Mapping of shallow water bathymetry and reef geomorphology using Sentinel-2 satellite imagery in Genteng Besar and Genteng Kecil Island, Kepulauan Seribu

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Abstract. Information on seafloor characteristics is one of the essential variables in coastal management and marine ecosystems. Application methods in remote sensing technology to study about characteristics of shallow waters have continuously been done. This research consists of two parts: an estimation of depth using Sentinel 2B satellite imagery with the Lyzenga algorithm and geomorphological classification of the benthic area using the Benthic Terrain Modeler (BTM) approach. BTM is a method to analyze benthic habitat and shallow water geomorphology. Integrated Depth data were analyzed using BTM to obtain bathymetric position index (BPI), slope, and classification of reef geomorphological structures. The resulting BPI value range is directly proportional to the given spatial area (scale factor). The slope is ranged between 0.01° – 19.24°, while optimum depth estimation is applicable until 10-meter. The values of BPI and slope were used as variables to classify the geomorphology of shallow water benthic areas based on the previous classification dictionary. Six geomorphological classes resulting from this study are Back Reef, Deep Depression, Depression, Lower Bank Shelf, Mid-Slope Ridges, and Reef Crest.

Keywords: bathymetry, coral reef, geomorphology, Kepulauan Seribu, Sentinel-2

1. Introduction

Bathymetry is the primary information in mapping and studying the geomorphological structure of shallow-water habitats [1]. The application of optical remote sensing in mapping shallow water depth is determined by the penetration of electromagnetic waves in sensors installed in each type of satellite [2]. Each satellite imagery has its characteristic in electromagnetic wavelength (spectral resolution) that is different from each other. Differences are also found in spatial resolution, temporal resolution, and radiometric resolution, affecting shallow water depths estimation [2].

Several algorithms have been developed to estimate depth using satellite imagery. One algorithm utilizes the ratio of two optical bands penetrating into the water column until reaching the bottom [3-4]. This algorithm is the basis for developing this algorithm due to differences in the spectral response of the water column and the bottom of the water to the electromagnetic waves at different wavelengths [4]. Diverse benthic communities in shallow coral reefs and antecedent topography resulted in current bathymetry, thus allowing for studying reef geomorphological structure and rugosity [5]. Wright et al. [5] have developed an open-source package to study about geomorphological structure of shallow-water benthic habitats called Benthic Terrain Modeler (BTM) [5]. This BTM tool is integrated with

IOP Conf. Series: Earth and Environmental Science **944** (2021) 012048 doi:10.1088/1755-1315/944/1/012048

ArcGIS spatial data processing software. These tools provide convenience to users in assessing the geomorphology of aquatic habitats for research and resource management purposes [5-7]. This study consists of two parts: estimating the depth of the waters using Sentinel 2B imagery with the Lyzenga algorithm and geomorphological classification of the benthic area using the BTM.

2. Materials and methods

2.1. Field depth measurements and image data sets

Field data collection was carried out on November 8th, 2019, in Genteng Islands to measure the depth at different reef habitats. The depth measurement was conducted manually using a scale stick and recorded GPS points (Figure 1). A total of 94 ground-check points were collated in this study.

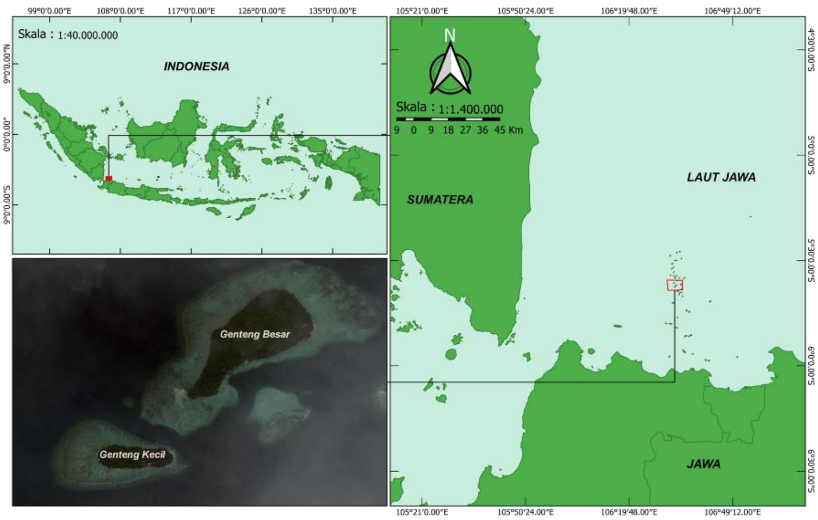

Figure 1. Research site, Genteng Kecil and Genteng Besar Island, Kepulauan Seribu.

