Mapping of Submarine Geomorphological Structures Using Satellite-Derived Bathymetry and Depth Data in the Waters of Lambasina Island, Kolaka Regency

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Abstract

This research examines the geomorphological characteristics of the seabed around Lambasina Besar and Lambasina Kecil Islands, Kolaka Regency, by integrating Satellite-Derived Bathymetry (SDB) and the Benthic Terrain Modeler (BTM). Depth estimates were derived from Sentinel-2 imagery using the Support Vector Machine (SVM) algorithm and compared with in-situ depth measurements. The validation results indicated a high level of agreement, with R^2 values ranging from 0.81 to 0.82. The bathymetric data were then processed using Bathymetric Position Index (BPI), slope, and rugosity parameters, which allowed the classification of the seafloor into 13 geomorphological structure classes. The analysis identified various seabed forms, including flat plains, steep slopes, broad slopes, ridges, narrow depressions, and localized basins. These morphological patterns correspond well with coral reef zonation observed in the field. The findings highlight the important role of geomorphological variability in shaping benthic habitats and influencing biodiversity distribution. This approach demonstrates strong potential for supporting marine spatial analysis, conservation planning, and the identification of areas suitable for marine protection. Moreover, the study provides a basis for further research on the relationships between habitat complexity, biomass, coral diversity, and reef-associated fish abundance, which are essential for advancing ecosystem-based coastal management strategies.

Keywords: Benthic Terrain Modeler; geomorphological; mapping; coral reef ecosystems

INTRODUCTION

The seafloor forms the foundation of marine ecosystems and plays a central role in shaping their structure and function. It provides habitat and support for a wide variety of benthic and pelagic communities; each closely linked to the physical characteristics of the seabed. The diversity of its geomorphological forms influences sediment distribution, current flow, and species interactions across different habitats (Harris *et al*., 2014; Diesing *et al*., 2020). Because of this complexity, information on seafloor morphology is vital for understanding ecosystem connectivity and resilience, as well as for guiding coastal resource management, spatial planning, and marine conservation efforts (Wright *et al*., 2005). In tropical coastal regions such as Indonesia, detailed mapping and classification of seafloor geomorphology are particularly important to monitor coral reef conditions, assess habitat suitability, and design ecosystem-based management strategies.

In recent years, developments in spatial analysis and remote sensing have greatly improved our ability to map underwater geomorphological features. One of the most widely used GIS-based approaches is the Benthic Terrain Modeler (BTM), which allows researchers to derive slope, Bathymetric Position Index (BPI), and surface roughness (rugosity) from bathymetric data to identify seafloor landforms (Lecours *et al*., 2017; Wright *et al*., 2012). At the same time, Satellite-Derived Bathymetry (SDB) has emerged as an effective method for estimating water depth using spectral reflectance from optical sensors (Casal *et al*., 2022). Combining these techniques with machine learning algorithms such as Support Vector Machine (SVM) and Random Forest (RF) has further increased the accuracy of depth estimation in complex coastal waters (Li *et al*., 2021; Prasetya *et al*., 2023). However, studies that integrate SDB and BTM approaches are still rare in Indonesia, especially for classifying geomorphological features and mapping shallow water habitats.

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Lambasina Island, located in Bone Bay within Kolaka Regency, Southeast Sulawesi, represents one such understudied area. Despite its ecological potential, limited information exists on its bathymetry and seafloor morphology, which hinders effective coastal planning and habitat management. To address this gap, the present study applies an integrated approach combining Sentinel-2–based bathymetric estimation using the SVM algorithm with geomorphological classification generated through the BTM framework. The primary goal is to produce a detailed seafloor geomorphological classification map of the Lambasina coastal area. This map will serve as a baseline for future studies on benthic habitat complexity, coral reef assessment, and sustainable coastal management in Southeast Sulawesi.

MATERIALS AND METHODS

The research was conducted on two islands, namely Lambasina Kecil Island and Lambasina Besar Island, located within the administrative region of Kolaka Regency, Southeast Sulawesi (Figure 1). Lambasina Island is situated at coordinates 121°25'4.69" E longitude and 04°7'34.99" S latitude. Field surveys were carried out from November 21 to 25, 2020. Bathymetric data were obtained by direct field measurements using a motorboat and a depth-measuring instrument, specifically a map sounder, along pre-established transects to acquire depth data (Z) and geographic position data (X, Y). Bathymetric data were collected in the coastal areas of both Lambasina Kecil and Lambasina Besar Islands. The depth measurements obtained with the map sounder were corrected for tidal variations and transducer pole offsets. The Geospatial Information Agency provided the tidal data used for correction for the period of November 2020 over 30 days. Bathymetric observations were corrected to the Lowest Low Water Level (LLWL). The resulting bathymetric data from the field survey were then integrated with bathymetric data derived from Sentinel-2 satellite imagery transformation using the Support Vector Machine (SVM) algorithm (Prasetya *et al*. 2023).

