting conservation and management of marine protected áreas

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ABSTRACT

Brazilian corals are unique ecosystems with high endemism and low functional redundancy. Hence, mapping its geomorphology is an important step to inferring analyzes on benthic habitats. We observe several difficulties during this mapping of coastal areas by remote sensing and a lack of fine-scale depth data for reef areas in Brazil. The present study aims to present the bathymetry extracted by satellite imagery in murky waters using a mosaic of Sentinel-2 images in Google Earth Engine (GEE) calibrated with field samples. We used the satellite extracted DBM to map the bottom geomorphology through BTM (Benthic Terrain Modeler). We then present the first detailed geomorphological map for the largest marine coastal protected area in Brazil- MPA Costa dos Corais. The geomorphological raster was differentiated into seven classes: Flat Plains, Depressions, Gentle Slopes, Slopes, Terrestrial Reef Flat, Reef Flat, and Crest. Altogether, we estimate >275 km^2 of area representing reef structures (coral reef or beachrocks), or about 48% of the total MPA area. Mapping coral reefs can contribute to conservation, particularly in selecting areas for in situ monitoring activities and in prioritizing the application of remedial actions in the event of environmental disasters or threats to coral health, such as oil spills and bleaching episodes. Our findings encourage the applicability of these methodologies in other reef areas and collaborate for the management and monitoring of marine protected areas. In addition, all mapping is available online for any user.

1. Introduction

Coral reefs are among the most important ecosystems on Earth yet are extremely threatened by human impacts. The pressure of climate change and the impacts of human activities in coastal areas are aggravating factors for the conservation of coral reefs (Lyons et al., 2020, Sagar et al., 2020, Burke et al., 2011, Foo and Asner, 2019, Hughes et al., 2003, Moberg and Folke, 1999, Purkis, 2017, Roelfsema et al., 2018; Pereira et al., 2022a, 2022b). Therefore, remote sensing (e.g. satellite imagery) emerges as a solution capable of providing crucial information for the optimization of environmental monitoring of coral reefs worldwide (Carlson et al., 2019; Foo and Asner, 2019; Purkis, 2017). High resolution mapping of shallow bathymetry is fundamental for the identification and characterization of coastal environments (Kutser et al., 2020; Li et al., 2021; Roelfsema et al., 2018), providing basis for mapping and monitoring benthic habitats, tracking fishing activity, planning actions in situations of environmental disasters, maritime operations and transport (Erdey-Heydorn, 2008, Goes et al., 2019, Li et al., 2019, Rajendran et al., 2021, Xu et al., 2020, Zhao et al., 2014).

Several methodologies have been developed to derive satellite bathymetry using a wide range of sensors with low spatial resolution (>30 m) and images typically used for terrestrial studies (Alves et al., 2018; da Silveira et al., 2020a, 2020b; Hedley et al., 2018; Li et al., 2019; Suggett et al., 2012; Vargas et al., 2021). Low spatial resolution sensors can lead to uncertainties in the land-water boundary and in the perception of features. In addition, they may have a low temporal frequency, resulting in a low supply of cloudless images, especially in tropical coastal regions (Li et al., 2021; Purkis, 2017). In Brazil, other factors may limit the

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extraction of bathymetry by satellite, such as the high turbidity of coastal waters (Suggett et al., 2012) - limiting satellite mapping only to the period from late spring to late summer in the Southern Hemisphere, as well as by the scarcity of data on the physical conditions of the water column for modelling purposes. This limitation arises from attenuation processes in the atmosphere before and after light interacts with seawater. These processes are disruptive, interfering with information from the water column and not containing information about water.

Masses (Hill and Loder, 2013), which are fundamental to the process of establishing bathymetry. The most important interaction processes are those that occur at the water surface, specular reflection of direct sunlight (sunglint) or diffuse light from the sky (skyglint), and those that occur due to radiation from the water body resulting from the interaction of light with the aquatic environment, which is influenced by the effects of interaction with the various constituent particles such as dissolved organic matter, phytolactone, and suspended sediments (Barbosa et al., 2019; Bukata et al., 1995; Eugenio et al., 2015).

Shallow water bathymetry is fundamental for the characterization of geomorphology. Mapping reef ecosystems helps understanding the morphological organization of coral colonies, zoning areas of accumulation and removal of sediments, recognition of shallow lagoon flat top zones and preferential current paths (Greene et al., 1999; Harris, 2012; Araujo and Seoane, 2016; Harris et al., 2018; Ferreira et al., 2012). Through geomorphology, we can advance to the mapping of biological communities and, consequently, in ecosystem understanding, from the association of ecological niches of animals and plants with geomorphologically distinct areas (Harris and Baker, 2012; Heyman and Wright, 2011). Similarly, several studies have applied geostatistical methods to examine the relationship between physical parameters (relief) and seafloor biological features to define habitats with similar relief characteristics, such as flat areas, slopes, caves, and depressions, allowing association with distribution patterns of communities and species. (Brown et al., 2011; Lecours and Espriella, 2020; Menandro et al., 2020).

Several methods are used to study the structural complexity of coral reefs at different scales, such as transect methodology (e.g. Reef Check) and optical remote sensing. The transects are used to estimate the terrain roughness index (benthic cover) or to characterize the fish community (Hill and Wilkinson, 2004; Pereira et al., 2022a, 2022b). Transects are line segments marked with a tape measure that are established at a constant depth range below a reef habitat (reef crest, reef slope, reef wall, fringing reef leeward, fringing reef seaward, lagoon, and reef flat). The 20-m section will be divided into 5-m (more or less) bottles to create independent transect replicates (Hill and Loder, 2013). Optical remote sensing in coastal areas can be used to study landscape ecology, bathymetry, and bottom types and map the structural complexity of coral reefs (Hedley et al., 2016; Roelfsema et al., 2018; Wedding et al., 2019; Lyons et al., 2020). Despite the multiple possibilities of remote sensing, its usefulness may be limited by environmental conditions such as the presence of clouds, suspended sediments and depth (Li et al., 2021; Li et al., 2019; Hedley et al., 2016). Thus, the various methods available have their limitations in terms of sample size and environmental factors. Therefore, they must be used in a complementary manner or in accordance with the specific objectives of each mapping scale.

In addition to the challenges inherent to remote sensing in coastal waters and mapping large regions, in Brazil there is little investment in hardware and software for digital image processing at universities, and the revisit times of satellites in the territory are longer compared to countries that develop orbital sensors. Inspired by the mapping carried out by the Allen Coral Atlas initiative and aiming to overcome our challenges in mapping Brazilian reef areas, we use here the methodology proposed by (Li et al., 2021) to derive satellite bathymetry using the Google Earth Engine (GEE), a cloud-based computer system for processing satellite imagery. In Brazil and in the world, GEE has been used for different types of environmental studies, such as monitoring forests, fires, urban land use and coastal management (de Almeida et al., 2023; Barletta et al., 2022; Bratic and Brovelli, 2022; Chen et al., 2021; Noi Phan et al., 2020; Pontes-Lopes et al., 2022; Roteta et al., 2021; Terres de Lima et al., 2021). Using GEE, we built a mosaic of Sentinel-2 images with low percentages of clouds, sunshine, and other noise. We derived a bathymetry with a spatial resolution of 10 m in shallow marine environments without field data calibration using the methodology of Li et al. (2021) in the Marine Protected Area (MPA) Costa dos Corais region, in northeastern Brazil. After validation with field data (over 33,000 depth measurements), our bathymetry can be used with confidence to depths of up to 32 m. We also can associate several methodologies in the mapping of coral reefs, as in the present study, which used the bathymetry extracted by remote sensing with the Benthic Terrain Modeler (BTM) in ArcGIS to map the geomorphology.

BTM is a suite of tools hosted on ArcMap (ESRI) that performs semi-automatic seafloor classification by combining depth, slope, and wide and fine-scale bathymetric position index (BPIs) information. BPI was derived as a measure of where a georeferenced location, with a defined elevation, is relative to the overall landscape. The derivation involves evaluating the mean elevation differences between a focal elevation of the surrounding cells and a user defined circle (Lundblad et al., 2006), to identify benthic zones based on an area-specific classification dictionary (Walbridge et al., 2018). There is no generally applicable approach to creating a classification dictionary, so it must be created empirically.

For this study, we carried out geomorphological mapping based on the extraction of bathymetry by remote sensing in the coastal region of MPA Costa dos Corais. The mapping of benthic structures is important in ecosystem studies, as morphology directly affects the distribution of benthic communities.