The data used in this research is Sentinel 2B satellite imagery acquired on July 18th, 2021, where the characteristics can be seen below in Table 1.

Table 1. Characteristics of Sentinel 2B Imagery.

Band	WaveLength (Micrometer)	Spatial Resolution (Meter)
Band 1 – Coastal Aerosol	0.443	60
Band 2 – Blue	0.49	10
Band 3 – Green	0.56	10
Band 4 – Red	0.665	10
Band 5 – Vegetation Red Edge	0.705	20
Band 6 – Vegetation Red Edge	0.74	20
Band 7 – Vegetation Red Edge	0.783	20
Band 8 – NIR	0.842	10
Band 8a – Vegetation Red Edge	0.865	20
Band 9 – Water Vapour	0.945	60
Band 10 – SWIR (Cirrus)	1.375	20

Band	WaveLength (Micrometer)	Spatial Resolution (Meter)
Band 11 – SWIR	1.61	20
Band 12 – SWIR	2.19	60

2.2. *Pre-processing*

2.2.1. Radiometric correction. Radiometric calibration was used to convert the value of satellite data using top of atmospheric (TOA) and bottom of atmospheric (BOA) to obtain reflectance values from the image (surface and bottom reflectance). Radiometric correction, in general, uses the dark dense vegetation (DDV) algorithm, which assumes that the surface reflectance in the red channel is a constant ratio of the blue channel [8-9]. The equation of this algorithm is:

$$\rho_{red}^{s} = k\rho_{blue}^{s} \tag{1}$$

Where, ρ_{red}^{s} and ρ_{blue}^{s} are spectral surface reflectance angles at wavelengths of 0.66 micrometers and 0.47 micrometers, and k is a constant value.

2.2.2. Atmospheric correction. Atmospheric correction is carried out to eliminate atmospheric disturbances in image data. There are various methods of radiometric correction. The simplest method commonly used is to subtract the pixel dark value from the pixel initial value [10]. The algorithm is written with the equation below:

$$R_{ac} = R_i - R_{dp} \tag{2}$$

Where, R_{ac} is the corrected pixel value R_i is the initial pixel value and R_{dp} is the dark pixel value.

2.2.3. Sun glint correction. The removal of the influence of sun glint on the image using the simplified method by Hedley *et al* in [10] from the method developed by Hochberg *et al*. This method improved by the previous method by establishing a linear relationship between the NIR band and the visible band (RGB) using linear regression based on a sample of image pixels [10].

$$R'_i = R_i - b_i\,(R_{NIR} - Min_{NIR}) \tag{3}$$

Where, R'_i is the corrected pixel value, R_i is the initial pixel value, b_i is the slope of the regression line, and R_{NIR} is the minimum NIR value in the pixel sample.

2.3. *Empirical bathymetry*

Previous study suggested that the errors resulting from different bottom types could be corrected using two bands [11]. The ratio of the bottom reflectance between the two bands for all bottom types is constant over the scene [11]. The proposed model is:

$$Z = a_0 + a_i X_i + a_j X_j \tag{4}$$

Where

$$X_i = ln(R_{w,i} - R_{dp,i})$$

$$X_j = ln(R_{w,j} - R_{dp,j})$$

$a_0, a_i X_i, a_j X_j$ = coefficients determined through multiple regression using known depths and the corresponding reflectance.

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$R_{w,i}, R_{w,j}$ = Observed reflectance in band *i* and *j*
$R_{dp,i}, R_{dp,j}$ = Reflectance of dark water pixel in bands *i* and *j*

2.4. Benthic terrain modeler
Benthic terrain modeler (BTM) is a set of spatial analysis packages for benthic characteristics developed by Oregon State University Department of Geosciences with the National Oceanographic and Atmospheric Administration (NOAA) Coastal Service Center's GIS Integration and Development Program [5]. The concept of BTM is an analysis of characteristics of benthic features from a geomorphological perspective. BTM analysis was carried out by the bathymetric data and will produce several outputs in the form of bathymetric position index (BPI), geomorphological zone/structure, slope, the surface rugosity of the waters, and several other outputs required for benthic habitat analysis. The use of algorithms in BTM applications can be seen in Table 2 [12].