Benthic Terrain Modeler (BTM)

The Benthic Terrain Modeler (BTM) application consists of several toolsets capable of generating information about the geomorphological structure of bathymetry using input data such as the Bathymetric Position Index (BPI) and slope. Assessing benthic habitat characteristics requires data on geomorphological zones/classes, slope, and benthic substrate rugosity of the seafloor. The algorithm used to implement the benthic terrain modeler can be seen in the Table 1.

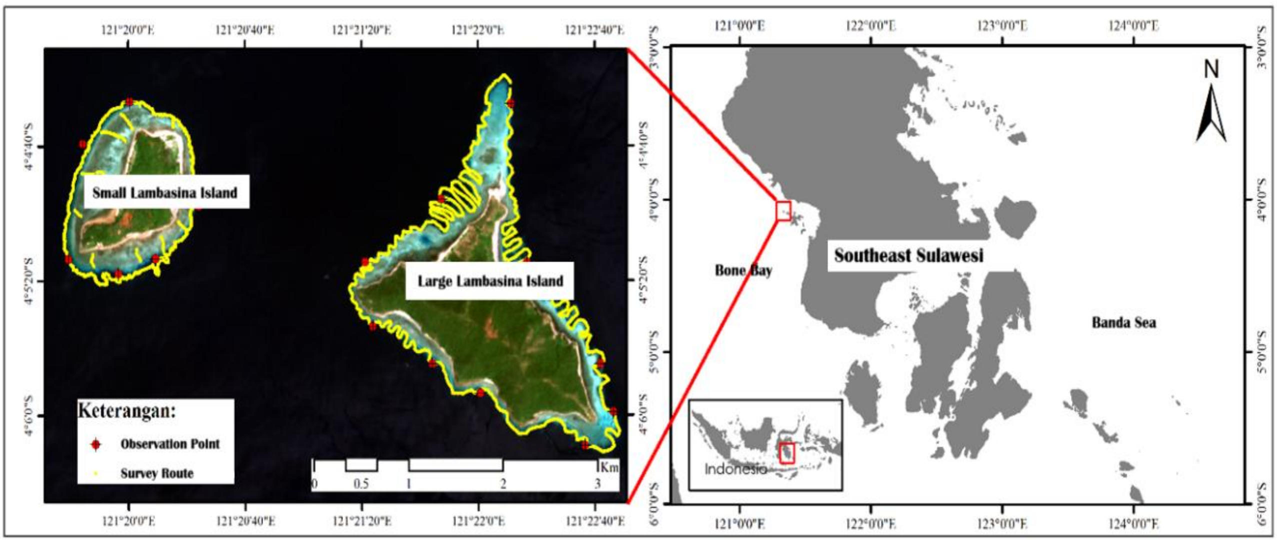

Figure 1. Research Location and Sampling Stations at Lambasina Island, Bone Bay, Southeast Sulawesi

Bathymetric Position Index (BPI)

Bathymetric data derived from satellite imagery, integrated with field survey data, serve as the initial dataset to generate BBPI (Broad Bathymetric Position Index) and FBPI (Fine Bathymetric Position Index) values. The standardization of BBPI, FBPI, and slope values is carried out to obtain geomorphological structure class values using the classification dictionary developed by Agus (2012), as shown in the Table 2.

Table1. Benthic Terrain Modeler Algorithms

Name	Algorithms	Description
BPI	$Z_{xy} - Z_{annulus}$	Calculation of the distance for each 3x3 adjacent pixel
Standard Deviation	$\frac{\sqrt{\sum_{i=x-(n+1)/2}^{x+(n+1)/2} \sum_{j=y-(n+1)/2}^{y+(n+1)/2} (Z_{ij} - Z)}}{n^2}$	Average slope value per pixel
Mean Depth	$\frac{\sum_{i=x-(n+1)/2}^{x+(n+1)/2} \sum_{j=y-(n+1)/2}^{y+(n+1)/2} Z_{ij}}{n^2}$	*n as the pixel size*
Variance	σ^2	σ Standard deviation calculated from neighboring pixels
Interquartile Range	$CDF^{-1}(0.75) - CDF^{-1}(0.25)$	Function to calculate all pixel distribution values through analysis *neighborhood*
Statistical Aspect	57,29578 x arctan 2$(\frac{dz}{dy} + \frac{dz}{dx})$	Generates east and north directions
Slope	arctan$\sqrt{(\frac{dz^2}{dx} + \frac{dz^2}{dy})}$	Calculates values based on pixel neighborhoods larger than 3 x 3

