

# Geomorphological classification of benthic structures of Kaledupa Atoll Wakatobi National Park, Indonesia

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Manuscript received: 29 March 2022. Revision accepted: 29 June 2022.

**Abstract.** *Setiawan A, Siregar VP, Susilo SB, Mardiasuti A, Agus SB. 2022. Geomorphological classification of benthic structures of Kaledupa Atoll Wakatobi National Park, Indonesia. Biodiversitas 23: 3784-3792.* Geomorphological mapping is one solution to understanding the complexity of the seabed pattern. This research aims to map the benthic structure of Kaledupa Atoll using the Remote Sensing and Geographic Information System with the Benthic Terrain Modeler (BTM) extension. The data used is in situ bathymetry data using Mapsounder 585 and Sentinel 2A satellite image data downloaded for free. BTM is a technique for examining benthic habitat and shallow water geomorphology. BTM was used to analyze integrated depth data to determine the bathymetric position index (BPI), slope, and classification of reef geomorphological structures. Thirteen structural classes of habitat geomorphology resulting from this research are Flat plain with the largest area of 17142.35 ha, and the class with the smallest area is Crevices class, with narrow gullies rock outcrops 1.64 ha. While the other classes in a row are Broad slope 9104.53 ha; Flat ridge tops, upper slopes 4262.67 ha; Current scoured depressions on a slope 3420.98 ha; Narrow depressions at the base of rock outcrops 2348.20 ha; Rock outcrop highs, narrow ridges 1792.45 ha; Local ridges, boulders, pinnacles on slopes 879.29 ha; Scarp, cliff or small local depressions on a slope 703.02 ha; Local ridges, boulders, pinnacles on broad flat 490.17 ha; Local depressions, current scoured on flat 416.39 ha; Local ridges, boulders, pinnacles on broad depressions 16.63 ha; and Steep slopes 2.88 ha.

**Keywords:** Benthic structure, geomorphology, Kaledupa Atoll, Wakatobi National Park

## INTRODUCTION

One way to comprehend the complexity of the sea bottom pattern is to use geomorphological mapping (Van Lancker et al. 2012; Walbridge et al. 2018; Goes et al. 2019). These patterns are similar to those found on lands, such as mountains, slopes, plains, and valleys. The patterns can affect a variety of aquatic environmental characteristics, including light intensity, current and wave patterns, nutrient availability, substrates, erosion, and sediment deposition, as well as habitat suitability (Harris and Baker 2012; Shen et al. 2018; Storlazzi et al. 2018), and place where benthic fauna and flora can live (Lecours et al. 2015).

Seabed habitats have been defined and utilized in a variety of ways. Harris and Baker (2012) describe benthic marine habitats as geographically distinct areas of the seafloor where physical attributes are linked to species or communities that occur in clusters. Other researchers have examined the relationship between the seafloor's physical, chemical, and biological features to geographically designate habitats with similar characteristics using (geo) statistical approaches (Lecours et al. 2016). With some benthic habitat mapping studies adopting a landscape-scale

strategy similar to mapping biophysical patterns in the terrestrial environment, spatial scale in defining habitat is often problematic (Lecours et al. 2015). This broad-scale approach is known as "seascape" mapping, and it is commonly anchored by acoustic seabed mapping data corroborated with in situ ground validation (Brown 2012).

Kaledupa Atoll is one of the Atolls that is remote from the mainland and, as a result, has a distinct basic geomorphological pattern. It is part of a marine national park, the Wakatobi National Park. Ecosystems located far distance from land will be far from terrestrial and anthropogenic influences (Armstrong et al. 2006). Furthermore, it can serve as a refuge for corals and other species during times of environmental stress and increase sources of larvae increasing reef resilience (Tkachenko and Soong 2017). According to the formation process, the Kaledupa Atoll was formed by the sinking of the base plate, which began with the emergence of several islands and was then followed by the growth of corals surrounding the island. The coral reefs surrounding the island continue to grow upwards, eventually forming an Atoll (Terry and Goff 2013).

Geomorphological information on the sea bottom of the Kaledupa Atoll's waters is still very limited. However,

changes in the coral reef community of Kapota Atoll, which is adjacent to Kaledupa Atoll and has similar characteristics, have been studied using Landsat TM and ETM images (Schuyler et al. 2005). In addition, changes in benthic habitat communities in Wakatobi National Park have been detected using Landsat Imagery (Hafizt et al. 2021).

This study examines the benthic structure through geomorphological classification by using bathymetric data from direct measurements and data from Sentinel 2A satellite imagery. The benthic structure was determined using remote sensing and Geographic Information Systems (GIS). Satellite photography is used to determine depth using an algorithm that uses the ratio of two optical bands penetrating the water column until they reach the bottom. Benthic Terrain Modeler (BTM) is an open-source package for studying the geomorphological structure of shallow-water benthic habitats. BTM is integrated with ArcGIS spatial data processing software. This technology can assist in providing convenience to users in assessing the geomorphology of aquatic habitats.

## MATERIALS AND METHODS

### Study area

Kaledupa Atoll is situated in the west of Wakatobi National Park, located at coordinates (5.7481°S 123.6959°E) and borders the Flores Sea. This shark-shaped Atoll is approximately 48 kilometers long, 18 kilometers wide, and has a maximum lagoon depth of 57 meters (Figure 1). The atoll is protected from strong winds from June to August (East Wind Season), March to May (Transition Season I), and September to November (Transition Season II).