Table 2. Calculation of terrain attributes using BTM.

Name	Algorithm	Description
Slope	$\arctan\sqrt{(\frac{dz^2}{dx}+\frac{dz^2}{dy})}$	Calculate more than 3 x 3 pixels that close each other
Statistical aspect	57,29578 x arctan 2 $(\frac{dz}{dy}+\frac{dz}{dx})$	Produces east and north directions
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 is the pixel size
Standard Deviation	$\sqrt{\frac{\sum_{i=x-(n+1)/2}^{x+(n+1)/2}\sum_{j=y-(n+1)/2}^{y+(n+1)/2} (Z_{ij}-\bar{Z})^2}{n^2}}$	$\bar{Z}$ is the average elevation value of the pixels in the *neighborhood analysis.*
Variance	σ^2	σ is the standard deviation of the adjacent pixels
Interquartile Range	$CDF^{-1}(0.75) - CDF^{-1}(0.25)$	*CDF* is the cumulative distribution function of all pixels in the *neighborhood analysis*
Kurtosi	$\frac{\mu_4}{\sigma^4}$	μ_4 is the fourth central moment and σ^4 is the standard deviation of all pixels in the *neighborhood analysis*
BPI	$z_{xy} - \acute{Z}_{annulus}$	$\acute{Z}_{annulus}$ is the average value of the elevation of all pixels in the *annulus-shaped neighborhood*
VRM	$R = \frac{A_{contoured\ area}}{A_{planalar\ area}}$	Rugosity

2.4.1. Bathymetric position index and slope. The calculation of BPI and slope of the shallow water surface area from the depth data is carried out first before classifying the structure and geomorphological zone of shallow water habitats at the research site. BPI is a calculation that describes the elevation of each point on the bottom surface of the waters with reference to the elevation ratio of the surrounding points [13]. Each point represents the pixel size in the bathymetric data used. Limiting the area or radius of the number of neighboring pixels included in the calculation from a point (focal point) is necessary for calculating the BPI value. The value of the bottom slope of the benthic habitat is calculated separately with BPI calculations to obtain the bottom surface level of slope using the BTM packages.

2.4.2. Classification dictionary. The combination of broad BPI (BBPI), fine BPI (FBPI), standardized results from BBPI and FBPI, and slopes are used to classify reef geomorphological structures and zones using the classification dictionary [14] to build a classification scheme at the Point Reyes National Seashore location and [12] established a classification scheme for the Buck Island Reef National site. The combination of the two classification dictionaries can be seen in Table 3.

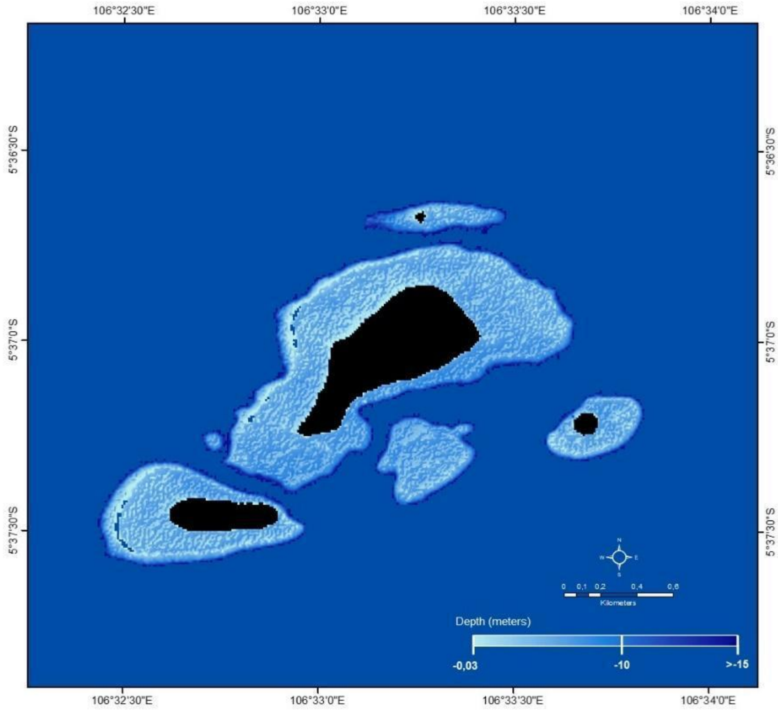
Table 3. Combined classification dictionary from [6, 12-13].