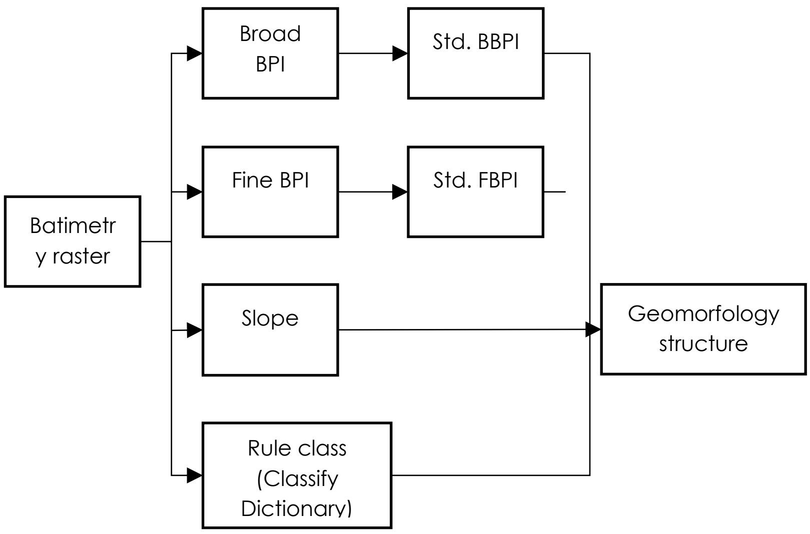

Figure 2. Flowchart Diagram of the Benthic Habitat Geomorphology Classification Procedure Using BTM

Table 2. Parameters in the Classification Dictionary of Geomorphological Structures

No	Zone	Broad BPI		Fine BPI		Slope		Depth	
		Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
1	Broad slope	-100	100	-100	100	5	45		
2	Crevices, narrow gullies rock outcrops	100			-100		5		
3	Current scoured depressions on slope		-100	-100	100	5			
4	Narrow depressions at the base of rock outcrops		-100		-100		5		
5	Flat plains	-100	100	-100	100		5		30
6	Flat ridge tops, upper slopes	100		-100	100	5		28	
7	Local depressions, current scours on flat	-100	100		-100		5		
8	Local ridges, boulders, pinnacles on slopes	-100	100	100		5			
9	Local ridges, boulders, pinnacles on broad depressions		-100	100			5		
10	Local ridges, boulders, pinnacles on broad flat	-100	100	100			5		
11	Rock outcrop highs, narrow ridges	100		100			5		
12	Scarp, cliff or small local depressions on slope	-100	100		-100	5			
13	Steep slopes	-100	100	-100	100	45			

RESULTS AND DISCUSSION

The bathymetric data used in this study, derived from satellite image transformation, is based on a previous work by the authors (Prasetya, Siregar, and Agus, 2023). That study employed the Support Vector Machine (SVM) algorithm to estimate bathymetry in the waters surrounding Lambasina Island, yielding accurate depth estimations with coefficients of determination (R^2) of 0.81 for Lambasina Kecil Island and 0.82 for Lambasina Besar Island.

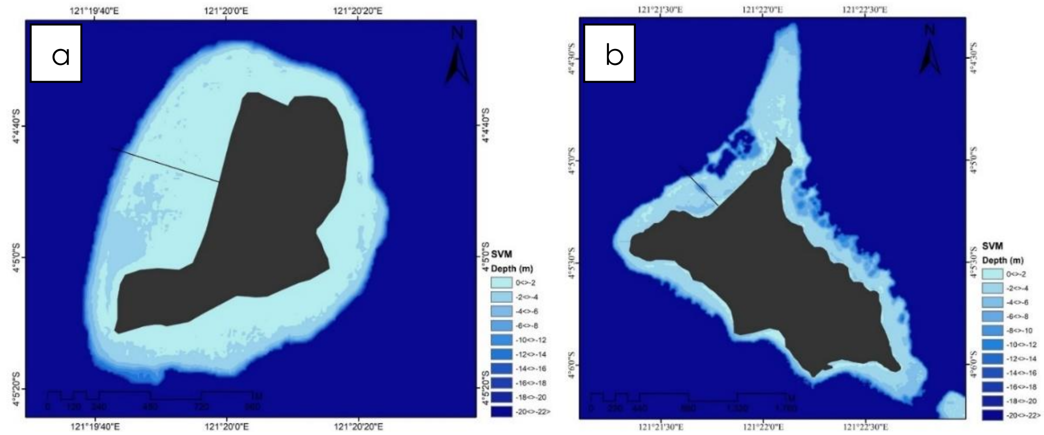

Figure 3. Support Vector Machine (SVM) algorithm model for bathymetric estimation in the Lambasina Islands: (a) Lambasina Kecil Island, (b) Lambasina Besar Island. Source: Prasetya, Siregar, and Agus (2023).