The data used in this study are in situ bathymetry data and Sentinel 2A satellite imagery data. Bathymetry data measurement was carried out for three days, from July 16, 2019, to July 18, 2019, with 1193 observation points. The

satellite image was acquired on November 4, 2019, and was downloaded for free via <https://scihub.copernicus.eu>. The global positioning system (GPS), Mapsounder 585 (single-beam), diving equipment, diving stationery, and underwater cameras were used to collect field data for this study. The tools used for data processing are ArcGIS software version 10.6, QGIS Desktop 3.15.14, and Sentinel application platform (SNAP) software version 7.0.

### Procedures

#### Pre-processing

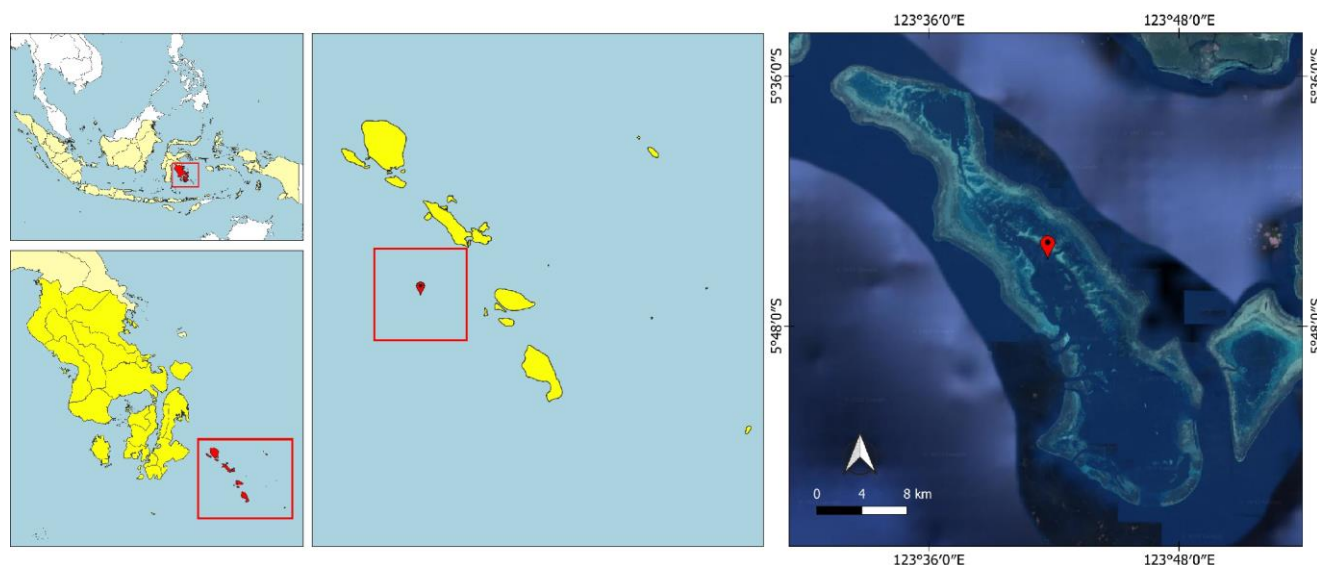
Pre-processing is the initial processing before further image processing is carried out. This procedure aims to correct the image data distorted due to the atmospheric and sunlight at the sea surface. First, atmospheric correction is performed by using the semi-automatic classification method in QGIS 3.16.14 software. This method automatically uses a plugin available in the application. The corrected image is then cropped to delimit the research area. Next is the de-glint process to eliminate the disturbance effect caused by the specular reflection of sunlight on the sea surface. Finally, the correction is done by using the formula (Mobley 1994):

$$R'_i = R_i - b_i[R_{Nir} - R_{minNir}] \quad (1)$$

Where,  $R_i$ : reflection value of each channel;  $b_i$ : gradient value from regression test;  $R_{Nir}$ : reflection value of the near-infrared channel;  $R_{minNir}$ : a minimum reflection of the near-infrared channel.

#### Empirical bathymetry

Estimation of water depth derived from satellite imagery is carried out to determine the variations of water depth. The depth obtained was calibrated with the depth measured in-situ directly to obtain the actual depth. Furthermore, it is used as one of the parameters to determine shallow water bottom geomorphological variations.



**Figure 1.** Map of locations and depth observation points of Kaledupa Atoll, Wakatobi National Park, Indonesia

A linear transformation algorithm is one of the methods used in the empirical bathymetry method. On Sentinel Image 2A, the linear transformation was performed using the ratio transformation algorithm (Casal et al. 2019).

In general, this linear log model implements one or two wavelength bands. Equation (2) depicts the algorithm for this log-linear model.

$$Z = a_0 + (x + a)^n = \sum_{i=1}^N a_i \ln(R(\lambda_i) - R_{\infty}(\lambda_0)) \quad (2)$$

Where,  $a_i$  ( $i: 0.1, \dots, N$ ) coefficient constant;  $N$  is the number of spectral bands;  $R(\lambda_i)$  radiance after atmospheric correction and solar radiation for the spectral band  $i$ .

