Estimating bathymetry using sentinel-2a for shallow-waters mapping: a case study in Kelapa Dua Island

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Abstract. Many algorithms have been developed to map shallow waters from satellite images, but there is no standard algorithm for all waters. The accuracy of the algorithms developed for each body of water has a different level of accuracy. This research aims to use the Stumpf and Lyzenga algorithms to estimate shallow water bathymetry mapping in Kelapa Dua Island. Shallow water bathymetry mapping with both algorithms uses a combination of blue-green bands from Sentinel-2A satellite image data. In addition to Sentinel-2A satellite image data, the data used in this research are depth, water clarity, and tide data. Satellite image processing includes pre-processing, algorithm application, and fit testing. The fit test through determination test and root mean square error analysis was used to see the level of fit of the shallow water bathymetry model. The analysis shows that the log-ratio transform algorithm tends to be better at mapping bathymetry in Kelapa Dua Island, Kepulauan Seribu with a coefficient of determination (R2) of 0.56 and an RMSE of 0.648, while the log-linear transform algorithm has a coefficient of determination (R2) of 0.54 and an RMSE of 0.742. The depth of shallow water on Kelapa Dua Island is in the range of 0 - 7 m depth.

1 Introduction

Kelapa Dua Island is one of the islands of the Kepulauan Seribu, DKI Jakarta, which is included in the Marine National Park and is classified as a small island as defined in Law 1 of 2014 concerning Coastal Zone Management. Kelapa Dua Island has an area of 1.9 hectares and is a small island compared to the other islands in the Thousand Islands region [1]. Kelapa Dua Island is located in the north of Java Island and includes relatively narrow shallow waters that are influenced by tides. This tidal influence causes the dynamics of other oceanographic parameters such as temperature, salinity, current speed and water clarity to be very high.

Shallow waters in oceanographic terms are defined as the water area extending from the coastal boundary to a depth of 200 meters, while in the scope of remote sensing, shallow marine waters are more emphasized on the ability of satellite images to penetrate the water column, then the energy interact with the constituents in the water column and or with bottom objects [2]. Especially for shallow waters that are quite clear, optical remote sensing methods

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are able to pass through a maximum water depth of 25 to 30 meters and will decrease as it gets deeper and murkier [3]. Shallow water mapping is done up to the limit of water depth detected by satellite sensors. Shallow water depth information is usually presented in the form of a bathymetry map. Bathymetry is defined as the study of conditions below the water surface in the form of depth [4]. Bathymetry or water depth is also defined as a measure of depth from the water surface to the seafloor. Bathymetry information is important for studying the ecosystem of the water bottom as well as basic information on potential zones for marine tourism, aquaculture and marine resource management [5,6].

Shallow-waters bathymetry mapping technology has evolved with the times and the demand for bathymetry information. Remote sensing as an alternative tool has been proposed for shallow waters bathymetry mapping [7,8]. Many studies related to bathymetry using satellite imagery have been conducted, for instance, bathymetry mapping using Sentinel 2 and Landsat 8 satellite imagery in the Sunrise Waters, Bali which obtained the results that bathymetry estimation using Sentinel-2A satellite imagery is better than Landsat 8 imagery where the coefficient of determination (R^2) of Sentinel-2A imagery is better than Landsat 8 imagery [9]. Another study related to bathymetry estimation using Landsat 8 and Sentinel - 2 images was also conducted in Poteran Gili Iyang Waters, Madura with the result that the Landsat 8 image obtained better bathymetry estimation results compared to Sentinel - 2, this is because the Landsat 8 image has a greater reflectance value than the Sentinel-2A image because in estimating depth using satellite imagery requires the reflectance value of waters in satellite images [10].

Utilization of passive sensor images to obtain bathymetry data can be done with the Satellite Derived Bathymetry (SDB) method. The SDB method is an alternative method for measuring depth that is generally applied in relatively clear shallow waters [11]. The SDB method was developed using the Lyzenga algorithm [7] and the Stumpf algorithm [12]. The Lyzenga algorithm uses linear logarithms in its operation and can be used with one or a pair or three channels of optical imagery (blue, green, and red channels). Stumpf's algorithm uses a ratio approach in its operation, and utilizes both the blue band and the green band. Both algorithms are capable of detecting depths up to 20 meters deep [13]. Visualization of bathymetry maps using the SDB method uses a combination of blue (2) and green (3) channels. This combination of channels is used in visualizing an object because colors are almost visible to the human eye [14]. Estimating the bathymetry of shallow waters on Kelapa Dua Island using satellite imagery has never been done so this research is important.