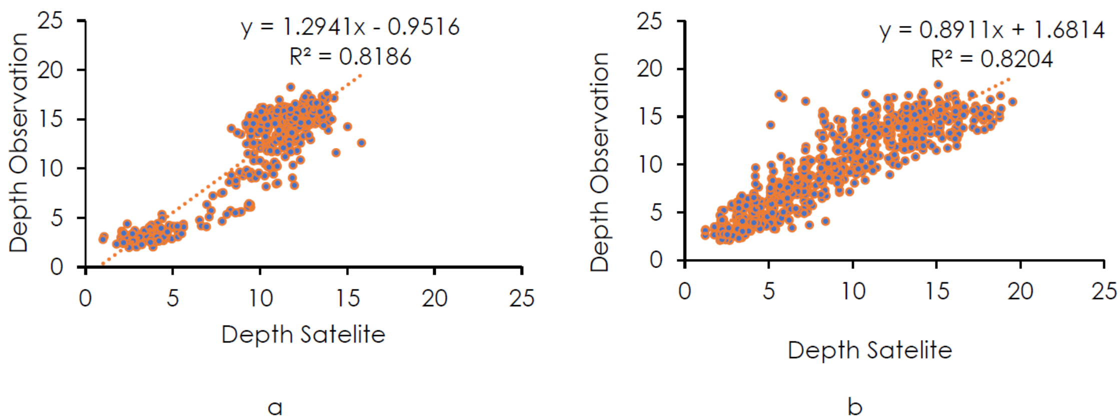

Figure 4. Regression plots comparing field-measured depth and SVM-estimated depth: (a) Lambasina Kecil Island, (b) Lambasina Besar Island. Source: Prasetya *et al*. (2023).

The estimation process was conducted using the reflectance ratio of the blue and green bands from Sentinel-2 imagery, processed with the Radial Basis Function (RBF) kernel in R software (e1071 package). The resulting bathymetric estimates were subsequently integrated with field-measured data to generate a Digital Elevation Model (DEM), which served as the primary input for classifying seafloor geomorphological structures using the Benthic Terrain Modeler (BTM) version 3.0.

The analysis for determining Fine BPI and Broad BPI begins by identifying the optimal scale factor using the inner and outer radius values as key parameters. This process aims to define the appropriate pixel radius around a focal point by applying a trial-and-error approach with several scale factor values. The selected spatial scales for Fine BPI and Broad BPI then serve as parameters for classifying seafloor surface structure types. The determination of the pixel radius around the focal point is based on the researcher's observations and adapted to the conditions of the study area. The inner and outer radius values are tested incrementally to obtain scale factors that are suitable for the study area. According to Subarno (2016), in underwater areas with wide basin-like features, the use of a too-small BPI radius may result in such areas being misclassified as flat zones. Conversely, using an excessively large BPI radius may cause areas with similar characteristics to appear as deep canyons.

The resulting BPI values varied considerably across several value ranges (Table 3). As shown in Table 3, an increase in scale factor corresponds to a wider range of BPI values. In this study, various BPI values were tested to select the most appropriate range and scale factor for application in the classification of seafloor structure types. Following a series of tests, suitable range values and scale factors were identified for use as input data. The selected scale factors were 86 for Fine BPI and 139 for Broad BPI, as these produced visualizations that closely represented actual field conditions, which were validated through in situ observations and coordinate-based feature sampling of benthic elements. Alternative scale factors resulted in visual outputs that differed significantly from what was observed at the study site. A previous study by Subarno (2016) applied a scale factor of 10 for Fine BPI and 120 for Broad BPI using a 2-meter pixel resolution in the waters of Pulau Kelapa, Harapan, and Pulau Kelapa Dua. The BPI value analysis results based on the selected scale factors are presented in Figure 5.

In addition to utilizing Fine BPI and Broad BPI data, the subsequent analysis incorporates slope data in raster format. Slope represents the degree of inclination or elevation change of the seafloor surface, measured in degrees. It indicates the maximum rate of elevation change within each pixel of the bathymetric raster dataset (NOAA Coastal Services Center, 2013).