2. Materials and methods

2.1. Study area

The present study was conducted in the largest multiple-use Brazilian coastal MPA (Costa dos Corais, APACC in the Portuguese acronym), created in 1997 to protect coral reef systems on Brazilian waters (Fig. 1). This MPA stretches for 120 km along northeastern Brazil, including two states (Pernambuco and Alagoas) and 12 municipalities. MPA Costa dos Corais covers a large range of different ecosystems, including shallow reefs, mangroves, seagrass beds, rhodolith and sponge beds and mesophotic reefs, extending from the coast to the break of the continental shelf (Pereira et al., 2022a, 2022b). Depth data collection was carried out in 2 (two) no-take zones, Maragogi and Carro Quebrado (Alagoas). No take zones (NTZ, are areas with no human disturbance allowed (no fishing and no visiting) and which only allows research activities (Pereira et al., 2023). The satellite-derived maps cover the entire coastline of the MPA Costa dos Corais up to a depth of 32 m (bathymetric map) and 20 m (geomorphic map). These sites were chosen since they are among the long-term monitoring sites selected by the MPA management team, from among high coral cover areas within the MPA. This study was conducted with the full approval of the Sistema Nacional de Informação sobre Biodiversidade (SISBIO) issued by the Brazilian Government.

2.2. Bathymetry mapping

We used an adaptation of the automatic bathymetric mapping method in Google Earth Engine (GEE) developed by (Li et al., 2021) for different geographic areas of the globe. Bathymetry was generated from a surface reflectance mosaic of Sentinel-2 images for shallow water. Sentinel-2 images have 13 spectral bands with a resolution of 10, 20 and 60 m (European Space Agency, 2012).

According to (Li et al., 2021), we used the QA60 band to exclude pixels with clouds. To mask non-aquatic targets, we apply the Scene Classification map (SCL) band. To avoid selecting images affected by murky waters, sun glint and waves, we used a threshold value in each band (green band >0.01, red border 1 band <0.1, NIR band <0.03,

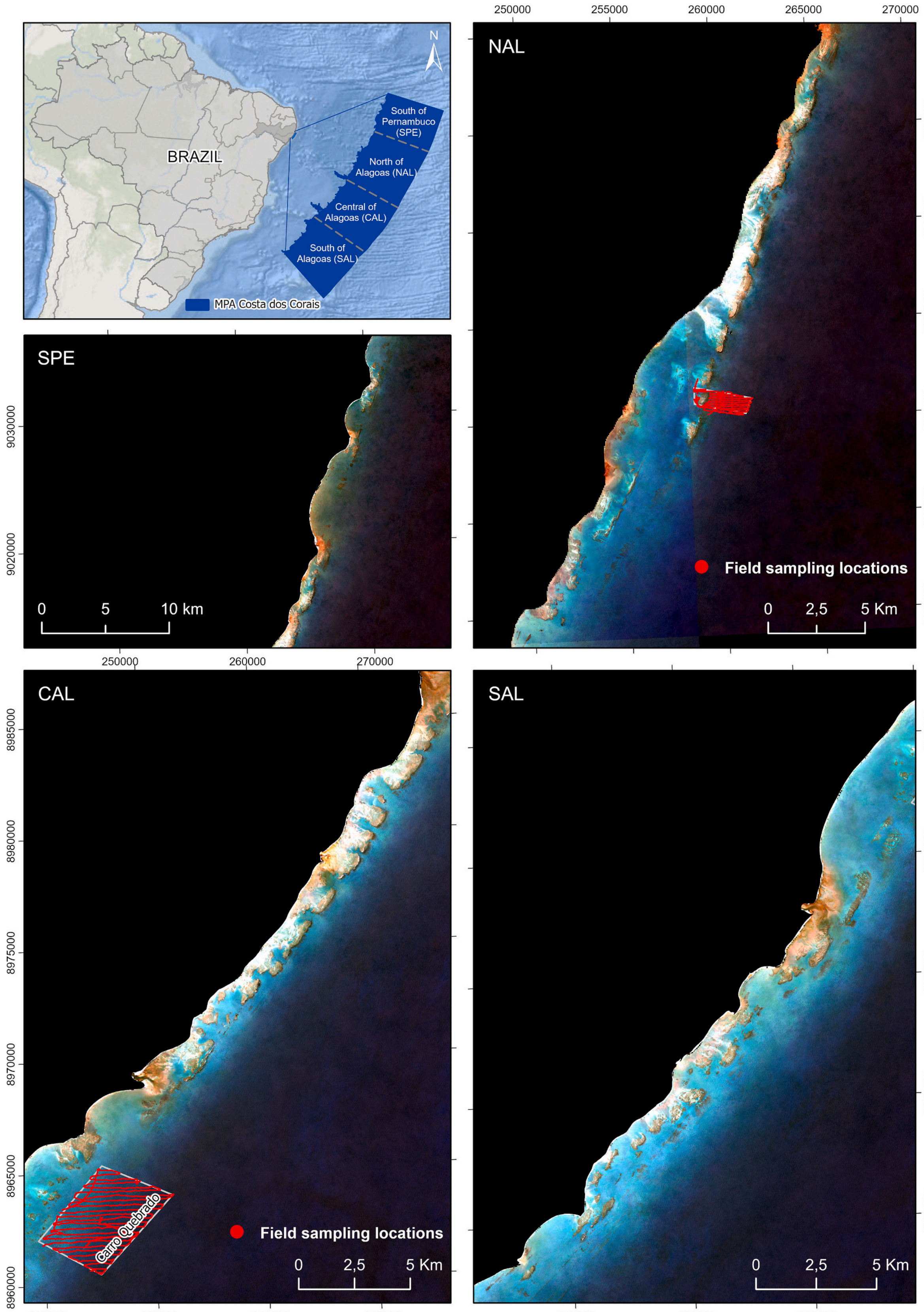


Fig. 1. Study area for bathymetric and geomorphological mapping. Sentinel-2 true color mosaics (24-month mosaic) and field sample locations Maragogi (15.481 points collected) and Carro Quebrado (18.427 points collected). Yellow pixels are no-data areas, mostly located in surf zones or areas above sea level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

0.005 < band of water vapor <0.03), the same way that Li et al. (2021). In addition, we used the normalized difference water index (NDWI) to mask non-aquatic targets, selecting only pixels with positive NDWI values (Gorelick et al., 2017). Where, Green (green band) and NIR (near infrared).

$$NDWI = \frac{\rho(Green) - \rho(NIR)}{\rho(Green) + \rho(NIR)}, \quad (1)$$

Images with low cloud cover, sunglint and water turbidity from January 2018 to December 2019 were selected. Images with low noise content reduce the uncertainties caused by the attenuation of the water column. The water reflectance values in the mosaic represent an average value over time (in our study, 24 months).

According to (Li et al., 2021), from the mosaic surface reflectance $\rho(\lambda)$, we calculate the remote sensing reflectance R_{rs}, as (Vanhellemont, 2019). Where $\rho_m(\lambda)$ is water-leaving radiance reflectances.

$$R_{rs} = \frac{\rho_m(\lambda)}{\pi} \quad (2)$$

Then, we calculate the below-surface remote sensing reflectance ($r_{rs}(\lambda)$) from the $R_{rs}(\lambda)$ to remove the air-water surface effect (Lee et al., 2013).

$$r_{rs}(\lambda) = \frac{R_{rs}(\lambda)}{0.52 + 1.7R_{rs}(\lambda)} \quad (3)$$

To estimate bathymetry in shallow waters, we quantified different levels of attenuation between the blue and green bands, as (Stumpf et al., 2003):

$$Depth = m_0 \frac{ln(1000^* r_{rs} blue)}{ln(1000^* r_{rs} grenn)} - m_1 \quad (4)$$

To calculate the bathymetry parameters (m0 and m1) in the mosaic, we used a fixed value of chlorophyll-a (Chl-a = 0.5 mg m-3), as established by (Li et al., 2021; Li et al., 2019) for other regions of the world. Despite the particularities, the value used for Chl-a is within the average found in Brazilian coastal waters (Kampel et al., 2019).

$$m_0 = 52.073^* e^{(0.957^* Chl_a)} \quad (5)$$

$$m_1 = 50.156^* e^{(0.957^* Chl_a)} \quad (6)$$

On the GEE platform, we generated the final DBM (Digital Bathymetric Model) with a spatial resolution of 10 m. However, with the objective of optimizing the processing of the classification of geomorphological structures, we chose to export it with a spatial resolution of 20 m.

To verify the bathymetry extracted by satellite, we used depth samples collected in the field in the closed areas of Carro Quebrado (Santos, 2021) and Maragogi (Table 1). Depth data were collected from the planning of survey lines with a spacing of 200 m (Carro Quebrado) and 100 m (Maragogi) using a single-beam echo sounder, side scan sonar and GPS (Raymarine Axiom, with RV- 100 All-In-One). In total, we collected 33,908 depth points (Fig. 2). Points have been corrected for tidal effects through the values of the tide table for the days of navigation, published by the Brazilian Navy.

Satellite-derived bathymetry was validated by comparing image values with depth-of-field measurements, applying root mean square error (RMSE) and the coefficient of determination (R^2) to evaluate the results. Subsequently, in the ArcGIS PRO software, we adjusted the satellite-derived bathymetry for the depth of field points through a linear equation.

Table 1
Location of no-take zones and information about depth data collected.