2 Method

2.1 Study site

This study is consisted of two steps, namely field survey and data processing and analysis. Field survey was conducted at Kelapa Dua Island, Kepulauan Seribu on March 6-10, 2023 with coordinates 106°33'32.42"E - 106°34'49.68"E and 5°39'05.09"S - 5°38'51.02"S (**Fig. 1**). The field survey aims to collect primary data such as in situ depth measurements, water clarity, and ground control points (GCPs). Data processing and analysis were conducted at the Computer Laboratory, Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, IPB University.

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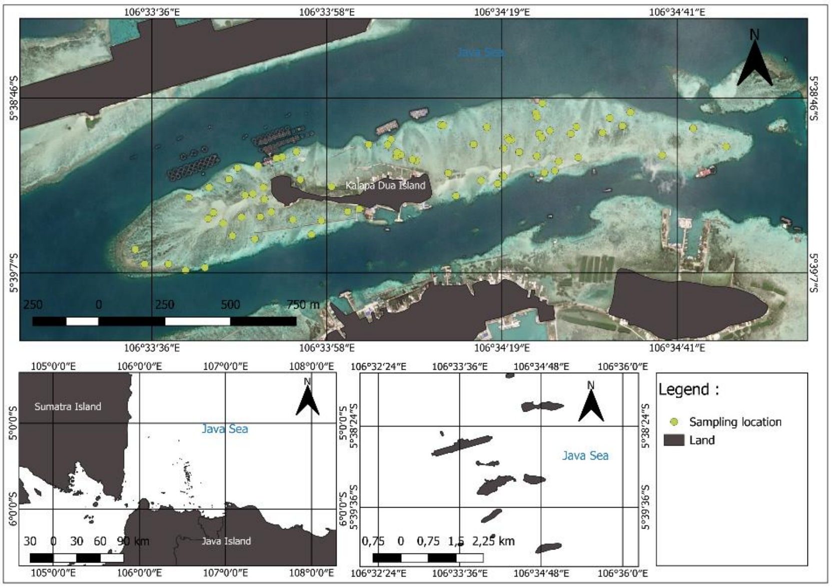

Fig. 1. Study site map of bathymetry mapping in Kelapa Dua Island, DKI Jakarta, Indonesia

2.2 Data Collection and Data Processing

Data collection in this study includes primary (in situ depth measurements, water clarity, and GCPs) and secondary data (tidal data and satellite images). In situ depth measurements was conducted using a rope equipped with a weight station. Water clarity was collected using a secchi disk. In this field survey, we used Garmin Etrex-10 GPS to record coordinate points.

Tidal data was obtained from the Indonesia Geospatial Information Agency (BIG) (https://srgi.big.go.id/) for 1 month (31 days) in March 2023. Sentinel-2A image (tail grid 48MXU) acquired on January 1, 2023 with a spatial resolution of 10 m in the blue, green, red, and near-infrared bands were otained from the Copernicus website (https://dataspace.copernicus.eu/).

2.2.1 In situ depth measurement

In situ depth measurements were performed using the conventional method. First, a 2 kg weight is tied to a 20 m long rope. The distance between data collection stations was >10 m. The number of stations taken was 114 points using purposive random sampling method. Depth data collection was carried out starting from 6 – 10 March 2024 at 09.00 - 11.00 AM. The time of data collection is calculated to avoid the sunglint phenomenon from the results of the data taken and adjusted to the recording time of the Sentinel-2A satellite image. The depth data were divided into two, 75 data used for algorithm model development and 39 data for model goodness of fit analysis.

2.2.2 Tidal data collection

The depth measurement data is corrected using the Mean Sea Level (MSL) datum to equalize the water conditions in the image and the depth data must be tidal correction. Tidal data was taken from the Geospatial Information Agency (BIG) website in March 2023 (31 days) on

Kelapa Dua Island, Kepulauan Seribu and Mean Sea Level (MSL) data from processing results in Ocean Data View (ODV). Tidal correction was performed using the equation:

$$\Delta MSL = Ct - MSL \tag{1}$$

Where:
ΔMSL : correction value to MSL datum (m)
Ct : tidal value (m)
MSL : Mean Sea Level value of Kelapa Dua waters (m)

The correction results are then averaged to get the corrected depth value with the equation:

$$D = Dt - \underline{X}\Delta MSL \tag{2}$$

Where:
D : corrected depth value (m)
Dt : uncorrected in situ depth value (m)
$\underline{X}\Delta MSL$: average correction value to MSL datum (m)

