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 $0.01^\circ$ – $19.24^\circ$, 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
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.](image)

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.

| 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                         |
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:

\[ \rho_{\text{red}}^s = k \rho_{\text{blue}}^s \]  

(1)

Where, \( \rho_{\text{red}}^s \) and \( \rho_{\text{blue}}^s \) 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:

\[ R_{\text{ac}} = R_i - R_{dp} \]  

(2)

Where, \( R_{\text{ac}} \) 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].

\[ R'_{i} = R_i - b_i (R_{\text{NIR}} - \text{Min}_{\text{NIR}}) \]  

(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 \( R_{\text{NIR}} \) 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:

\[ Z = a_0 + a_i X_i + a_j X_j \]  

(4)

Where

\[ X_i = \ln(R_{\text{wi}} - R_{dp,i}) \]

\[ X_j = \ln(R_{\text{wj}} - R_{dp,j}) \]

\( a_0, a_i, a_j, X_i, X_j = \) coefficients determined through multiple regression using known depths and the corresponding reflectance.
\[ R_{w,i}, R_{w,j} = \text{Observed reflectance in band } i \text{ and } j \]
\[ R_{dp,i}, R_{dp,j} = \text{Reflectance of dark water pixel in bands } i \text{ and } j \]

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].

| Name                     | Algorithm                                                                 | Description                                                                 |
|--------------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| **Slope**                | \( \arctan \sqrt{\frac{dz^2}{dx^2} + \frac{dz^2}{dy^2}} \)              | Calculate more than 3 x 3 pixels that close each other                       |
| **Statistical aspect**   | 57,29578 x \( \arctan \left( \frac{dz}{dx} + \frac{dz}{dy} \right) \)   | 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**   | \( \sqrt{\frac{\sum_{i=x-(n+1)/2}^{x+(n+1)/2} \sum_{j=y-(n+1)/2}^{y+(n+1)/2} (z_{ij} - \bar{z})^2}{n^2}} \) | is the average elevation value of the pixels in the neighborhood analysis. |
| **Variance**             | \( \sigma^2 \)                                                             | \( \sigma \) 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**              | \( \frac{\mu_4}{\sigma^4} \)                                            | \( \mu_4 \) is the fourth central moment and \( \sigma^4 \) is the standard deviation of all pixels in the neighborhood analysis. |
| **BPI**                  | \( z_{xy} - \hat{z}_{annulus} \)                                        | \( \hat{z}_{annulus} \) is the average value of the elevation of all pixels in the annulus-shaped neighborhood |
| **VRM**                  | \( R = \frac{A_{annulus \text{- shaped area}}}{A_{planar \text{- shaped area}}} \) | 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 (Upper) | Depth (Lower) | 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 Shelf      | -100              | 100               | -100             | 100              | 28.907        | 28            | 88.099        |               |
| 7              | Open Slopes           | -100              | 100               | -100             | 100              | 28.907        |               | 88.099        |               |
| 8              | Depression            | -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.
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.
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.

![Broad BPI](image1.png)

![Fine BPI](image2.png)

**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.
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.

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