No-take Zone	Latitude / Longitude	Number of Depth Points Collected	Depth Variation (m)
Carro Quebrado	−9,37 / -35,43	18.427	1,77 - 20,62
Maragogi	−9,03 / -35,17	15.481	1,03 - 23,64

2.3. Geomorphological classification

The DBM created from the mosaic of Sentinel-2 images with a spatial resolution of 20 m was used to generate the geomorphological classification using the Benthic Terrain Modeler (BTM) tool of ArcMap 10.8. The geomorphological classification (BTM) is based on the DBM, broad-scale and fine-scale of the Bathymetric Position Index (BPI), and slope. The internal and external radius parameters (Inner and Outer radius) used in Broad-scale and Fine-scale were defined based on the DBM pixel size, as indicated by Lundblad et al. (2006), Table 2. To avoid the autocorrelation observed in elevation data, the Broad and Fine grids were standardized to 1 standard deviation, as indicated by (Weiss, 2001).

A decision table containing the classes and limits was applied to the data to classify the relief structures of the bottom existing in the study area (Table 3). The classes were defined from a literature review involving the main geomorphological mapping research in reef areas or that used BTM (Erdey-Heydorn, 2008; Wienberg et al., 2012; NOAA, 2013; Walbridge et al., 2018; Goes et al., 2019; de Oliveira et al., 2020; Conti et al., 2020; Kennedy et al., 2021; Santos, 2021) see (Supplementary Material). In total, seven geomorphological classes were defined, namely: (ID 01) Flat Plains; (ID 02) Depressions; (ID 03) Gentle Slopes; (ID 04) Slopes; (ID 05) Terrestrial Reef Flat; (ID 06) Crest and (ID 07) Reef Flat.

The slope was used to define the limits of the geomorphological structures between (ID 01) Flat Plains (up to 2 degrees of slope), (ID 03) Gentle Slopes (between 2 and 3 degrees of slope) and (ID 05) Slope (between 3 degrees and 10 degrees of tilt). Studies in areas with wide variation in depth used this information as another class limiter (Erdey-Heydorn, 2008; Walbridge et al., 2018; de Oliveira et al., 2020). In our study, the area is limited to the isobath of −22 m, not presenting a great variation in depth; therefore, this criterion was not used as a limiting factor, as in Goes et al. (2019). The classes were validated by associating the model with photos and videos taken in the field by scientific diving and snorkeling. The study area, MPA Costa dos Corais, will be divided into 4 (four) sectors to compare the bottom geomorphology, they are: South of Pernambuco (SPE); North of Alagoas (NAL); Central of Alagoas (CAL) and South of Alagoas (SAL), Fig. 1.

The methodology is presented in the flowchart below (Fig. 3). Each step is detailed in the following sessions.

3. Results

3.1. Digital Bathymetric Model (DBM)

The mosaic created in the 24-month interval (2018–2019) using the GEE resulted in a final image (Fig. 1) of clear and cloudless waters, low pixels representing crashing waves and sun glare. In total, 254 Sentinel-2 images were used to form the mosaic. Fig. 3 shows a RBG composition (B4-red, B3-blue, B2-green) of the mosaic for the coast of MPA Costa dos Corais. Different types of benthic habitats are discernible, such as coral reefs, hard bottom, beachrocks and sandy bottom, as well as deeper formations, showing the quality of the mosaic. Pixels with no data (in yellow in Fig. 1) are mainly located in surf zones or above sea level.

To analyze the mosaic reflectance, we investigated the surface reflectance values of four typical benthic targets (coral, sand, rubble and seagrass) at about 4 m deep, as well as the ocean reflectance at over 10 m deep (Fig. 4). We sampled each target in the mosaic based on field coordinates in the vicinity of Maragogi. The spectral signature and corresponding values represent reflectance variations in different benthic targets. For instance, sandy bottom had the highest mean value of reflectance, followed by seagrasses, gravel, coral and ocean. We

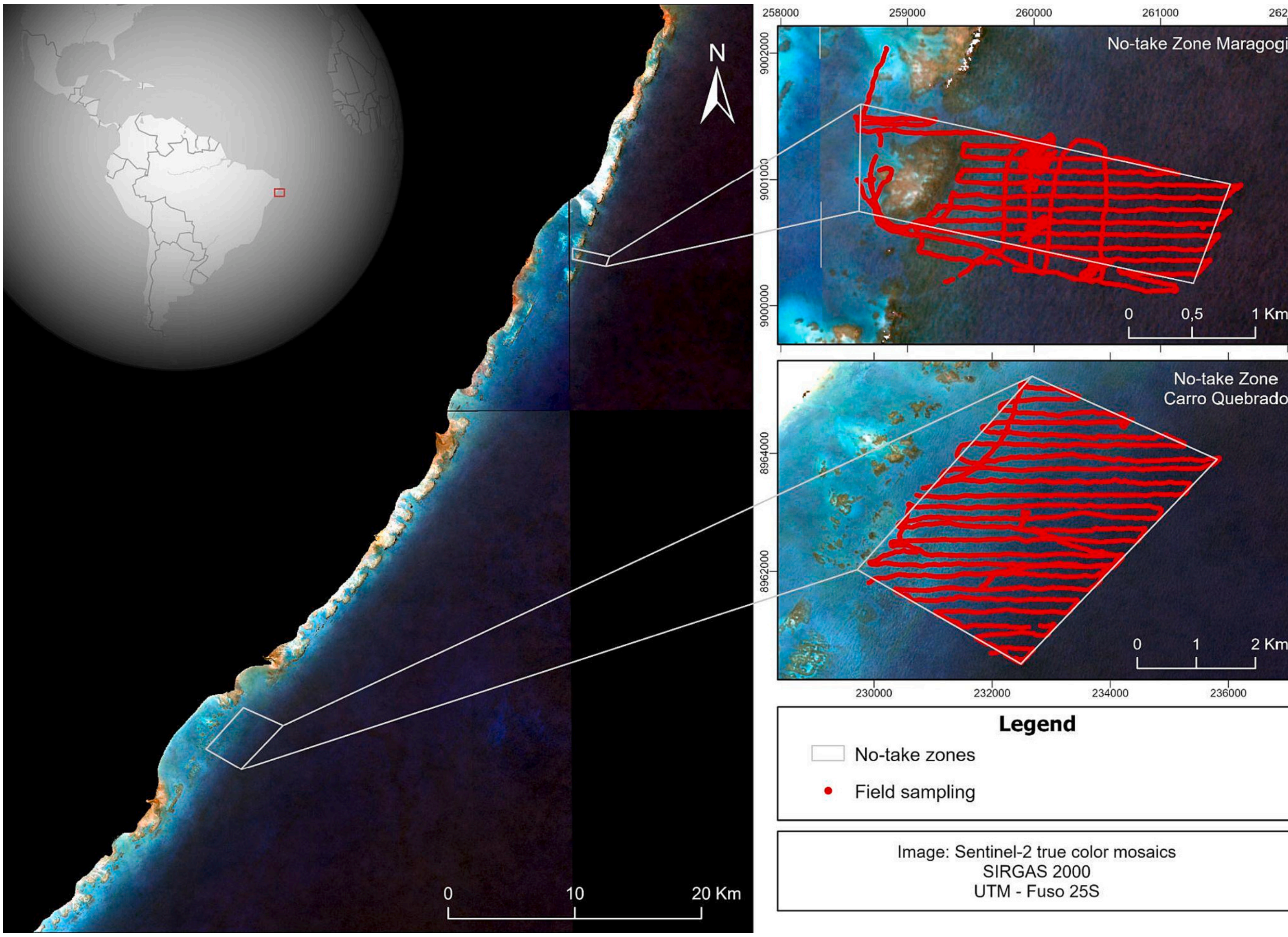


Fig. 2. Sentinel-2 true color mosaic (24-month mosaic) and field sample locations for the two study sites (Maragogi and Carro Quebrado).

Table 2
Values applied to the Inner and Outer radius parameters for Broad Scale BPI and Fine Scale BPI and the automatically calculated values for the Scale factor.

Parameters	Broad Scale	Fine Scale
Inner radius	50	10
Outer radius	500	50
Scale factor	10.000	1.00

Table 3
Decision table with the factors used for the definition of geomorphological compartments in the study area.

ID	Zone	Broad-scale BPI		Fine-scale BPI		Slope (in degrees)	
		Lower	Upper	Lower	Upper	Lower	Upper
01	Flat Plains	−150	150	−150	150		2
02	Depressions	−150	150		−150		
03	Gentle Slopes	−100	100	−100	100	2	3
04	Slopes	−100	100	−100	100	3	10
05	Terrestrial Reef Flat	150		−150	150		
06	Crest	150		150			
07	Reef flat	−100		−100			

observed a decrease in the surface reflectance values of the red bands for NIR was observed in all targets (Fig. 4).

Result of the bathymetry map generated using a 24-month mosaic created in the GEE was also performed (Fig. 5). The DBM showed bathymetry values within the expected spatial pattern, increasing from shallow to deeper water in the direction from the coast to the ocean. This pattern was consistent throughout the MPA Costa dos Corais area.