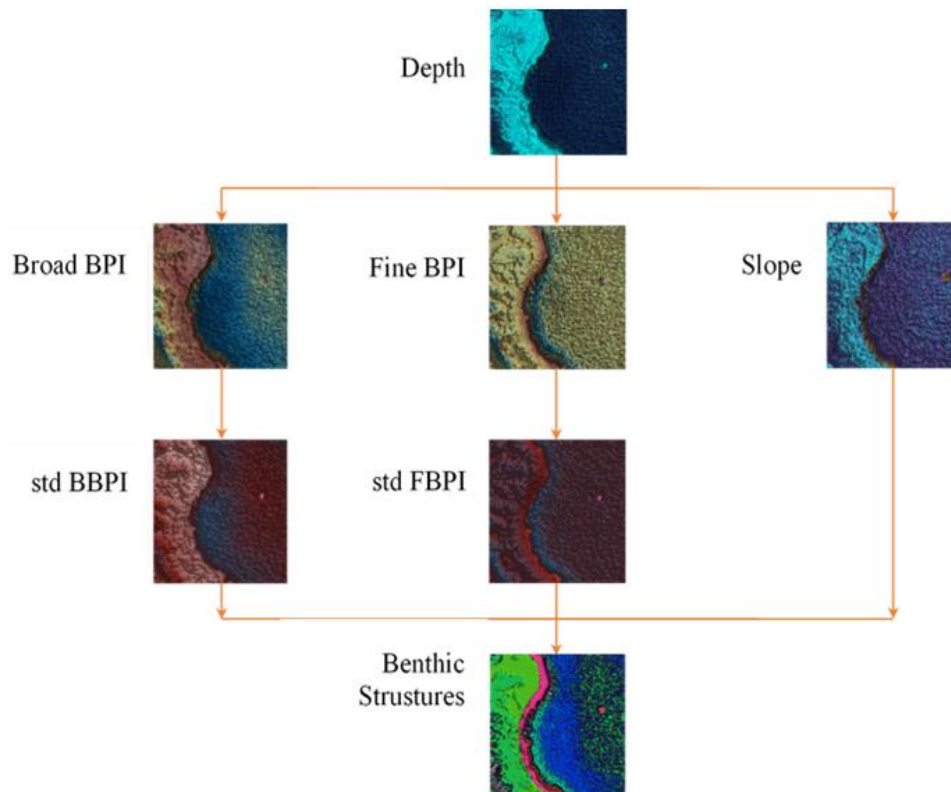
#### *Benthic terrain modeler*

The Benthic Terrain Modeler (BTM) is a GIS classification approach that divides the seabed into geomorphic classes using derived terrain attributes (de Oliveira et al. 2020; Lavagnino et al. 2020; Menandro et al. 2020). It was created by Oregon State University's Department of Geosciences in collaboration with the National Oceanic and Atmospheric Administration's (NOAA) GIS Integration and Development Program (Lundblad et al. 2006; Wright et al. 2007). Bathymetric data is subjected to BTM analysis. It will generate numerous outputs, including a bathymetric position index (BPI), geomorphological zone/structure, slope, water surface rugosity, and other required outputs. BPI and slope were calculated using the BTM method, and then used to

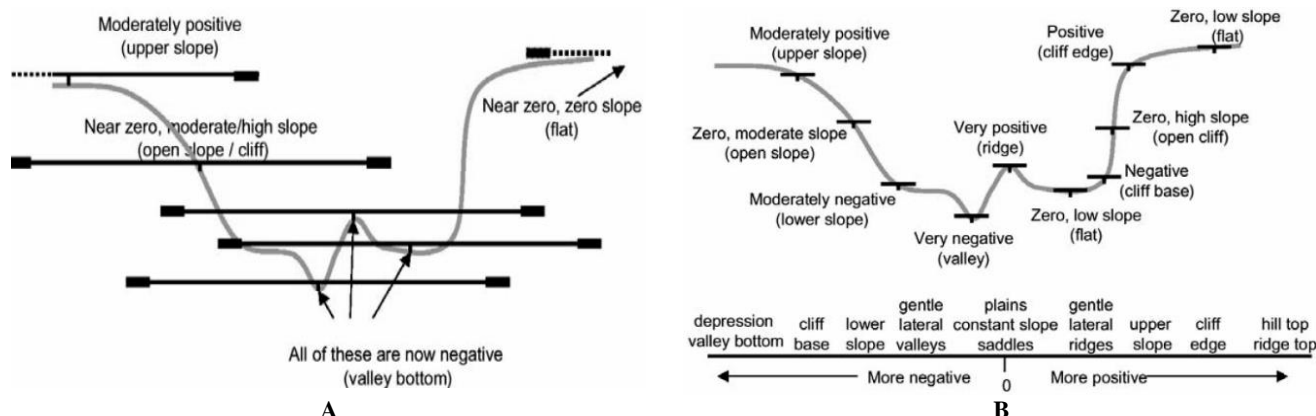
categorize benthic structures. In this work, the BTM analysis was used to produce a final result in the form of a geomorphological structure class, as shown in (Figure 2).