Class	Zone	Broad BPI (Lower)	Broad BPI (Upper)	Fine BPI (Lower)	Fine BPI (Upper)	Slope (Lower)	Slope (Uppe r)	Depth (Lowe r)	Depth (Upper)
1	Reef Crest		-100		-100				
2	Mid-Slope Ridges		-100	-100	100				
3	Back Reef		-100	100					
4	Upper Slopes	-100	100		-100				
5	Lower Bank Shelf	-100	100	-100	100		28.907		30
6	Upper Reef Flat	-100	100	-100	100		28.907	28	
7	Open Slopes	-100	100	-100	100	28.907	88.099		
8	Depression	-100	100	100					
9	Back Reef		100		-100				
10	Mid-Slope Depressions		100	-100	100				
11	Deep Depression	100		100					
12	Reef Flat	-9	541	-459	1333		67	-8	
13	Channel	-323	384	-907	1333		53	-12	-1
14	Fore Reef	-323	541	-1355	2229		61	-14	
15	Lagoon	-166	463	-459	1333		49	-7	
16	Salt Pond	-9	-9	-11	-11		53	-7	
17	Shoreline Intertidal	-9	384	-11	436		19	-2	

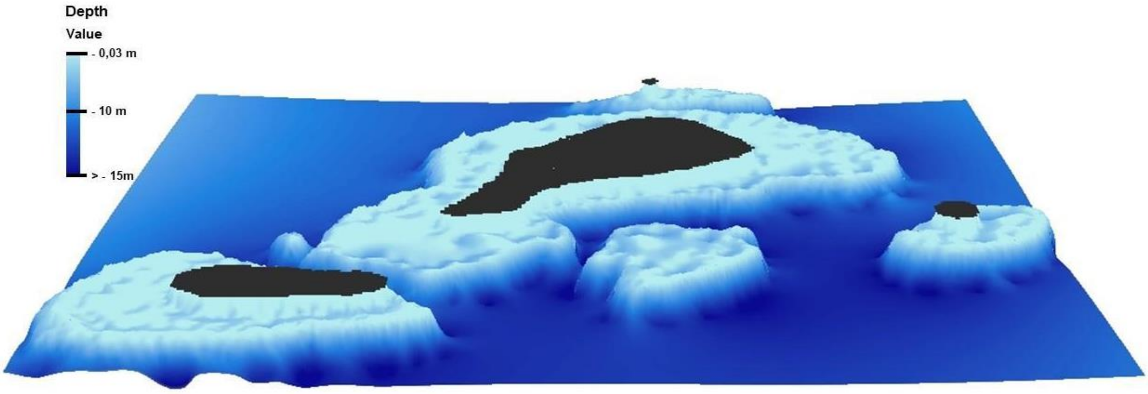
3. Results and discussion

3.1. Bathymetry

Depth estimation using Sentinel 2 imagery was resulted from regressing values from blue and green bands. According to Lyzenga [3, 13], using two or more bands for bathymetric estimation is helpful in bottom albedo correction. In this case, the blue and green bands showed a reasonably good coefficient of determination so that the equations from the regression of these two bands are used for the actual depth transformation, as presented in Figure 2. The algorithm was optimum to profile 10 m-depth.



(a)



(b)

Figure 2. Empirical Bathymetry using Lyzenga Algorithm: (a) 2D; (b) 3D.