For example, in Maragogi (Alagoas) in the region close to the no-take area, shallow depths (<5 m) were observed at 500 m, transitioning to medium depths (5–10 m) at a distance from1 to 3.5 km from the coast, followed by a new elevation at 0 m about the crests at the beginning of the no-take area. 4.5 km away from the coast, and seawards, we observe deeper waters (>12 m) up to the limit of the no-take area (see Transect Maragogi in Fig. 5).

Close to the no-take area of Carro Quebrado (Alagoas), we also found the expected depth pattern for the region. Up to 1 km from the coast, the depth goes from 0 to 5 m with an abrupt rise to 0 indicating a reef crest. In the area within the no-take zone of Carro Quebrado, 2.5 km away from the coast, we observe a large extension of reefs emerging interspersed with shallow depressions (5 to 7 m). Average depths (from 10 to 15 m) are observed from 4 to 5 km from the coast, where depths from 15 m to 22 m occur, indicating areas of plains with relative slope (see Transect Carro Quebrado in Fig. 5).

3.2. DBM evaluation

To assess the quality of the DBM, we compared the values of depth from the remote sensing-generated bathymetric map to the depths measured in the field at the 2 surveyed locations (no-take zones Maragogi and Carro Quebrado). We used two error metrics to indicate the differences between satellite-derived bathymetry and depth values

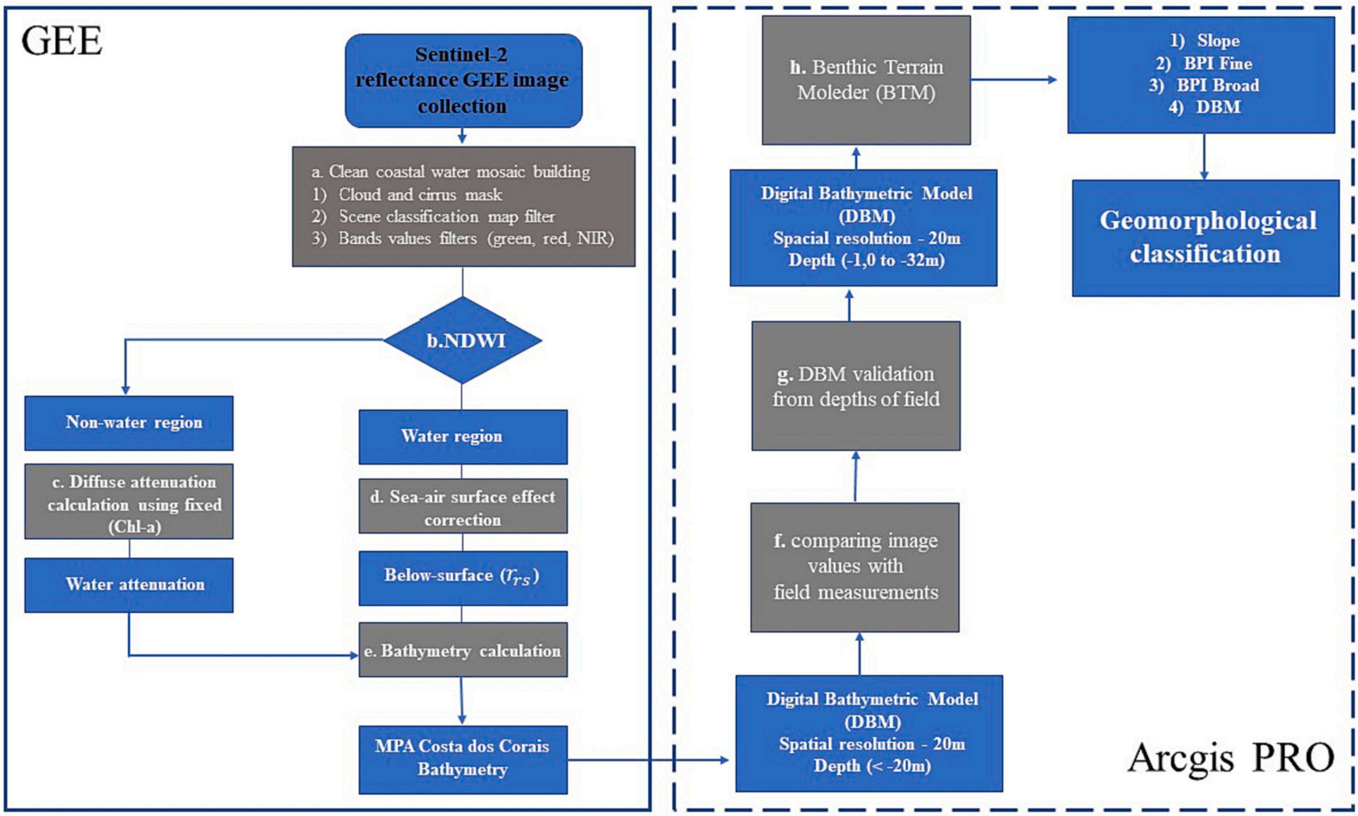


Fig. 3. Flowchart of satellite bathymetry estimation in GEE and geomorphological classification by BTM for MPA Costa dos Corais.

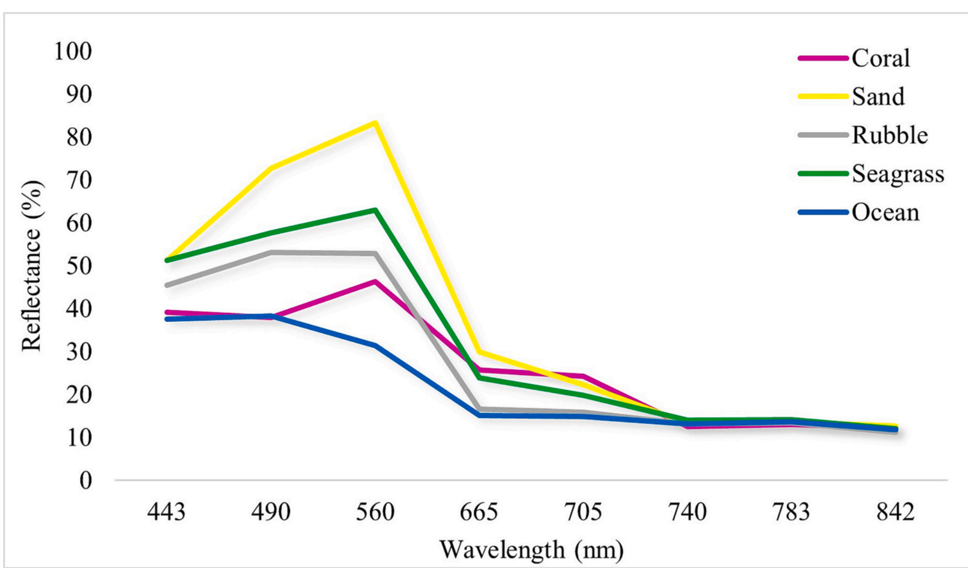


Fig. 4. Surface reflectance plots for different benthic habitats at Maragogi (AL, Brazil).

collected by field echo sounder. The DBM showed a Root Mean Square Error (RMSE) of 6.58 m. We corrected the DBM with a linear equation derived from the comparison (Fig. 6), the RMSE decreased to 2.98 m, further fitting the model. The R^2 value shows a high correlation between the bathymetry derived from GEE and the field measurements (R^2 = 0.70), even before applying the correction.

We also evaluated the performance of the model through different depth ranges (0 to 5 m, 5.1 to 10 m, 10.1 to 15 m, 15.1 to 20 m and > 20 m). Similarly, to the general model, the intervals of 0–5, 5–10, 15–20 and > 20 m presented RMSE with an average of 3.30 m. The 10–15-m interval showed a RMSE 44% lower value when compared to the average RMSE of the other intervals. Overall, the model performs better in shallow water (0 to 5 m, 5 to 10 m) and medium depths (10 to 15 m), and worse in deeper waters (15–20, >20 m). Deep water RMSE values are almost 35% higher than shallow water. Due to the properties inherent in the process of interaction between light and environment in remote sensing, the model is limited in deriving bathymetry in deeper areas.