Table 3. Parameters of BPI value ranges and scale factors

Uji Kombinasi	*Inner radius*	*Outer radius*	Skala BPI	*Scale factor*	Rentang nilai
1	5	8	*Fine*	86	-66
	10	13	*Broad*	139	-76
2	8	13	*Fine*	139	-76
	15	24	*Broad*	268	-75
3	10	15	*Fine*	161	-73
	10	13	*Broad*	139	-74
4	13	17	*Fine*	182	-72
	10	20	*Broad*	214	-73
5	13	23	*Fine*	246	-74
	25	30	*Broad*	321	-75
6	20	25	*Fine*	268	-77
	30	35	*Broad*	375	-71
7	18	22	*Fine*	236	-75
	30	40	*Broad*	428	-71
8	23	28	*Fine*	300	-75
	40	45	*Broad*	482	-75

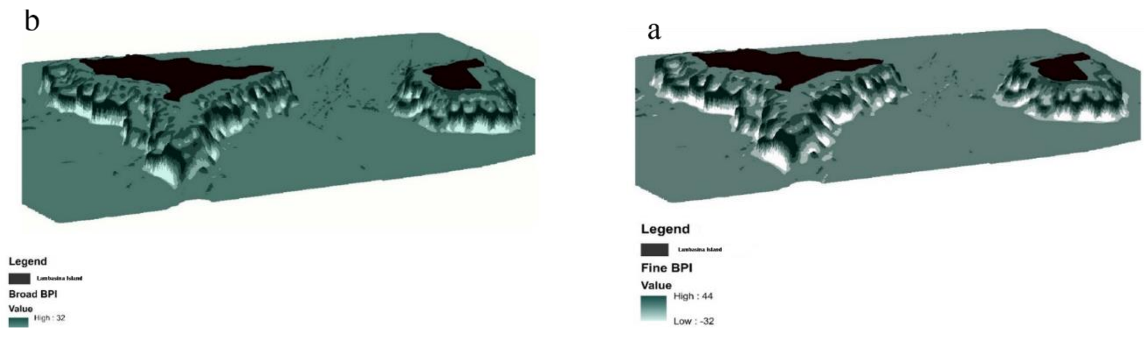

Figure 5. Bathymetry Position Index: (a) Fine BPI scale factor 86 (b); Broad BPI scale factor 139

A slope value of 0° denotes an entirely flat area, while higher values indicate increasingly steeper terrain. In this study, slope values were derived through the integration of remote sensing imagery and in-situ depth measurements, using a spatial resolution of 10 meters. The resulting slope values range from 0° to 70° degrees, reflecting the morphological variation of the seabed across the study area (Figure 6).

For comparison, a study conducted in the Duxbury coastal waters of the United States applied a 5-meter spatial resolution, producing slope values ranging from 0° to 40.8° degrees (NOAA Coastal Services Center, 2013). The choice of spatial resolution is critical, as it influences the accuracy in identifying geomorphological features such as reef slopes, terraces, and transitional zones between shallow flats and steep underwater slopes.

A study conducted by Agus (2012) in the coastal waters surrounding Pramuka Island, Panggang Island, and Karya Island utilized raster data with a spatial resolution of 1 meter, producing slope values ranging from 0° to 83.5° degrees. The high spatial resolution allowed for more detailed and accurate identification of seafloor morphological features within the study area.

In contrast, a subsequent study by Subarno (2016) applied a 2-meter pixel resolution to slope analysis across several other islands, including Panjang Island, Kelapa Dua Island, Kelapa Island, Harapan Island, and Kaliage Island. The resulting slope values ranged from 0° to 75.6° degrees, reflecting the complex bottom topography of these marine environments.

The visualization of slope data for Lambasina Kecil Island and Lambasina Besar Island in this study is presented in Figure 6. This spatial visualization illustrates the variability of seabed inclinations, which plays a crucial role in understanding the geomorphological structure and habitat characteristics of shallow marine ecosystems.

The use of the Benthic Terrain Modeler (BTM) for seafloor structure classification requires input data such as the Bathymetric Position Index (BPI) and bathymetric slope, as well as a classification dictionary that serves as the main parameter for defining geomorphological classes. This dictionary contains the number and types of classes determined according to the analytical objectives of benthic terrain mapping and is usually prepared in Microsoft Excel and saved in CSV format for automated classification by BTM. The classification scheme is based on threshold values of BPI and slope, following the guidelines of the NOAA Coastal Services Center (2013).