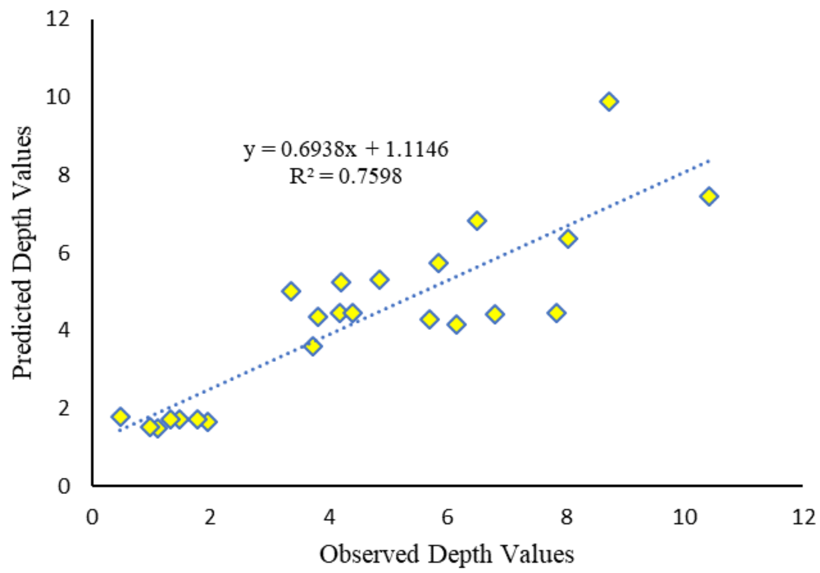


Figure 3. Correlation between observed depths and predicted depths.

Tidal correction against collated depth data was conducted despite the small nature of the tidal range, approximately 0.8 m between Mean Highest High Water to Mean Lowest Low Water. Accuracy assessment was applied to determine the difference between the depth of the estimation results and the depth of field measurements. The coefficient of determination (R^2) from the correlation between field depth data and depth of transformation (Figure 3) is 0.7598.

3.2. Benthic terrain modeler

3.2.1. Bathymetric position index (BPI) and slope. Bathymetric Position Index (BPI) is one of the derivatives of bathymetric data. It is used to determine a location with specific areas and features relative to other areas and features in the same dataset (raster) [15]. In another explanation, BPI is a calculation that describes the elevation of each point on the surface of the bottom of the water for the reference comparison with the surrounding points [13]. The dots represent the position (X, Y), depth (Z) and pixel size (spatial resolution), and the bathymetric raster data used.

The calculation of BPI is a modification of the Topographic Position Index (TPI), which was developed by Weiss [16] for use in terrestrial environments [5]. In its application to characterize the bottom surface of the waters, modifications have been made from the BPI, including using the elevation (Z) value to be negative, which describes the depth [13].

The BPI calculation results are in the range of negative to positive values representing each raster pixel. A negative value describes the pixel's lower position than the surrounding pixels, for example, a valley formation. A positive value describes the position of a pixel higher than the surrounding pixels, for example, the formation of a ridge [13]. The more negative or positive the BPI value is produced in a pixel, the more extreme the pixel's benthic characteristics. Conversely, a flat area or an area with a constant slope will produce a BPI value close to 0 (zero).

BPI analysis requires radius input in the form of inner and outer radius, which is the limit of the number of neighboring pixels from a focal point of each pixel. The radius is needed as a multiplier against the pixel resolution to get the BPI_Scalefactor. In addition, the BPI analysis process is carried out on two scales, namely a wider scale (Broad BPI) and a narrow scale (Fine BPI). Determination of the radius value is a trial and error that is adjusted to the area of the study area.

IOP Conf. Series: Earth and Environmental Science **944** (2021) 012048 doi:10.1088/1755-1315/944/1/012048

The radius value used in the study is for Broad BPI using an inner radius of 25 and an outer radius of 250, while for Fine BPI uses an inner radius of 3 and an outer radius of 25. The Broad BPI and Fine BPI results are obtained in a range of -4 – 5 for broad BPI and -3 – 6 for fine BPI. The combination of values applied in determining BPIs was related to generating a more detailed bathymetry suitable with complex reef benthic environments [1]. In general, seascape features of Genteng Islands are represented Figure 4. There are at least three seascape structures, namely plains, which surround the entire islands, and valleys, in areas where reef slopes existed in the outer part of the coral cays.