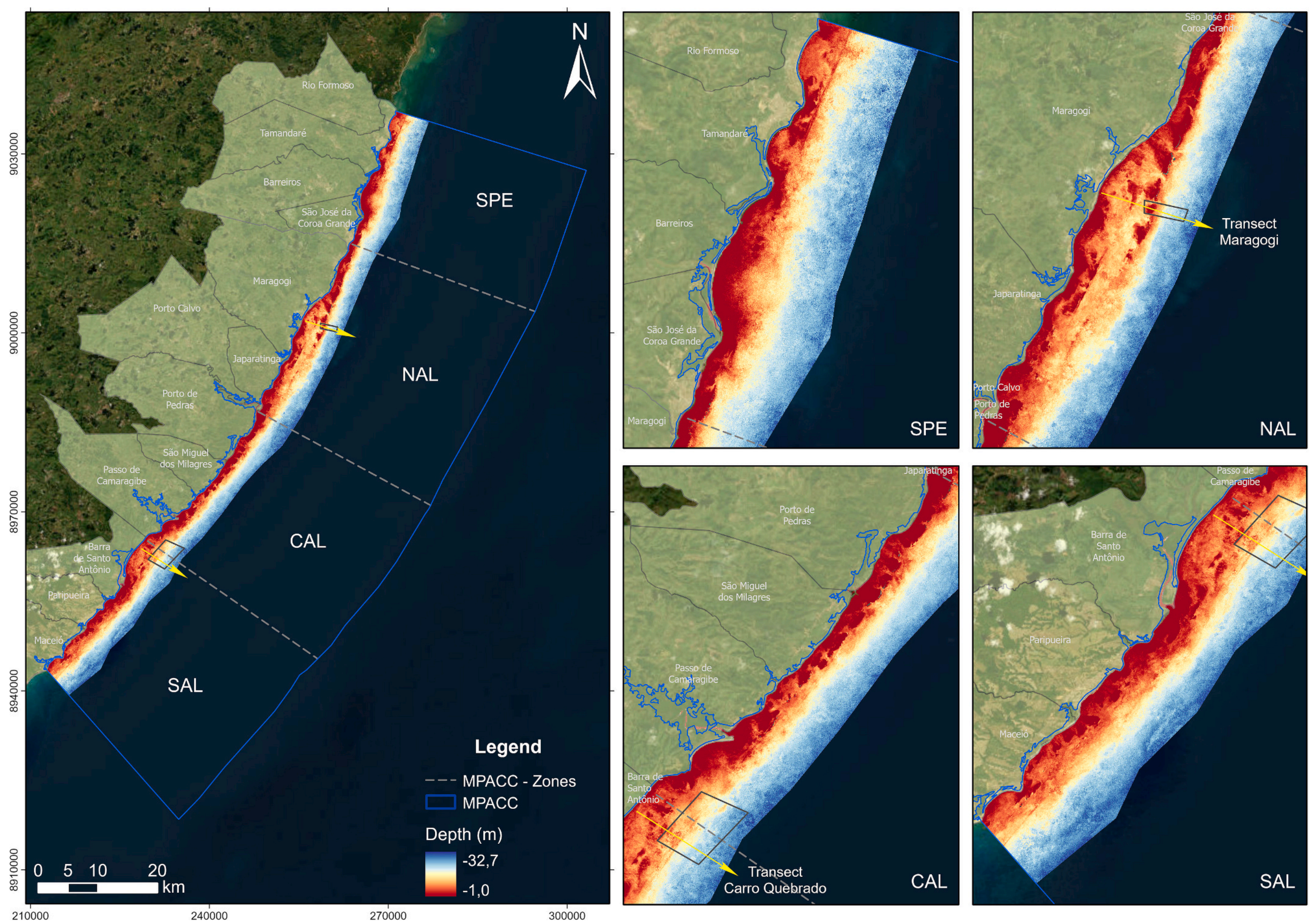


Fig. 5. Spatial variations of shallow bathymetry models created using 24-month mosaics. Zoom of the four sectors of the marine protection área. The bathymetry represents the spatial variation of the benthic geomorphology. Sector ID as in Fig. 1.

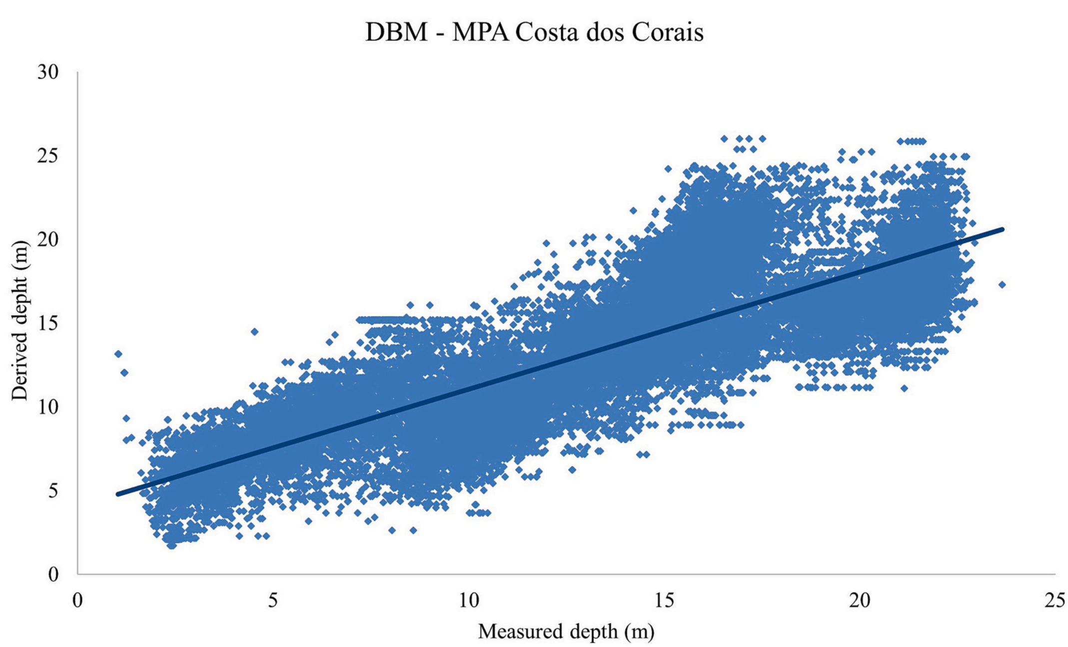


Fig. 6. Bathymetry estimation validation using the field measured depth sampling points.

In addition, we compared satellite-derived depths with values measured in the field along two transects at Maragogi and Carro Quebrado (Fig. 7). These transects traversed different geomorphological regions and background types and therefore provided varied environments for performance testing.

3.3. *Coral reef geomorphology (or benthic structures)*

The first derivative of the satellite generated bathymetry results in a map of the slope of the area, and BPI in broad-scale and fine-scale are calculated. With the bathymetry, slope, BPIs and the decision table (Table 3), we generated a benthic terrain model (BTM) with the geomorphological classification for the study area divided into seven classes (Fig. 8). See the mapping in detail on the online dashboard: (https://jcaon.maps.arcgis.com/apps/dashboards/57158942f9a246e1a0e74e044618c571).

The DBM (Fig. 5) identifies a variety of geomorphological features present along the study area, along about 120 km of coastline. From north to south, the occurrence of different sizes of reef banks, channels, lines of beachrocks (paleolines of beaches) and isolated reefs were interpreted. In the South of Pernambuco (northern part of MPA Costa dos Corais), we observe reef banks next to the coast and prominent lines of beachrocks. In the central portion, the reef banks begin to move away from the coast, increasing in size and depth. Towards the south, it is possible to observe a greater diversity of features, with emphasis on isolated reefs, deeper reefs and elongated lines of submerged beachrocks. As mentioned earlier, the seven classes are: (ID 01) Flat Plains; (ID 02) Depressions; (ID 03) Gentle Slopes; (ID 04) Slopes; (ID 05) Terrestrial Reef Flat; (ID 06) Crest and (ID 07) Reef Flat. Next, Table 4 highlights the main aspects of each class.

We observed divisions of the relief in the different sectors of the MPA Costa dos Corais: in South of Pernambuco there is a predominance of flat reef formations and consequently of the Slope class; in North of Alagoas, we observed a decrease in the Reef Flat class and an increase in Flat areas; on the Central of Alagoas sector, we have the greatest influence of continental drainage, forming large areas of Terrestrial Reef Flats and in South of Alagoas, we observed a large area of flat reef concentrated in deeper areas, and Flat Plains between isolated Reef Flat areas.