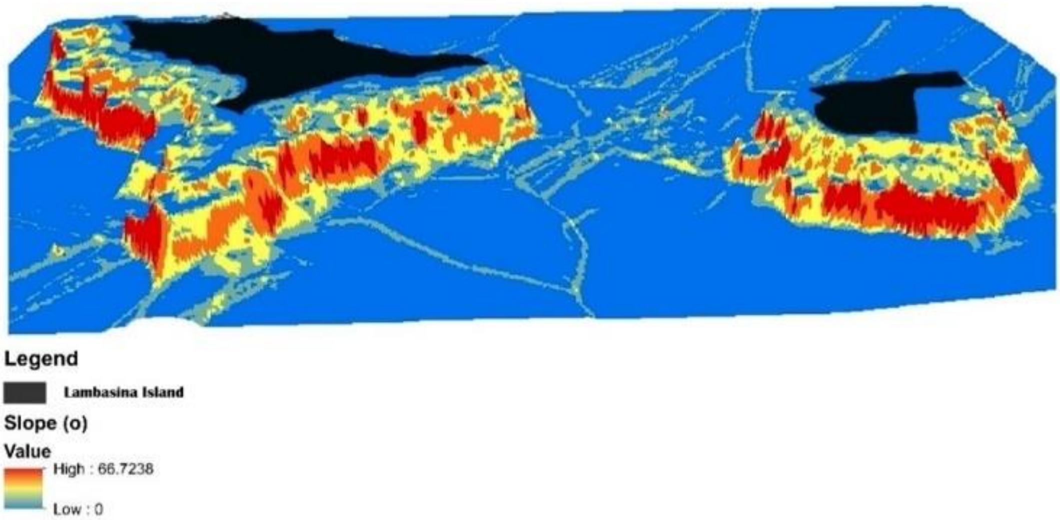

Figure 6. 3D visualization of slope data

According to the classifications proposed by Erdey-Heydorn (2008) and Agus (2012), the seafloor structure can be grouped into several main classes. Broad Slopes are gently inclined reef areas (5°–45°) that act as transitional zones between shallow flats and deeper waters. Crevices or Narrow Gullies are small fissures between reef or rock outcrops serving as microhabitats for marine organisms. Current-Scoured Depressions are U-shaped erosional features formed by persistent currents, while Flat Plains are nearly level seabed areas (<5° slope) composed of sand, coral rubble, or soft sediment.

Other classes include Local Ridges, Boulders, or Pinnacles, representing isolated elevated structures that increase habitat complexity; Rock Outcrop Highs or Scarps, which are steep or raised reef formations clearly visible in BPI analyses; and Steep Slopes, sharply inclined reef sections (>45°) marking the transition between shallow and deeper marine environments.

The analysis derived from the combined input of Fine BPI, Broad BPI, and slope data produces a set of benthic geomorphological classes, represented in the form of raster outputs. Each class or geomorphic zone consists of clusters of pixels, which are grouped based on shared spatial characteristics and classified according to pre-defined threshold values for each parameter.

Following classification, the raster data can be converted into vector format SHP (shapefile) to enable further spatial analysis. This transformation facilitates more precise area calculations for each geomorphic class and allows seamless integration with other geospatial datasets within a Geographic Information System (GIS) environment. Such a process is essential for applications in habitat mapping, marine spatial planning, and the development of ecosystem-based management strategies for coastal and marine areas.

Observations from the cross-transect survey conducted on Pulau Lambasina Kecil illustrate the condition of the coral reef zones, which include deep sea, reef slope, outer reef flat, lagoon, inner reef flat, land, reef flat, reef crest, reef slope, and patch reef. The placement of the transect line in this area was based on field observations, taking into account the diverse benthic habitat conditions. The coral reef zonation profile at this location reflects a complex seabed environment with excellent live coral cover extending to depths of up to 29 meters (Figure 7).

Table 4. BPI value range parameters and scale factors

No	Pixel Count	Structure Class	Area (Ha)
1	110181	*Local ridges, boulders, pinnacles on broad depressions*	47,19
2	311705	*Broad slope*	133,51
3	442	*Crevices, narrow gullies rock outcrops*	0,19
4	105022	*Current scoured depressions on slope*	44,98
5	480313	*Narrow depressions at the base of rock outcrops*	205,72
6	1252172	*Flat plains*	536,32
7	62044	*Flat ridge tops, upper slopes*	26,57
8	24099	*Local depressions, current scours on flat*	10,32
9	15970	*Local ridges, boulders, pinnacles on slopes*	6,84
10	5888	*Local ridges, boulders, pinnacles on broad flat*	2,52
11	504297	*Rock outcrop highs, narrow ridges*	215,99
12	35112	*Scarp, cliff or small local depressions on slope*	15,04
13	8664	*Steep slopes*	3,71

Each coral reef zone contains a variety of life forms, particularly in the reef flat, reef crest, and reef slope areas. The live coral lifeforms found in the reef flat and reef crest zones are dominated by hard corals with massive and *Acropora branching* growth forms, as well as coral rubble. In the outer parts of the reef crest and slope, extensive coral rubble is observed, resulting from destructive fishing practices such as blast fishing and damage from boat anchors. At depths between 20 to 29 meters, soft corals and sponges of various sizes and types are more commonly found. Each coral species has different tolerance levels for depth and light requirements, which leads to structural variations in reef biomass. It can be assumed that the condition of soft coral cover is influenced by depth, as depth is a key factor affecting the vertical distribution of corals and the diversity of benthic marine fauna (Supriharyono, 2000).