#### *Bathymetric position index and slope*

Before classifying benthic structures and geomorphological zones of shallow-water habitats at the study site, BPI and shallow water slope of surface area from depth data are calculated. BPI is a calculation that refers to the elevation ratio of the surrounding points to describe the elevation of each point on the bottom of the water. Each dot represents a pixel in the bathymetric data. Negative BPI values indicate that focal cells have lower values than surrounding cells, resulting in the formation of structures such as valleys. Positive BPI values indicate that focal cells have higher values than surrounding cells, resulting in structures such as ridges. BPI values close to zero are associated with areas with a flat or constant slope (Lundblad et al. 2006). The BPI calculation is carried out with two scales called Fine-scale BPI (FBPI) for calculating BPI with a narrow radius and Broad-scale BPI (BBPI) for a wider radius. Furthermore, FBPI and BBPI were then standardized. The outputs generated in the BPI calculation include valley bottom, flat area, slope, and several other identifiable features (Erdey-Heydorn 2008). The slope value is calculated separately from the BPI calculation to get the level of the base surface slope using BTM. The illustration of BPI calculation results can be seen in Figure 3.



**Figure 2.** Benthic structure classification procedure by BTM analysis



**Figure 3.** Illustration of BPI from bathymetric data (Weiss 2001). (A) Describes broad scale BPI; (B) Describes fine scale BPI values

*Geomorphology dictionary*

The benthic structure classification scheme employed 13 classes in this study, based on the classification scheme produced by Lundblad et al. (2006) in American Samoa seas, Erdey-Heydorn (2008) in Point Reyes National Seashore research area, and the class scheme applied by Agus et al. (2012) in a study Panggang Island and its surroundings.

Broad slope: the slope of coral reefs with a slope between 5-45°; Crevices, narrow gullies between rock outcrops: a narrow slit or hole is between the features on the reef slope. The slope can be awakened by a rock, coral massive, or another type of reef lifeform; Current scoured depression on the slope: Continually sloped terrain or flat areas can have deep U-shaped depressions; Narrow depressions at the base of rock outcrops: show the reef which is lower than the surrounding; Flat plains: a form of a flat surface of the seabed with a maximum slope is 5°, generally have sand or rubble; Flat ridges tops, upper slopes: limiting the area in gentle slope or flat area; Local depression, current scours on the flat: refers to the presence of a deep or narrow trench that has been eroded due to the current path; Local ridges, boulders, and pinnacles on slopes: refers to the formation of coral colonies, coral boulders, or coral masses on the reef slope; Local ridges, boulders, pinnacles on broad depression: a small-scale reef ridge, and the other mounting features. Physically, referring to the formation of coral, boulder, or coral massive dikes colonies in reef trenches; Local ridges, boulders, pinnacles on broad flats: a dike formation reef or massive coral colonies on a flat area; Rock outcrop highs, narrow ridges: a boulder forming a narrow outcrop; Scarp, cliff; or small local depression a slope: is formed by small-scale slopes, boulders, or bottom overdraft on a reef slope; Steep slopes: a steep reef slope, with slope values greater than 45°.

**RESULTS AND DISCUSSION**

**Sun glint correction**

Because the specular reflection of the sunlight recorded by the sensor has an extreme value compared to the

surrounding pixels, the object's reflection value should be chaotic. However, waters have very low reflections in the near-infrared channel. Therefore, the sunlight effect is not very visible; this is used as a benchmark in comparing the linear relationship of the near-infrared channel with the three visible channels, namely blue, green, and red.

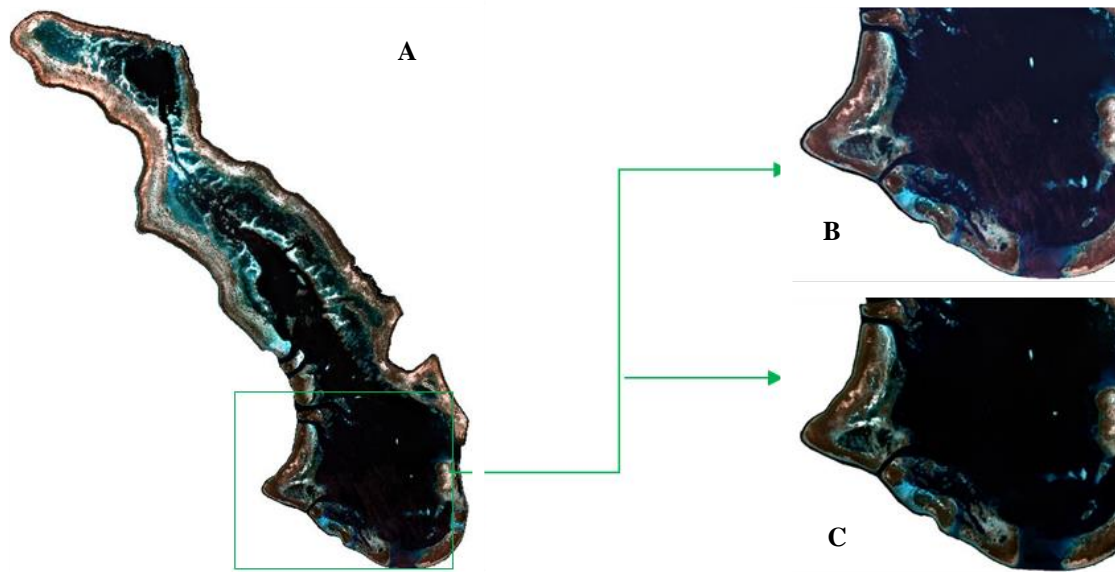
The comparison results show that the gradient. Value the lowest blue channel is 0.8936, the green channel is 0.9542, and the red channel has the highest gradient: 1.0439. This result is then used as input in the Sunglint correction algorithm using the equation (1). The images before and after the sunglint correction are presented in Figure 4.