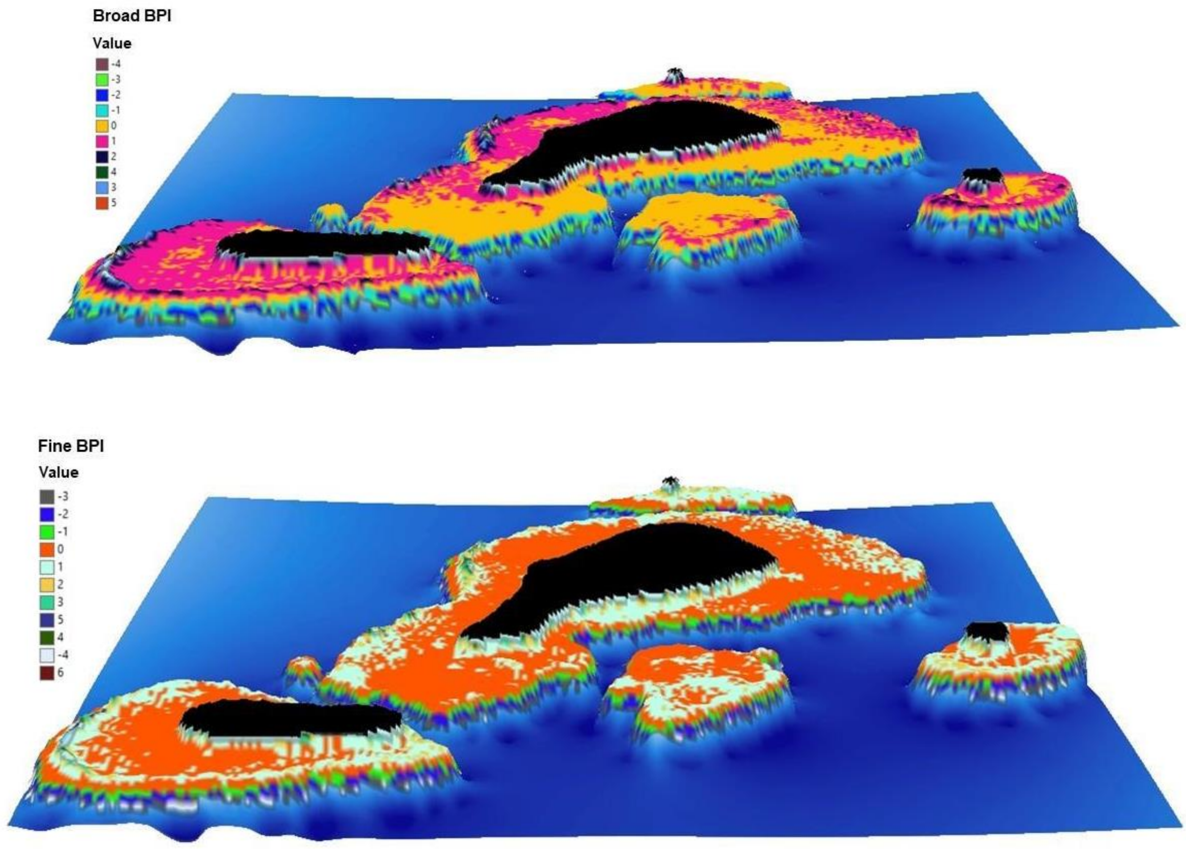


Figure 4. Broad BPI (above) and Fine BPI (below).

The slope or gradient of the surface is the maximum change value for each pixel of the water level/depth raster data [15]. The slope calculation data from the bathymetry raster produces the position values of each pixel to the surrounding pixels. The resulting value is in degrees. The lowest value at 0 describes a pixel equivalent to the surrounding pixels (flat). The maximum value depends on the characteristics of the bottom surface of the water and the pixel size (spatial resolution) of the raster data used. The slope value obtained is in the range of 0.01° – 19.24° (Figure 5). Furthermore, the slope value from this calculation is used to classify the basic surface structure of the water along with the standardized broad and fine BPI. Meanwhile, the rugosity value ranges from 0.024 to 0.103 (Figure 6), referring to a more surface roughness with a higher value.