No class assigned - This is a class produced by BTM for areas not classified according to the limits established in the decision table (dictionary). The entire unclassified area (3.74%) is located in the deepest region of the DBM (below −22 m). This can be explained by the limit of

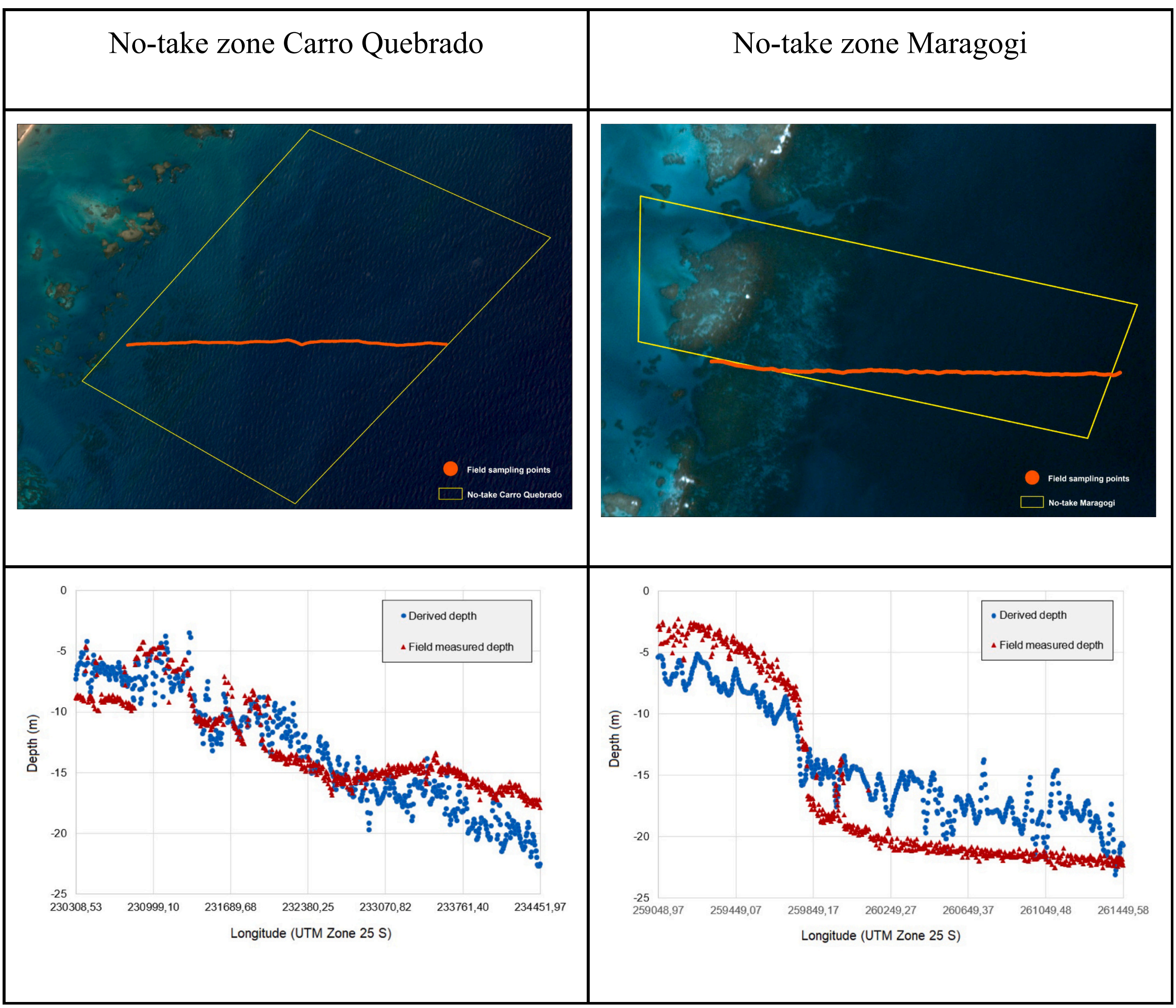


Fig. 7. Comparisons between Google Earth Engine derived depth with field measured depth at Carro Quebrado and Maragogi, Alagoas, Brazil.

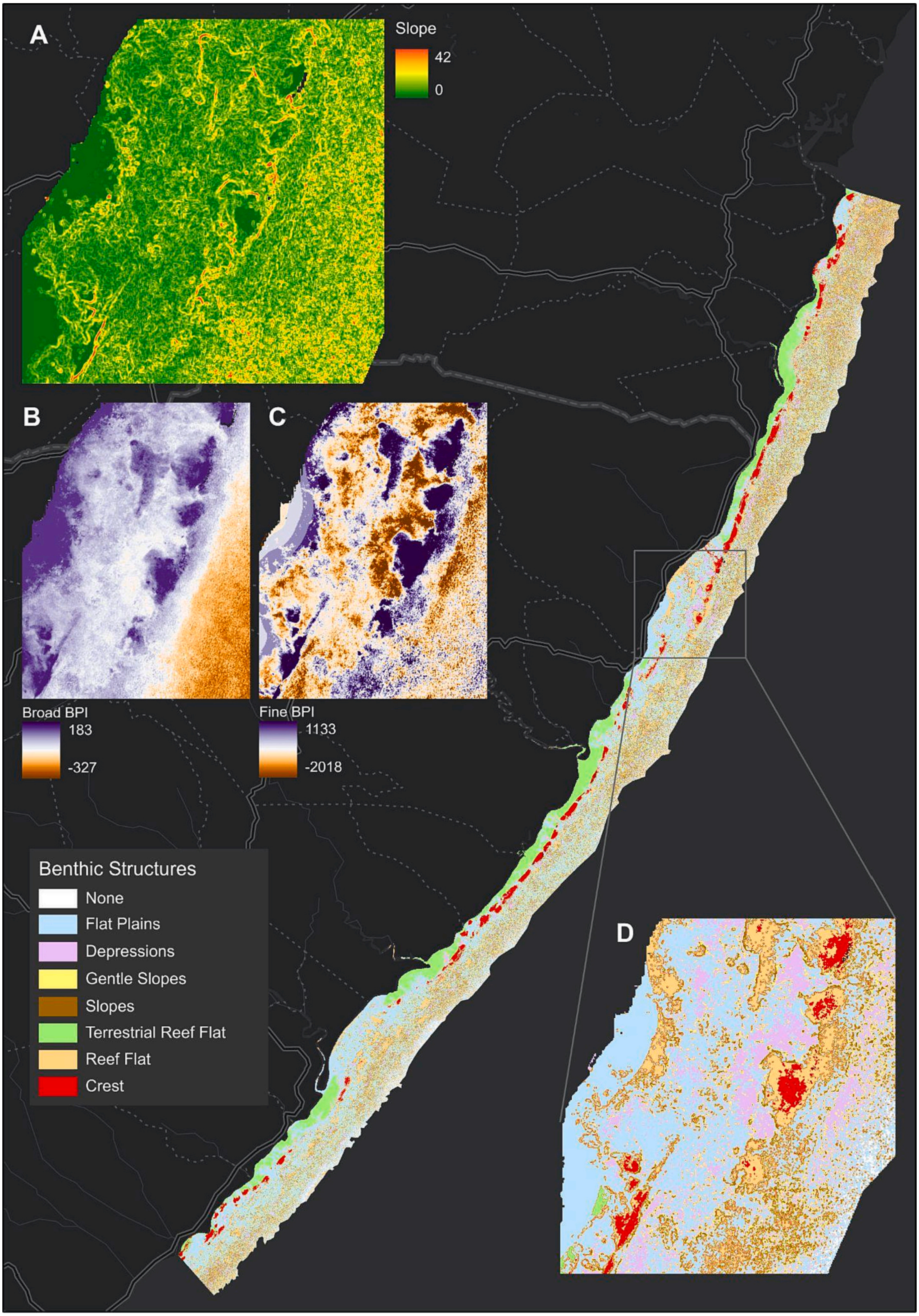


Fig. 8. Map of the geomorphological classification (benthic structures) for the MPA Costa dos Corais region. The highlighted areas are located on the coast of Maragogi (Alagoas, Brazil): (A) Slope; (B) Broad-scale Bathymetric Position Index (Broad-BPI); (C) Fine-scale. Bathymetric Position Index (Fine–BPI); (D) Geomorphological classification of the study area.

Table 4
BTM Classes with respective areas (km^2) and percentagens.

Code	Class/Zone	Area (km^2)	Area (%)
–	No class assigned	21,06	3,74
ID 01	Flat Plains	228,72	40,66
ID 02	Depressions	37,47	6,66
ID 03	Gentle Slopes	66,68	11,85
ID 04	Slopes	67,76	12,04
ID 05	Terrestrial Reef Flat	52,19	9,28
ID 06	Crest	19,58	3,48
ID 07	Reef Flat	69,10	12,28
	TOTAL	562,56	100

the method: without samples depth of field remote sensing bathymetry does not work beyond depths of −20 m (Gao, 2009; Hedley et al., 2018; Hedley et al., 2016).

Flat Plains (ID 01) - The class with the highest occurrence (40.66%), extending throughout the study area, occupying different depths. It is defined from flat regions with a BPI value close to zero. Flat areas are also defined by low slope, that is, slopes between 0 and 2 degrees.

Depressions (ID 02) - They are concave areas on the ground, points of negative bathymetry. They are represented with negative BPI values greater than one standard deviation from the mean in the negative direction, occurring in 6.66% of the area. They are important sedimentation areas, presenting coarser grains (rubble). They are often located at the rear of reef flats.

Gentle Slopes (ID 03) - They are areas of slope between 2 and 3 degrees, without differentiation of concave or convex shapes. They are located between flat areas and on the edge of slopes, occurring in 11.85% of the study area.

Slopes (ID 04) - These are areas of steep slopes, between 3 and 10 degrees, and occur in 12.04% of the total area, located around reef features. Values above 10 degrees were not representative in the study area. The slope limiting values of each class may be different for other study areas, as they are determined from the measured slope.

Terrestrial Reef Flat (ID 05) - This class represents broad, flat and shallow areas in association with fringe reef areas. They are directly connected to the coast and, therefore, subject to the influence of fresh water and continental sedimentation and occur in 9.28% of the area.