Seabeed surface around Pulau Lambasina displays considerable complexity, both in terms of benthic cover and reef fish diversity in the area. Observations of geomorphological structure classes were conducted using cross-transects and analyzed with ArcGIS tools, specifically the Benthic Terrain Modeler (BTM), revealing highly varied structure classes in different parts of the island. Representative observations were conducted along a straight transect from the northern to the southern part of the island to characterize the geomorphological structure classes (Figure 8).

The structural profile of geomorphological classes around Pulau Lambasina Besar shows variation in depth structures at different depth levels. Observations along the transect line revealed a steep slope with depths reaching up to 65 meters. This study refers to the classification scheme developed by Lundblad *et al*. (2006) and Erdey-Heydorn (2008), as well as the number of classes used by Agus (2012) in his research around Pulau Panggang and surrounding waters. In this study, conducted in the waters of Pulau Lambasina, a benthic structural classification scheme with 13 classes was applied, each representing a different type of benthic habitat structure (Figure 9).

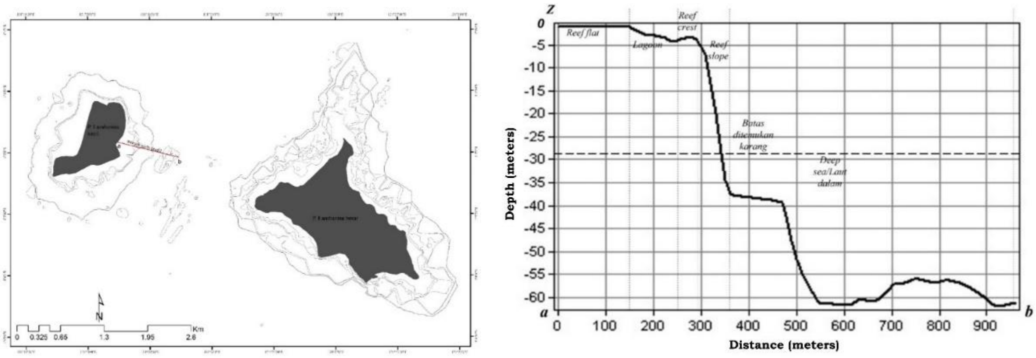

Figure 7. Depth Profile and Coral Reef Zonation

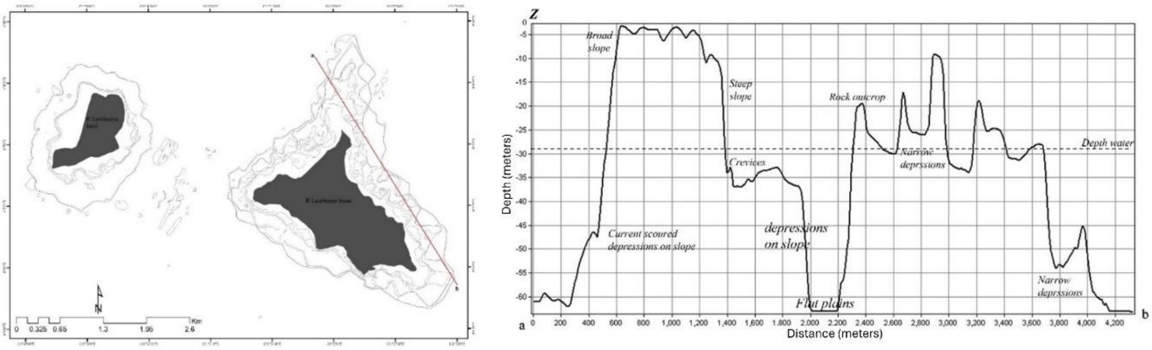

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Figure 8. Depth Profile and Geomorphological Structure Classes

Benthic habitats with diverse geomorphic structures were commonly found in steep slope areas, particularly in the patch reef and reef slope zones. Field observations on both Pulau Lambasina Kecil and Pulau Lambasina Besar revealed a wide variety of benthic features that could be identified through coral lifeforms (growth forms). In areas with slope values close to 0°, the benthic features were identified as flat plains inhabited by massive coral colonies. In contrast, benthic features such as broad slopes, crevices, and narrow gullies between rock outcrops were found in areas with slopes approaching 90°, where numerous coral fragments and breakage were observed. The visualization of geomorphological structures across both islands provides a clear depiction of the area's condition based on the derived classes (Figure 9).

The coral reef ecosystem area can be utilized for further research, such as examining and analyzing the geomorphology of shallow seabeds. Several studies have linked habitat complexity representing geomorphological structure with biomass abundance in coral reef ecosystems. Agus (2012) studied fish spawning habitats and their relationship with benthic geomorphology in the waters around Pulau Panggang. The study found that areas with high habitat complexity often contain unique benthic geomorphological features, particularly on reef slopes favored by fish, where many spawning sites were also identified.