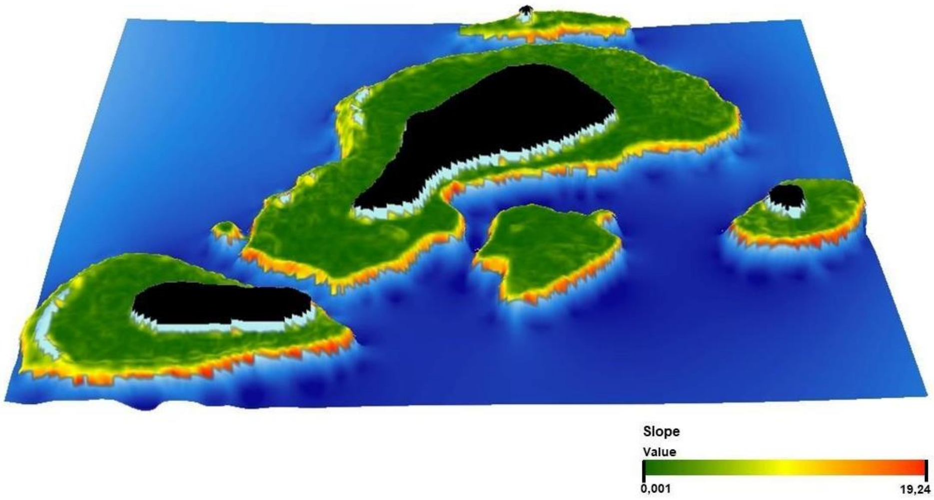


Figure 5. Slope.

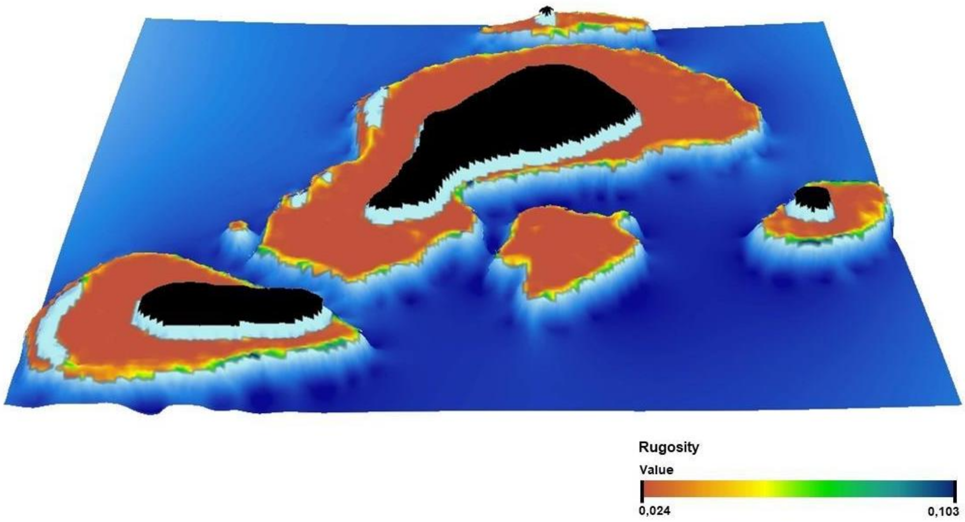


Figure 6. Rugosity.

3.2.2. Geomorphological terrain structure classification. Classification of the basic surface structure of the water using BTM analysis and using BPI and slope data also requires a classification dictionary that has been prepared. The classification dictionary contains classification scheme information, in this case, the number of terrain classes classified based on parameters that refer to the BPI value and slope. The classification dictionary is compiled using Microsoft Excel and stored with the CSV (Comma Separated Value) extension. Figure 7 is a 3D visualization of the classification of shallow water geomorphological structures in the waters of Genteng Besar and Genteng Kecil Island.

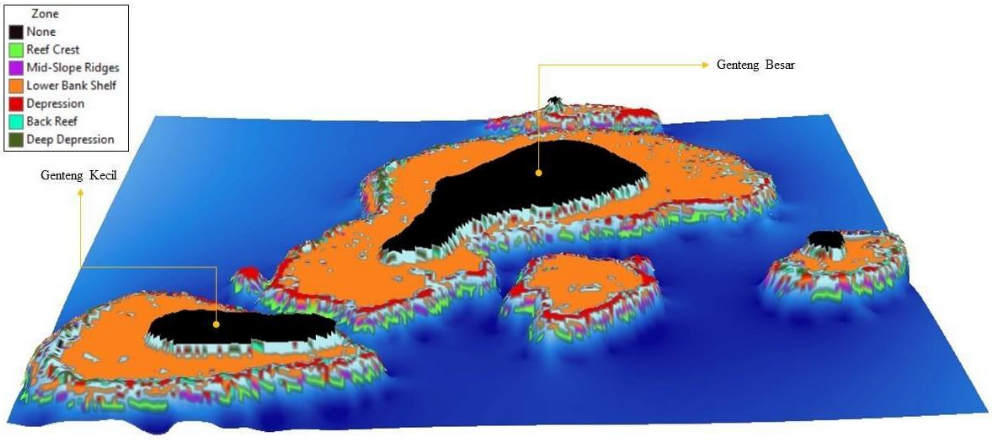


Figure 7. 3D visualization of benthic geomorphological structures in Genteng Besar and Genteng Kecil Island.