Crest (ID 06) - They are represented by elongated shapes, associated with old beach lines (beachrocks) and the top of structures parallel to the current shoreline. They are concentrated in shallower areas, creating surf zones. They occur in 3.48% of the area, located mainly in areas of higher energy.

Reef Flat (ID 07) - Areas of more accentuated relief may have a more elongated body or isolated as pinnacles at greater depths. Normally, they are adjacent to reef crests, occurring in 12.28% of the area.

The size and shape of reef features help determine the geomorphic zone. In this way, the spatial arrangement of the zones can contribute to the understanding of the mapping. The association of geomorphological classes with field images is presented below (Table 5). More photo examples for each class can be found in Supplementary Material.

To estimate the total area of reef structures in each sector of MPA Costa dos Corais and establish the region with the greatest morphological complexity, we considered the sum of the area of the classes: Gentle Slopes, Slopes, Terrestrial Reef Flat, Crest and Reef Flat. Table 6 presents the estimation of complex structures for each sector.

It is possible to notice that the sectors with more complex geomorphology are located in the north of the MPA Costa dos Corais, SPE sectors (71.40 km^2) and NAL (80.30 km^2), followed by sectors with more homogeneous morphology, although with relative complexity, CAL (63.65 km^2) and SAL (59.84 km^2).

4. Discussion

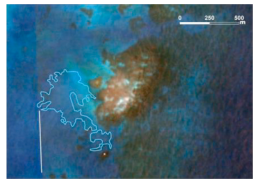
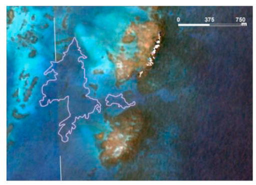
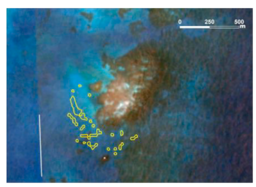
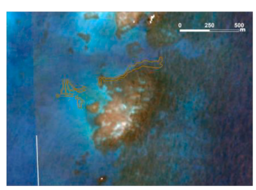
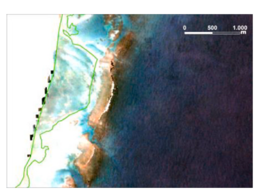
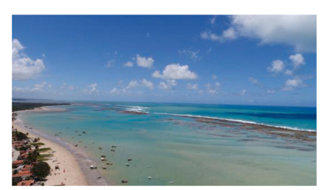
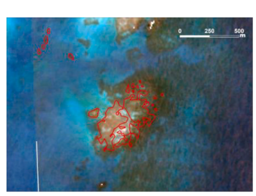
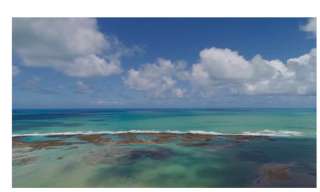
Several studies have proposed the characterization of underwater geomorphology based on the analysis of local bathymetry from different approaches in Brazilian coast and worldwide (Torres et al., 2003; Motoki et al., 2012; Lucatelli et al., 2020; de Oliveira et al., 2020; Ang et al., 2021). In the present study, we went beyond the visual representation of the relief, we used remote sensing to extract the bathymetry and spatial analysis techniques in GIS to better represent the local geomorphology at the largest Brazilian MPA. We consider different morphological descriptors to determine relief zones and structures. This approach is unique and pioneering for the Brazilian reef areas, and through the results, new inferences can be made, such as the benthic classification, classification of geodiversity, distribution of coral cover, biomass estimation, among others. We bring a facilitator guide so that end users (managers, field inspectors, researchers, students, fishermen, tourism agents, and dive operators) can use this spatial information (underwater relief – bathymetry; spatial relief patterns – geomorphology; types of bottom – benthic map) in the monitoring and management of the marine protected area. In addition, we provide online mapping and encourage the application of the methodology in other reef areas.

Freely available bathymetry data for the Brazilian coast have coarse resolutions (Velozo and Alves, 2006; Becker et al., 2009; GEBCO, 2022) making high-precision studies necessary for conservation impossible. Herein, we apply the methodology proposed by Li et al. (2021) to perform automatic bathymetric mapping in shallow water using Sentinel-2 imagery with a spatial resolution of 10 m. Furthermore, we also used Google's platform for digital image processing in the cloud, GEE. We efficiently derived bathymetry for the coast of MPA Costa dos Corais, a region with high biodiversity of benthic habitats, such as coral reefs, and great geomorphological variety. The extraction of bathymetry is necessary for the construction of the Brazilian reef atlas, as it allows specific mappings such as the geomorphological and benthic. We built our mosaic from filtering images over a period of 24 months (January 2018 to December 2019). (Li et al., 2021) achieved excellent results through a 12-month mosaic. Thus, due to the specificities of the South Atlantic coral reefs, such as the high sedimentary input (e.g. river discharge) - the qualitative-quantitative water balance of the Costa dos Corais MPA region is considered highly critical by the Brazilian Water Authority (ANA, 2021). The water balance considers the capacity for absorption of inland organic loads by water bodies, i.e., the rivers of the region are an important source of sediment and wastewater discharges on the coast of the study are) that produces high turbidity in coastal waters. This process may difficult the acquisition of clean images for bathymetry extraction. Furthermore, due to continuous cloud cover, we have increased the time interval for the imagery search. GEE made it possible to use a powerful automatic search tool capable of filtering images without clouds, shadows, sunglint, and breaking waves and water saturated in suspended sediment. This methodology presents itself as an advance for coral reefs studies, mainly due to the reduction of time in the search for the best images and the need for hardware for processing, compared to other bathymetry extraction methods used elsewhere (Agus et al., 2021; Cao et al., 2019; Poursanidis et al., 2019; Vargas et al., 2021).

We have also evaluated the quality of the mosaic from the reflectance value of the different benthic habitats (sand, gravel, seagrass, coral and ocean). As expected, and observed in other remote sensing studies on coral reefs (Garcia et al., 2015; Li et al., 2019), benthic habitats show specific spectral signatures according to their physicochemical properties and depth. This result confirms the efficiency of the mosaic also for mapping benthic habitats. The mosaic created for the MPA Costa dos Corais region can provide highly detailed information for various types of studies in coastal environments, such as bathymetry for mapping and monitoring benthic habitats in protected areas, navigation, and fishing activity. Excellent results for South Atlantic waters were achieved, proving the possibility of the method being applied to other coastal areas of the country.

To validate the bathymetry, we used depth of field measurements collected for two *no-take* zones within the MPA. The selected areas have

Table 5
Representation in clean water mosaic and photographic example of each class.

Zone	Example	Field Photo Example
Flat plains		
Depressions		
Gentle Slopes		
Slopes		
Terrestrial Reef Flat		
Crest		

(*continued on next page*)

Table 5 (*continued*)

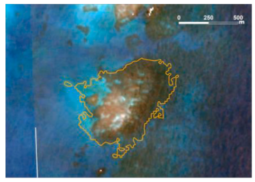
Zone	Example	Field Photo Example
Reef Flat		

Table 6
Estimation of the area of morphologically complex structures.

Zone/Class Area (Km^2)	Sector			
	SPE	NAL	CAL	SAL
Gentle Slopes	15,13	19,69	15,21	16,60
Slopes	21,13	20,44	12,69	13,48
Terrestrial Reef Flat	12,65	10,67	18,72	10,13
Crest	4,94	5,94	5,66	3,02
Reef Flat	17,55	23,56	11,37	16,61
TOTAL	71,40	80,30	63,65	59,84

a variety of benthic habitat types, with relative depth variation. Therefore, bathymetry variations could be validated in a diverse geomorphological range. In addition to the validation, we used the field depth measurements to further adjust the DBM, decreasing the RSME to 2.98 m after correction. The 10–15 m interval showed a 44% lower RMSE value compared to the average RMSE of the other intervals, which can be explained by the lower influence of continental sedimentation providing clearer waters in the average of the images. Overall, DBM performed better at shallow to moderate depths (0–15 m). In coastal waters, as those found on the Brazilian coast, some initiatives can help in refining the model, such as collecting field data related to chlorophyll-a indices to predict the influence of water column attenuation in the bathymetry calculation and taking depth measurements at spaced points in the study area to increase model fit. Contrary to Li et al. (2021), we corrected the final DBM due to the need for greater precision for geomorphological mapping using the BTM.