2.2.3 Water clarity data collection

Water clarity is related to the attenuation depth and the ability of satellite sensors to detect objects in the water column and bottom. This data was collected using a secchi disk at 5 points the secchi disk measurement should be done at the deeper water not in the shallow water of study area. (**Fig. 1**) representing each waters location. The relationship between the attenuation depth (k^{-1}) and the secchi disk depth (D_s) is formulated as follows [15]:

$$k^{-1} = \frac{D_s}{1.7} \tag{3}$$

dimana:
k^{-1} : attenuation depth (m)
D_s : secchi disk depth (m)

2.2.4 Sentinel-2A image processing

In this study, we used ENVI 5.3 to perform Sentinel-2A image processing and QGIS to produce the map. The first step in satellite image processing is cropping the image for the study area. Then, atmospheric correction is performed using the Dark of Substraction (DOS) method. DOS is an approach that the pixel reflectance value of the entire image is reduced by the reflectance value of the dark object. It is assumed that the resulting minimum reflectance value is zero [16]. Next, image masking is performed. There are 2 algorithms used in this research, which are:

a. Log-linear transform algorithm (Lyzenga algorithm)
The Lyzenga algorithm employs an algorithm that uses either one or a pair of passive satellite waveforms. The following equation (4) explains the Lyzenga algorithm [7]:

$$Z = a_0 + \sum_{i-1}^{N} a_i \, ln \, ln \left(R(\lambda_i) - R_\infty(\lambda_i)\right) \tag{4}$$

Where:
Z : depth (m)
ai (i = 0,1, … , N) : constant coefficient, N is the number of spectrum bands

$R(\lambda i)$: Reflectance after atmospheric correction for spectral band λi
$R\infty(\lambda i)$: Average deep-sea reflectance in spectrum band λi

b. Log-ratio transform algorithm (Stumpf Algorithm)
Discovered the ratio transform method to analyse water depth with the principle of band comparison. The log-ratio transform algorithm has the principle that light weakens exponentially based on the depth of the water and to obtain the value of water depth can use two bands that can minimise the influence of albedo. Mathematically, the model can be formulated as follows [12] :

$$Z = m_1 \frac{ln\ ln\ (nR_w(\lambda_b))}{ln\ ln\ (nR_w(\lambda_g))} - m_0 \quad (5)$$

Where:
Z : depth (m)
n : fixed constant for all areas
$R_w(\lambda_b)$: reflectance of the water, from the blue band
$R_w(\lambda_g)$: reflectance of the water, from the green band
m_1 : tunable constant to scale the ratio to depth
m_0 : offset for a depth of 0 m

2.3 Validation Test

The validation test uses statistical analysis of coefficient of determination (R2) and Root mean square error (RMSE).

2.3.1 Coefficient of determination (R^2)

Coefficient of determination test is a test to explain the proportion of variation in the independent variable explained by the dependent variable. In addition, the coefficient of determination test is used to measure how good the regression model is. The following is the formula for the coefficient of determination [17].

$$R^2 = \frac{n(\sum XY) - (\sum X)(\sum Y)]^2]]}{\sqrt{([n)(\sum [X^2) -](\sum X)]^2][n(\sum [Y^2) -](\sum Y)]^2]}} \quad (6)$$

Where:
X: independent variable
Y: dependent variable
n: number of data

2.3.2 Root Mean Square Error (RMSE)

Root Mean Square Error (RMSE) is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are. In other words, it tells you how concentrated the data is around the line of best fit [18].

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\widehat{y_i} - y_i)^2}{n}} \quad (7)$$

3 Results and Discussion

3.1 Bathymetry Algorithms

The bathymetry algorithms developed for shallow water bathymetry mapping in Kelapa Dua Island are log-ratio transform [12] and log-linear transform [7] (Table 1).

Table 1 Analysis of both algorithms with observed depth

Bands combination	Log-linear transform			Log-ratio transform	
	A_0	A_1	A_2	M_0	M_1
ln B2, ln B3	1.7009	0.2088	-0.1891	17.2843	-15.6953