In Figure 7, it can be seen that the terrain class is dominated by the lower bank shelf and has various complexities found in areas with significant slopes, both in the deep depression, depression, and reef crest zones. The dominance of the lower bank shelf zone tends to be flat because in BPI calculations, both fine and broad, it is infrequent to detect various benthic features in this area.

4. Conclusion

The map of shallow water bathymetry and reef geomorphology structure was produced for Genteng Islands, Kepulauan Seribu. The combination of Sentinel-2B satellite with Lyzenga algorithm and field observation showed optimum depth-estimation at 10-meter depth. At the same time, BTM analysis has resulted in 6 classes of geomorphology structure, with lower bank shelf as the prominent class and reef environment with large slopes having a more complex structure.

References

[1] Agus S B, Siregar V P, Begen D G and Hanggono A 2012 Profil batimetri habitat pemijahan ikan terumbu hasil integrasi data indraja satelit dan akustik *Jurnal Teknologi Perikanan dan Kelautan* **3(**1) 45-61
[2] Misra A, Vojinovic Z, Ramakrishnan B, Luijendijk and Ranasinghe R 2018 Shallow water bathymetry mapping using support vector machine (SVM) technique and multispectral imagery *Int. J. Remote Sens.* **2018** 1-20
[3] Lyzenga D R 1978 Remote sensing of bottom reflectance using combined lidar and passive multispectral scanner data *Int. J. Remote Sens.* **6(**1) 115-25
[4] Stumpf R P, Holderied K and Sinclair M 2003 Determination of water depth with high resolution satellite imagery over variable bottom types *Limnol. Oceanogr.* **48(**1) 547-56
[5] Wright D J and Heyman W D 2008 Introduction to The Special Issue: Marine and coastal GIS for geomorphology, habitat mapping, and marine reserves *Mar. Geod.* **31** 223-30
[6] Lundblad E R, Wright D J, Miller J, Larkin E M, Rinehart R, Naar D F, Donahue B T, Anderson S M and Mattista T 2006 A benthic terrain classification scheme for American Samoa *Mar. Geod.* **29** 89-111
[7] Wedding L M, Friedlander A M, McGranaghan M, Yost R S and Monaco M C 2008 Using bathymetric lidar to define nearshore benthic habitat complexity: Implication for management of reef fish assemblages in Hawaii *Remote Sens. Environ.* **112** 4159-65
[8] Hsu C N, Tsay S C, King M D and Herma J R 2004 Aerosol properties over bright-reflecting *IEEE Trans. Geosci. Remote Sens.* **42(**3) 557-69

IOP Conf. Series: Earth and Environmental Science **944** (2021) 012048 doi:10.1088/1755-1315/944/1/012048

[9] Sterckx S and Wolters E 2019 Radiometric top-of-atmosphere reflectance consistency assessment for Landsat 8/OLI, Sentinel-2/MSI, PROBA-V, and DEIMOS-1 over Libya-4 and RadCalNet calibration sites *Remote Sens*. 11 2253
[10] Doxani G, Papadopulou M, Lafaxani P and Tsakiri S M 2012 Shallow water bathymetry over variabel bottom types using multispectral WorldView Image *Int. arch. photogramm. remote sens. spat. inf. sci.* **39(**8) 329-40
[11] Lyzenga D R 1981 Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data *Int. J. Remote Sens.* **2(**1) 71-82
[12] Walbridge S, Slocum N, Pobuda M and Wright D J 2018 Unified geomorphological analysis workflows with benthic terrain modeler *Geosciences* **8(**94) 2-24
[13] Erdey-Heydorn M D 2008 An ArcGIS seabed characterization toolbox developed for investigating benthic habitats *Mar. Geod.* **31** 318-58
[14] Lyzenga D R 1985 Shallow water bathymetry using combined lidar and passive multispectral scanner data *Int. J. Remote Sens.* **6(**1) 115-25
[15] NOAA Coastal Service Center 2013 Benthic Terrain Modeler for ArcGIS 10.1
[16] Weiss A D 2001 Topographic position and landforms analysis [poster] *Proceedings of The 21st Annual ESRI User Conference, San Diego, CA*