Regarding BTM, we obtained excellent results from the use of bathymetry extracted from Sentinel-2 image processing as a basis for benthic classification and description of the geomorphological structures of substratum. Few studies used satellite-extracted bathymetry for BTM; Conti et al. (2020) performed the classification from the bathymetry extracted from World View images and Agus et al. (2021) from a single Sentinel-2 scene. Both applied the BTM tool to small areas with reduced relief variation. Several studies on the Brazilian coast and around the world have used BTM based on bathymetric models created from depth data collected in situ with single-beam and multibeam echo soundings, or from data provided by the Brazilian Navy or by the National Oceanic and Atmospheric Administration (NOAA) (de Oliveira et al., 2020; Goes et al., 2019; Mayorga-Martínez et al., 2021; Menandro et al., 2020; Pereira and Bonetti, 2018). However, depth data at the appropriate scale for the study area are not always available or require extensive field surveys. BTM geomorphologic classes correspond to other researchs and maps in the region. Flat plains and depressions correspond to zones of sediment deposition (sand and gravel) and/or flat areas (sand); Gentle slopes and slope areas are sloping areas (coral reef walls); Terrestrial Reef Flat are areas of coral reefs associated with the continent, characterized by the deposition of finer sediments and the influence of tides and continental drainage; Crest and Reef Flat correspond to the reef body (biogenic reefs or sandstone reefs). The delineation of relief features is strongly influenced by bathymetry and slope. One of the variables that most affects habitat prediction in coral reefs is geomorphology. Therefore, delineating relief patterns is essential to relate them to species spatial distribution (Goes et al., 2019; Mayorga-Martínez et al., 2021). For example, according to Ferreira and Maida (2006), Brazilian reefs have a zone of corals generally found in most reef formations along the coast. In general, small colonies of *Favia gravida, Siderastrea stellata*, and *Porites* spp. are found on the reef tops; *Melobesiae* algae and vermetid gastropods form the reef crests; a zone of *Palythoa* and *Millepora* spp. occur below the algal crest; a zone of *Mussismilia* spp. on the intermediate slopes of the reefs; and a cave-like *Montastraea* zone in deeper waters. The results of the BTM geomorphological mapping for the Costa dos Corais MPA were consistent with the mapping conducted by the Brazilian Geological Survey (Mendes, 2017) and with georeferenced data collected in the field in the Carro Quebrado and Maragogi non-take areas and during the expedition through the deep reefs of the Costa dos Corais MPA (Pereira et al., 2022a, 2022b).

Using bathymetry extracted by satellite imagery and freely available software is an advantage for mapping coastal ecosystems and consequently for the conservation of habitats. For the MPA Costa dos Corais area (up to the isobath of 22 m) seven geomorphological classes by the BTM that can be associated with benthic structures. The mapping confirmed the diversity of the seabed and presented the first geomorphological map for the MPA. From a methodological point of view, BTM emerges as an important alternative for large-scale mapping without the need, a priori, of in situ data. Applying BTM from DBM created by clean water mosaic is an advantage as survey lines can create anisotropic features and influence classification.

One of the most commented difficulties in relation to the BTM classification method is the choice of classes and the establishment of limits, that is, the creation of the decision table (Walbridge et al., 2018; Goes et al., 2019; Conti et al., 2020). To determine the classes used, we performed a review of the nomenclature used by other authors that have worked with BTM (Supplementary Material). Some terms are widely used like flat plains, depression, slope and crest. Others may considerably vary such as reef flat, gentle slope and terrestrial reef flat. For geomorphological classification of reef areas, Kennedy et al. (2021) carried out an extensive review of the nomenclature to determine classes that could be applied in global coral reefs mapping. Differences in nomenclature can be explained by the mapping scale and depth variation of the study area. Regarding the creation of the decision table, Lundblad et al. (2006) presented a decision tree scheme that helps in determining values from the characteristics of the normalized models BPI Broad and BPI Fine.

Our results showed high morphological complexity of the seabed in the shallow portion of the MPA Costa dos Corais (<−22 m), which can be associated with the high levels of biodiversity and abundance found in the region, as stated by studies focused on the quantification of fish and benthic communities (Pereira et al. de Almeida et al., 2023; Pereira et al., 2018; Pereira et al., 2022a, 2022b). This result allows characterizing the background geodiversity in protected areas, which in general is an aspect little considered in the creation and management of conservation units (Pereira and Bonetti, 2018).

Almost 50% 49% of the studied area has greater morphological complexity (Terrestrial Reef Flat, Gentle Slope, Slope, Reef Flat and Crest), which may indicate greater possibilities for shelter and occupation of marine biodiversity.guiding the creation of preferential conservation zones for different marine species that occupy geomorphologically distinct areas associated with their ecological niche

(Greene et al., 1999; Harris, 2012; Harris and Baker, 2012; Heyman and Wright, 2011; Araujo and Seoane, 2016). Here these areas are mostly located in the NAL (80,3 Km^2) and SPE (71,40 km^2) sectors.

Previous studies demonstrated that management and zoning strategies can influence coral reef communities with different ecological effects (Mumby and Harborne, 2010; Harrison et al., 2012; Emslie et al., 2015; Williamson et al., 2019; Pereira et al., 2022a, 2022b). Pereira et al., 2023 identified areas of greater coverage and coral richness in the NAL, followed by the SPE and the lowest in the SAL. However, the highest levels of fish abundance were observed in SAL. The same occurs for specific zoning areas of the MPA Costa dos Corais, where greater coral cover was observed in no-takes zones (no fishing and no visiting). The results corroborate the geomorphological mapping realized in the present work, where we identified more complex areas in the NAL and SPE. Thus, the detailed mapping of marine geomorphology is an ally in the management and zoning of marine protected areas.

The greater the morphological complexity, the greater the capacity to protect high levels of biodiversity. However, about 47% of the area is composed of flat plains and depressions, located mainly in the CAL and SAL. The low morphological complexity of these areas may indicate areas of lower biodiversity. This was also observed at greater depths in the MPA Costa dos Corais, where mesophotic reefs at average depths of −35 m harbor a diversity of sponge, coral, and fish species (Pereira et al., 2022a, 2022b). Almost 10% of the area is occupied by Terrestrial Reef Flats, which despite the low slope are important areas for biodiversity, mainly due to the greater influence of tidal variation and freshwater flow, which provide a favorable connectivity environment for several species.

Depth also has effects on corals and fish communities (Pereira et al., 2018; Pereira et al., 2023). The authors observed that as depth increases, coral cover decreases while the abundance of fish and sponges increases. Likewise, we also observe complex structures that are little known at greater depths. Based on further investigations, zoning strategies can be used in these areas, such as the creation of no-takes areas parallel to the coastline and at greater depths, as suggested by Santos (2021) for the Carro Quebrado region (Alagoas).

As reefs are arranged over a large area, mapping coral reefs using traditional survey methods, such as transects and scientific diving, becomes challenging, time consuming and increasingly expensive. Large-scale geomorphic mapping for MPA Costa dos Corais should be used to support local management efforts with tourism, navigation, commercial and recreational fishing, research and monitoring. In addition, it will be used to classify benthic habitats, generating more information about reef habitats. The mapping carried out at the present study represents about 14% of the total area of MPA Costa dos Corais, but covers the entire coast, 8 (eight) NTZs and all main visitation areas, including the natural pools of Maragogi, which alone receive about 85% of the total visitors to the conservation unit annually. Improvements in the management of coastal areas through mapping were observed in several regions of the world, such as Australia, Indonesia and Caribe (Allen Coral Atlas, 2020; M. A. Ferreira et al., 2012; Roelfsema et al., 2020; Zitello et al., 2009). In this way, the use of remote sensing for mapping coral reefs aims to visually communicate information about these ecosystems, support research and conservation work and be an important tool in emergencies such as bleaching episodes and oil spills. (Ferreira et al., 2012; Kennedy et al., 2021; Mohanty et al., 2013; Pereira et al., 2022a, 2022b). Mapping marine habitats is the basis for evaluating the success of conservation measures. Maps can be used to analyze areas of thriving habitat, and this requires knowing the extent and arrangement of different habitat types(Brown et al., 2011; Lacharité et al., 2018; MESH, 2008). Our mapping of coral reefs for APACC can be seen as a stimulus to introduce satellite imaging systems in Brazil to monitor coral reefs over time, especially given the inevitable effects of climate change, such as environmental stress from ocean warming and acidification. Remote sensing mapping is critical to understanding the distribution and changes in the reef ecosystem, as it can cover isolated areas that are difficult to access for research in the field (Foo and Asner, 2019).

5. Conclusion

The present study highlighted the importance of using geotechnologies (remote sensing and geoprocessing) for the conservation of reef ecosystems. We extracted bathymetry using Sentinel-2 images and cloud processing in the GEE, proving the method's efficiency and applicability worldwide. DBM was able to provide accurate bathymetric data at a fine scale, ideal for BTM processing and geomorphological characterization for analysis of the structural complexity of reefs down to −22 m depth. The relief of MPA Costa dos Corais presented a great variety of morphological features, previously unknown at greater depths and the analyses performed at the present study can support efficient management and zoning strategies at Marine Protect Areas (MPAs.)

The mapping and quantification of morphologically complex areas contributes to the location of areas of greater biodiversity. This can direct measures for inspection and monitoring of coral reefs in the face of pressure from human activities, such as tourism and overfishing; climate change impacts such as ocean warming; and environmental disasters such as the recent oil spill.

This work reinforces the need for mapping marine conservation units in Brazil to increase knowledge on high ecological, social and economic import areas.

Declaration of Competing Interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seares.2023.102453.

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