The log-linear transform algorithm developed for shallow water bathymetry mapping in Kelapa Dua Island resulted in the following equation:

$$Z = 1.7009 + 0.2088X_1 - 0.1891X_2 \quad (8)$$

Where:
Z : depth (m)
X_1 : ln value of blue band
X_2 : ln value of green band

The log-ratio transform algorithm developed for shallow water bathymetry mapping resulted in the following equation:

$$Z = 17.2843 - 15.6953X \quad (9)$$

Where:
X : $\frac{ln ln\ B2}{ln ln\ B3}$

The band combination used in this algorithm is the blue-green band combination which has a wavelength of 410 - 500 nm and 500 - 610 nm. These results align with the research of [19] who reported that the correlation coefficient value of the blue band ratio with the green band is much higher than the ratio of other band combinations. Other researchs conducted by [20, 21, 22, 23] also reported that the combination of blue band and green band in Sentinel-2A image has excellent penetration among other band combinations in mapping bathymetry. The wavelength affects the strength of light penetration in the waters, the shorter the wavelength used, the stronger the ability to penetrate the water column. This blue and green band combination has a shorter wavelength than other band combinations so that the ability to penetrate the water column will be stronger [24].

3.2 Statistical Analysis

The goodness of fit of the log-linear transform and log-ratio transform algorithms was tested through the coefficient of determination (R2) and root mean square error (RMSE). These goodness of fit tests determine how accurate the observed frequency of events is to the expected frequency of events. The results of testing both algorithms with both tests can be seen in Table 2.

Table 2 Determination test results between algorithm and observation data

Algorithm	R^2	RMSE
Log-linear transform	0.54	0.742
Log-ratio transform	0.56	0.648

The coefficient of determination (R2) measures the influence of the independent variable (X) on the independent variable (Y) [25]. The determination test results of the two algorithms have almost the same value, with a difference of 0.02. The largest coefficient of determination (R^2) among the two algorithms is the log-ratio transform, with a value of 0.56. A large R^2 value (getting closer to 1) indicates the ability of the independent variables to explain the dependent variable, so the correlation is strong. The R^2 model can increase or decrease if an independent variable is added to the model [26]. Both models get a fairly good value for the determination test, and the log-ratio transform algorithm tends to be better than the log-linear transform.

RMSE results that have a value close to zero mean that the depth value produced by the algorithm used is not much different from the actual depth value. It can be seen that the RMSE test value generated by the log-linear transform algorithm is 0.742 and for the log-ratio transform algorithm is 0.648. The RMSE value generated from the log-ratio transform algorithm has a smaller value than the log linear transform, this result shows a better depth estimation equation model, so that in mapping the most accurate waters compared to the log-linear transform algorithm with an average estimated depth of 9.99 m. [18, 22].

This study shows that the log-ratio transform algorithm is better than the log-linear transform algorithm in mapping the depth of shallow water in Kelapa Dua Island, Kepulauan Seribu. The log-ratio transform (Stumpf) algorithm is better than the log-linear transform (Lyzenga) in mapping shallow water bathymetry with a depth range of 0-6 m [23]. The observation of shallow water bathymetry is closely related to the clarity of sea color. The results showed that the linear algorithm form is not better than the ratio transform, where the reflectance value of the sensor channel is linearly influenced by the estimated value of the sea color of the remote sensing observation object. Based on the results obtained, it proves that the two-channel ratio form is more suitable than the linear form where each channel has a separate influence. The log-ratio transform model is superior to the linear model by accurately estimating the depth of 3 m [27]. The results of this study are consistent with the results of early research developed by ocean color remote sensing (OCRS).

3.3 Map of Bathymetri

The maximum depth of shallow water detected from the satellite sensor on Kelapa Dua Island based on the calculation of the depth of attenuation is 7.04m. The water clarity value on Kelapa Dua Island is 6 m. This result indicates that the value of water clarity on Kelapa Dua Island is classified as clear because the value of water clarity is close to the bottom of the water. Based on the calculation with the equation [15], the depth of attenuation on Kelapa Dua Island, Kepulauan Seribu, is 3.52 m, which illustrates the satellite ability to penetrate the waters on Kelapa Dua Island by $2k^{-1}$ m. Bathymetry mapping by using algorithmic analysis of Sentinel-2A image extraction data with observed data and the ability of satellites to penetrate the waters on Kelapa Dua Island has a water depth of 0–7 m (**Fig. 2**).