**Empirical bathymetry**

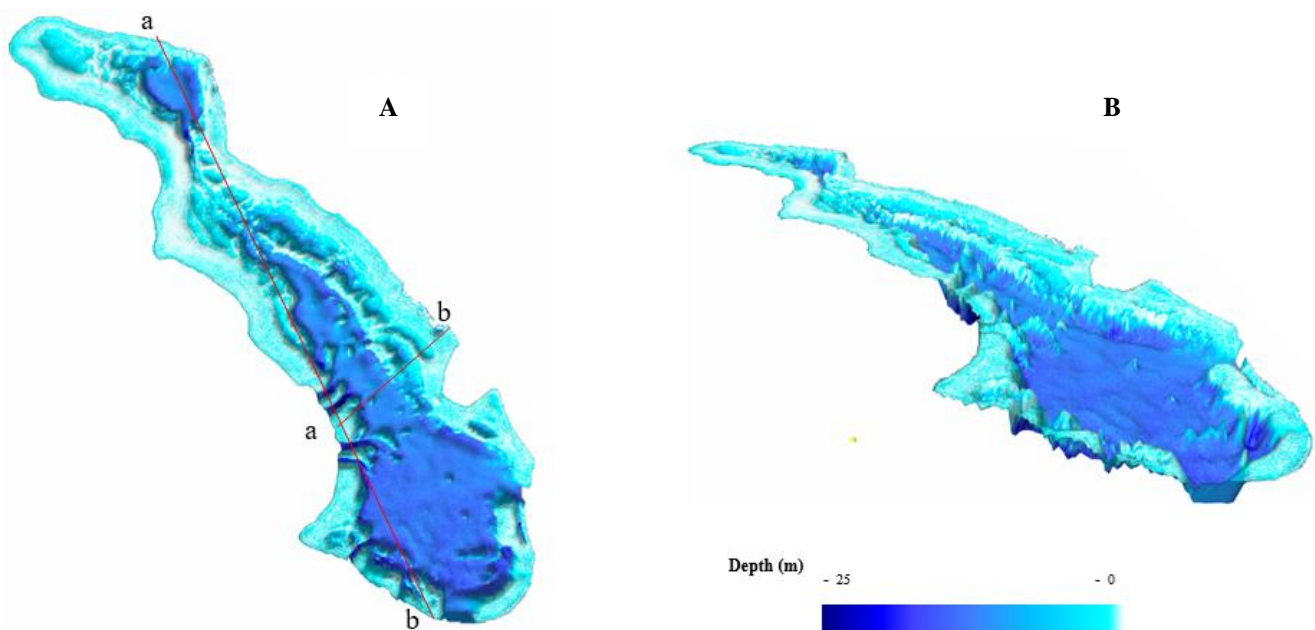
Regressing values from the blue and green bands resulted in depth estimation using Sentinel 2 imagery. According to Lyzenga (1978), using two or more bands for bathymetry estimation can assist in correction down albedo. In this case, the blue and green bands have a fairly good coefficient of determination, so the equation derived from the regression is used for the actual depth transformation. The algorithm works best when profiling at a depth of 25 m. The bathymetric analysis results obtained a bathymetric map (Figure 5) and the appearance of the vertical and horizontal profiles (Figure 6).

Based on Figure 6 (A) the vertical profile shows the condition of the maximum depth reaching 50 m at a distance of ±30 km from the north side of the Atoll. The distance is 2 km from the north side; the depth is between <2-20 m. At a distance of 7 km to 9 km is a gently sloping area, then a distance of 10 km to 19 km experiences depth variations caused by the presence of pencil-like coral ridges. Finally, enhancement depth occurs at a distance of 25-30 km to reach a depth of 50 m. The distance is 32 km, and the depth of descent is between 40 - <2 m.

Figure 6 (B) flat profile shows a distance of 0.1 km from the west side, the depth ranging from <2-4.9 m. The depth increases at a distance of >1.8 km to 2.3 km to a depth of 30 m, then becomes shallow from 5 km to 7 km. At a distance of 8 km to 9.9 km is a flat reef area with a depth of <5 meters.



**Figure 4.** (A) Satellite Imagery Sentinel-2A; (B) The comparison image before; (C) and after the sunglint correction process