Wedding *et al*. (2008) combined in-situ measurements of habitat complexity with remote sensing of fish biomass in the waters of Hanauma Bay, Oahu Island, Hawaii. They found a strong correlation between biomass volume and habitat complexity. This finding aligns with studies by Agus (2012), Wedding *et al*. (2008), and Kuffner *et al*. (2007), who analyzed the relationship between reef fish communities and habitat complexity using remote sensing in Biscayne National Park. Meanwhile, Fuad (2010) conducted research on the complexity of coral reef areas and coral biodiversity in Bunaken National Marine Park. Based on these studies, the current research can contribute valuable insights into biodiversity and biomass abundance both in the study area and in similar regions.

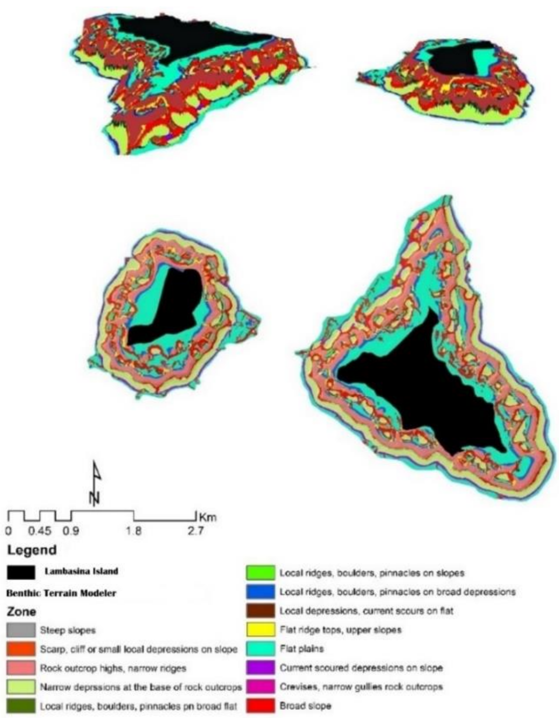

Figure 9. Representative structure classes in each area of Pulau Lambasina: a) Local ridges, boulders on broad slope; b) Crevices, narrow gullies between rock outcrops; c) Flat area / flat plains; d) Broad slope; e) Local ridges, boulders, pinnacles on broad flats; f) Steep slope.

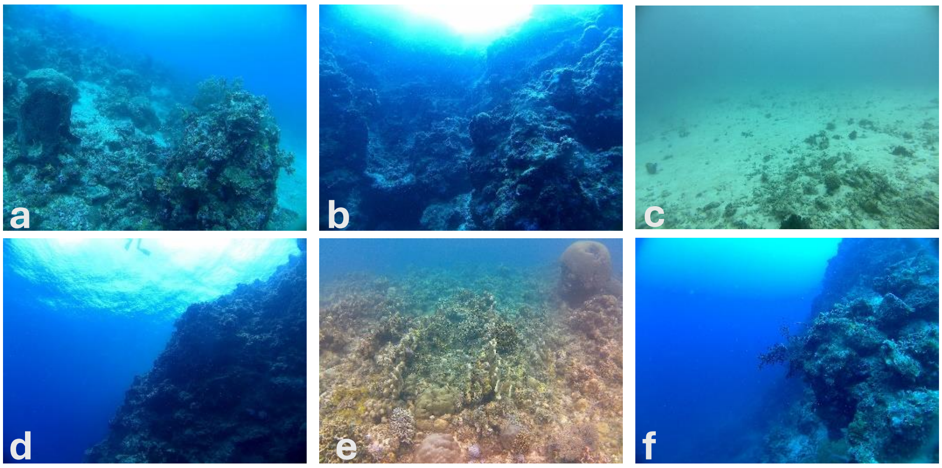

Figure 10. 3D Geomorphological Structure Classification of Lambasina Seafloor

CONCLUSION

This study successfully demonstrated the application of Satellite-Derived Bathymetry (SDB) and the Benthic Terrain Modeler (BTM) for mapping submarine geomorphological structures in the waters around Lambasina Besar and Lambasina Kecil Islands, Kolaka Regency. Using Sentinel-2 imagery processed with the Support Vector Machine (SVM) algorithm, accurate bathymetric estimations were obtained and integrated with field-measured data to produce reliable depth models. The classification of seafloor morphology identified 13 distinct geomorphological structure classes, revealing the complexity and variability of benthic habitats across the study area. These include flat plains, steep slopes, broad slopes, ridges, crevices, and other localized features that contribute to habitat diversity. Field observations confirmed that geomorphological structure plays a significant role in shaping benthic habitat types and coral reef zonation. The presence of diverse coral lifeforms and benthic features at varying depths and slopes illustrates the ecological richness and structural complexity of the area. This study highlights the importance of geomorphological mapping for understanding habitats and provides a basis for future research on habitat complexity and biodiversity.

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