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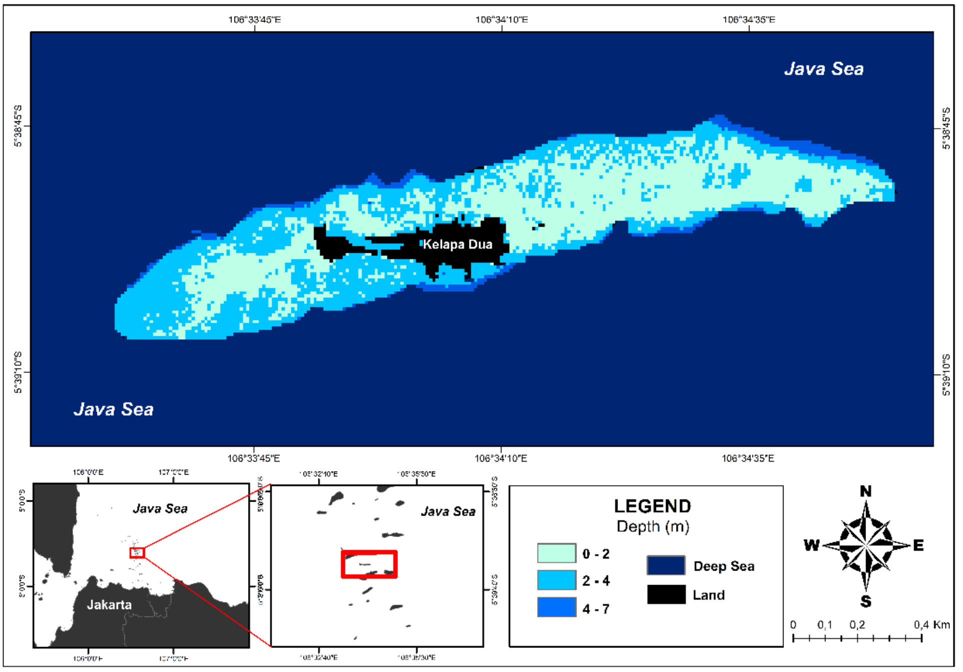

Fig. 2. Map of Bathymetri using algorithm log-ratio transform in Kelapa Dua Island

The ability of satellite imagery to detect water depth is influenced by the depth of attenuation in the water. The condition of the water brightness on Kelapa Dua Island is still in the good category and is suitable for the growth of seagrass ecosystems. Based on the criteria for the condition of seagrass ecosystem status in Government Regulation of the Republic of Indonesia Number 22 of 2021, the status of seagrass ecosystems on Kelapa Dua Island is categorised as poor (< 29.9%), which is around 26.77% [28]. Seagrass has an ecological function as a sediment trap, so at high tide, the waters become clearer due to the mass of sediment trapped by seagrass [29].

The variation in shallow water depth on Kelapa Dua Island can provide information on the suitability of the location for the growth of seagrass ecosystems, mangrove ecosystems, shipping, and underwater recreation. The bathymetry map of shallow marine waters with a depth of 0–2 m dominates Kelapa Dua waters and is in the waters near and adjacent to the mainland, which is in the littoral zone or coastal zone. The littoral zone is between the high tide line when the sea water is inundated and the low tide when it becomes land. Temperature, dissolved oxygen, and salinity factors in the littoral zone have a great influence on the survival of ecosystems and biota compared to other zones [30]. The depth of 0–2 m is filled with seagrass ecosystems, shallow coral reefs, and mangrove ecosystems. In this ecosystem, sunlight can still penetrate the water surface with sufficient intensity, allowing the growth of ecosystems and marine biota. The depth value on the bathymetry map has a value of 2–4 m in nearshore waters and is safe for ships to lean on the docks with a minimum depth of 1.98 m [31]. Water depths in the range of 4–7 m indicate the lagoon area to the seashore, and it can be seen on the bathymetry map that at a depth of 6–7 m, there are waters that have been included in the deep sea but are still visible by satellite imagery, so that the mapping results using the log-ratio transform algorithm show a greater depth value. The waters of the lagoon area also show many types of coral reefs and are also used for floating net cage fish farming on Kelapa Dua Island [32]. Water depth affects the penetration of sunlight into the water. If the depth is too deep, the amount of light required by organisms in the driftnet may be reduced, which may affect growth and productivity.

4 Conclusion

The results of the log-ratio transform algorithm used to estimate the bathymetry of shallow sea waters have results that are good enough to be used in estimating the bathymetry of waters compared to the log linear transform algorithm. This is supported by statistical analysis of the coefficient of determination of the relationship between in situ data and the log-ratio transform algorithm of 0.56, this result represents that the estimated bathymetry value from the satellite can represent the in situ bathymetry data by 56%. In addition to the RMSE value, the log ratio transform algorithm is smaller than the linear log algorithm which indicates that the log ratio algorithm has better results. Based on these results, the log-ratio algorithm bathymetry estimation is better in mapping bathymetry in shallow sea waters of Kelapa Dua Island using Sentinel-2A imagery, resulting in depth values with a range of 0-7 m.

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