**Figure 5.** Empirical Bathymetry using Lyzenga Algorithm: (A) 2D; (B) 3D

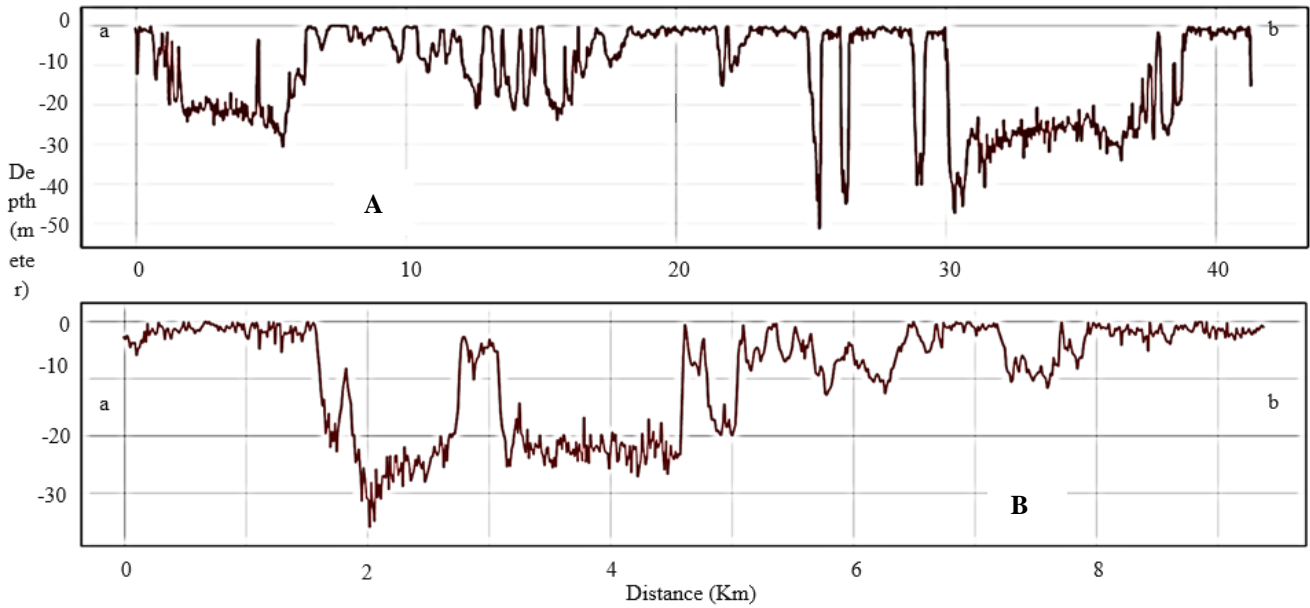
Despite the small tidal range, approximately 0.7 m between Mean Highest High Water and Mean Lowest Low Water, tidal correction against collated depth data was performed. To get the estimated value of absolute depth, regression modeling is used with in situ data.

Regression analysis was performed using up to 50 direct depth data points in relation to the reflectance of the Sentinel-2A visible light channel satellite image. The correlation coefficient (R) between depth of field data and depth of transformation (Figure 7) is 0.7176, and the correlation value (R<sup>2</sup>) is 0.8471.

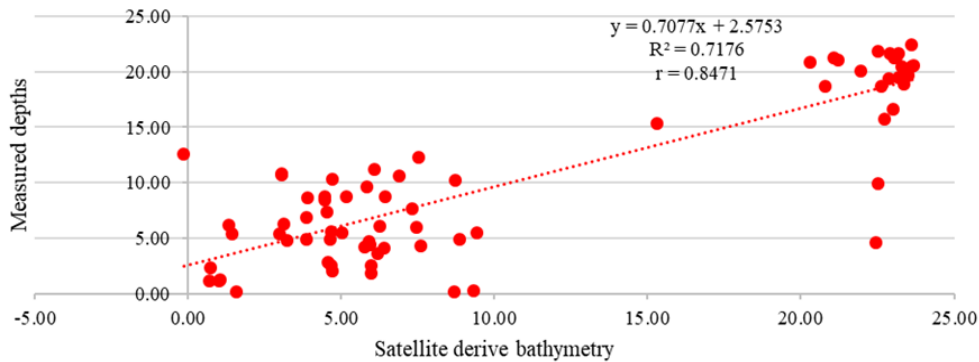
#### **Benthic terrain modeler**

##### *Bathymetric position index (BPI) and slope*

Bathymetric Position Index (BPI) is a bathymetric data derivative. It is used to locate specific areas and features concerning other areas and features in the same dataset (raster). In another sense, BPI is a calculation that describes the elevation of each point on the surface of the bottom of the water for comparison with nearby points. The dots indicate the position (X, Y), depth (Z), pixel size (spatial resolution), and bathymetric raster data used. In this study, the spatial resolution of the raster data used is 10 m (following the spatial resolution of the Sentinel-2A image used).



**Figure 6.** The bathymetric profile of Kaledupa Atoll. (A) Vertical distance; (B) Horizontal distance (m)



**Figure 7.** Model and correlation between measured depths (y) and satellite derive bathymetry (x)

The BPI calculation modifies Weiss's (2001) Topographic Position Index (TPI) for use in terrestrial environments. Modifications to the BPI have been made in its application to characterize the bottom surface of the waters, including using the elevation (Z) value to be negative, which describes the depth.

The BPI calculation results depict each raster pixel as a range of negative to positive values. A negative value denotes a pixel's lower location with its surroundings, such as in a valley formation. A positive value denotes a higher pixel than the surrounding pixels, such as when a ridge is formed. The more severe the pixel's benthic characteristics are, the more negative or positive the BPI value is produced. Flat terrain or one with a constant slope, on the other hand, will generate a BPI value near to 0 (zero).

The input radius is an inner radius and an outer radius, which is the limit on the number of neighboring pixels from the focal point of each pixel performed for BPI analysis. BPI scale factor calculation, radius multiplied by pixel resolution. The BPI analysis was carried out on a broad scale (BBPI) and a fine-scale (FBPI). The radius

value is determined by trial and error and is adjusted to the area of the research area.

In this study, an inner radius of 15 pixels, an outer radius of 25 pixels, and a vector scale of 250 were utilized for Broad BPI. In contrast, an inner radius of 25 pixels, an outer radius of 40 pixels, and a vector scale of 400 were employed for Fine BPI. Broad BPI, and Fine BPI yielded results of -43-25 for broad BPI and -42-23 for Fine BPI. In the calculation of BPI, no standard can be used as a reference for the level of variation in the characteristics of the surface of the bottom of the waters. Several experiments were carried out in this study to obtain the best results. The diverse benthic reef habitat produces more comprehensive bathymetry due to the combination of variables used to estimate BPI. (Figure 8B and 8C) depict the general aspect of the Kaledupa Atoll seascape.

The largest change value for each pixel of the water level/depth raster data is the slope or gradient of the surface. The location values of each pixel to the surrounding pixels are calculated using the slope calculation data from the bathymetry raster. The outcome is

a degree value. The lowest value of 0 denotes a pixel identical to the pixels around it (flat). The maximum value is determined by the water's bottom surface properties and the raster data's pixel size (spatial resolution). The obtained slope value is in the range of  $0.002^{\circ}$ - $52.52^{\circ}$  (Figure 8D). The slope value obtained from this computation is also used to classify the water's fundamental surface structure, and the standardized broad BPI and fine BPI.

#### Geomorphological terrain structure classification

Classification of the basic surface structure of the water using BTM analysis and BPI and slope data also necessitates the preparation of a classification dictionary. Thirteen classes of benthic structures were identified (Figure 8E) with different areas (Table 1).

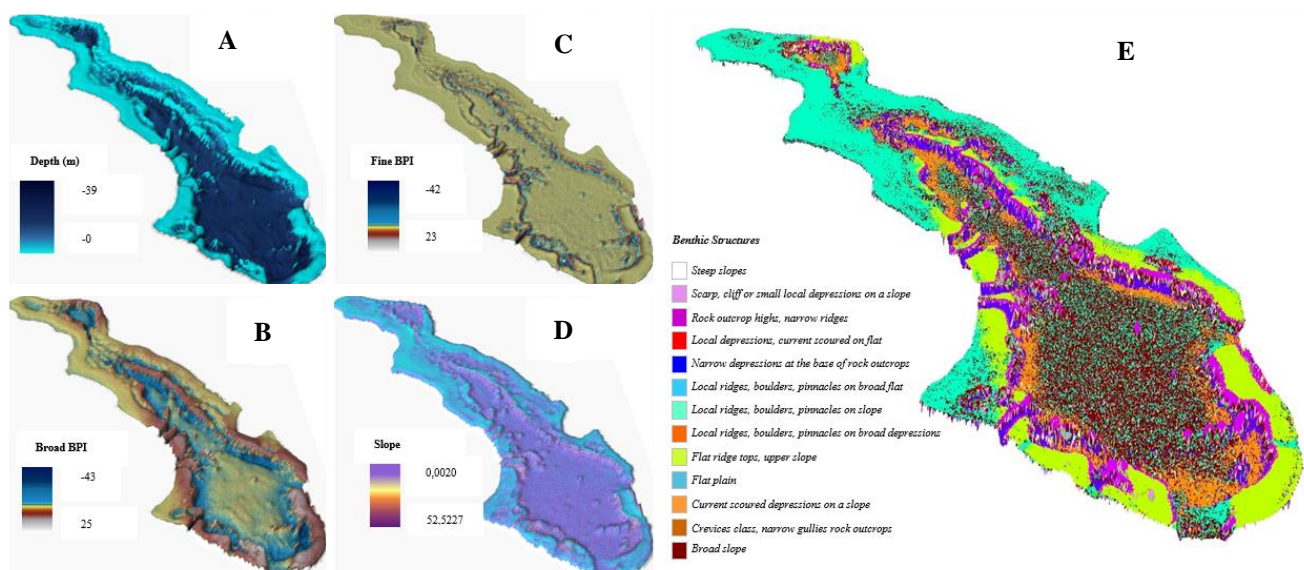
Table 1 above shows differences in the area of each class of benthic structures in Kaledupa Atoll. The most dominating structural class is Flat plain (17142.32 ha), and the lowest class is Crevices, narrow gullies rock outcrops (1.64 ha).

Figure 9 shows the diversity of basic geomorphological features of Kaledupa Atoll waters, especially the presence of coral reef ridges and valleys that extend inside the atoll. There is a coral ridge on the outer north side, and the lagoon side extends following a small channel to the south. Simultaneously, the southern half of the coral ridge prevails on the lagoon's side as compared to the outside. The geomorphological features are not very distinctive; there are only discontinuous features, namely reef flats. On the south side, the complexity of geomorphological features is very high. The west and east sides also have high complexity from the outer and inner sides of the lagoon. The most major slope changes are related to the complexity of the depth gradient, which describes the occurrence of positive and negative reliefs, especially in the center of the atoll to the southernmost tip.

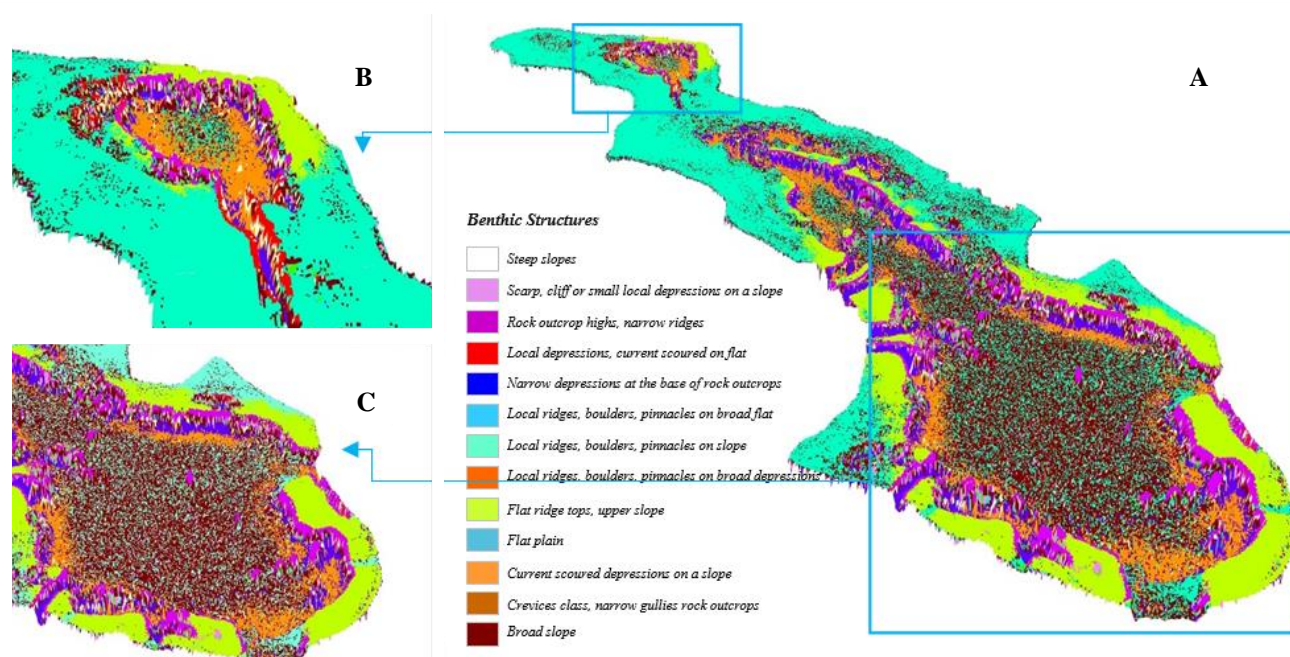
Areas of higher complexity tend to have significant biodiversity (Kovalenko et al. 2012; Hall and Kingsford 2021). On the other hand, low morphological complexity can be associated with lower biodiversity (Feldman et al. 2018). This complexity is influenced by the uplift of the reef platform by tectonic processes, underwater topography, wind direction, winter and summer direction and strength, seawater dynamics, and substrate characteristics associated with coral reef growth (Shen et al. 2018). In addition, the geomorphological complexity of coral reefs in Wakatobi has properties that are vulnerable to change, both from endogenous factors (geological processes) and exogenous factors such as coastal ecosystems, hydro-oceanography, and human activities (Azhar 2018). This condition allows the geomorphological structure of coral reefs in the Kaledupa atoll to be very dynamic.

**Table 1.** Area of the benthic structures of Kaledupa Atoll

Benthic structures	Area (ha)
Flat plain	17142.35
Current scoured depressions on a slope	3420.98
Flat ridge tops, upper slopes	4262.67
Broad slope	9104.53
Crevices, narrow gullies rock outcrops	1.64
Narrow depressions at the base of rock outcrops	2348.20
Rock outcrop highs, narrow ridges	1792.45
Local ridges, boulders, pinnacles on slopes	879.29
Scarp, cliff or small local depressions on a slope	703.02
Local ridges, boulders, pinnacles on broad flat	490.17
Local depressions, current scoured on flat	416.39
Local ridges, boulders, pinnacles on broad depressions	16.63
Steep slopes	2.88



**Figure 8.** Bathymetric database and its derivatives: (A) Digital Bathymetric Model (DBM); (B) Broad-scale Bathymetric Position Index (Broad-BPI); (C) Fine-scale Bathymetric Position Index (Fine-BPI); (D) Slopes; (E) Geomorphological classification



**Figure 9.** Geomorphological classification/benthic structures of the research site (A); Geomorphological Classification to the North of the Atoll (B); Geomorphological Classification to the East of the Atoll (C)

This methodological process recognizes the study area's relief patterns, which have not been described in previous studies. For example, studies on the Wakatobi Archipelago's coral reefs (Adji and Sejati 2014) add to our understanding of the area's environmental characteristics. Still they do not provide a thorough description of the benthic habitat in the study area. However, it is reasonable to suppose that shape influences benthic creature distribution and environmental circumstances (e.g., substrate, sediment erosion or deposition, currents, and available nutrients) (Jerosch et al. 2016).

In conclusion, Kaledupa Atoll has been mapped bathymetrically and geomorphologically. The ideal depth estimate is 25 meters, according to a combination of Lyzenga algorithm analysis on Sentinel-2A satellite imagery and field measurements. BTM analysis identified 13 habitat structure classes, with Flat Plain as the largest and Crevices, narrow gullies rock outcrops as the smallest structural class. While the other classes in a row are Broad slope; Flat ridge tops, upper slopes; Current scoured depressions on a slope; Narrow depressions at the base of rock outcrops; Rock outcrop high, narrow ridges; Local ridges, boulders, pinnacles on slopes; Scarp, cliff or small local depressions on a slope; Local ridges, boulders, pinnacles on the broad flat; Local depressions, current scoured on flat; Local ridges, boulders, pinnacles on broad depressions; and Steep slopes.

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