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Estimation of Attenuation Coefficient Values Using Remote Sensing and Its Relationship With Shallow Water Depth

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Abstract

In ocean remote sensing, the intensity of light entering the water column decreases exponentially with increasing depth due to scattering and particle absorption in the water column. This process of decreasing light intensity is called attenuation. Attenuation is a limiting factor in detecting objects in the water column and seafloor using remote sensing, which relies on light intensity. The attenuation coefficient (Kd) is an important optical property of seawater as it provides information about water clarity and the level of light attenuation. This study aims to analyze the estimation of the attenuation coefficient values and their variability using in-situ measurements and Sentinel-2 level 2A data in Karang Lebar, Pulau Panggang, and Pulau Air, in the Seribu Islands Regency, North Jakarta. We tested several algorithms to estimate the attenuation coefficient values. The research results show that the in-situ Kd and the estimated model values have a good correlation (r = 0.75-0.86). The distribution of attenuation coefficient values in the shallow waters of the study area ranges from 0.06 to 0.18m-1. The accuracy of estimating shallow water depth at the study sites was best represented by R^2 and RMSE values in the range of 0-5m with an attenuation coefficient of 0.06-0.11m^{-1}.

Keywords: Diffuse Attenuation Coefficient, Remote Sensing, Sentinel-2 Imagery, Algorithm.

1. Introduction

The utilization of optical-based remote sensing technology for estimating water depth, especially in shallow water areas, is currently experiencing rapid development. Methods and algorithms based on Satelite Imagery, known as Sateli\lite Derived Bathymetry (SDB), have become one of the research focus in this field. Passive remote sensing in the marine area relies on electromagnetic energy (EM) propagation into the water column. This electromagnetic wave undergoes absorption and scattering processes known as attenuation. Attenuation is a limiting factor in detecting objects on the seafloor and within the water column. Information regarding the diffuse attenuation coefficient (Kd) is crucial to enhance the accuracy of object detection from satellite sensors within water environments (Prasetyo et al., 2018).

The absorption and scattering processes that occur with electromagnetic waves cause the intensity of light that enters the water column decrease exponentially with increasing water depth. This phenomenon is due to interactions with the water column, the seafloor, and the water surface. Knowledge of the attenuation coefficient (Kd) can be used as initial information to assess the water quality of the water column. Furthermore, this information can be utilized to determine the depth of light penetration, thus providing insights into the accuracy of passive remote sensing for water depth detection (Mobley et al., 2004).

The attenuation coefficient values are measured in situ using a spectroradiometer. Prasetyo et al. (2017) conducted measurements at several locations, Pulau Panggang, Pulai Air, and Karang Lebar, using the TriOS Ramses instrument to obtain apparent optical properties (AOP) data. The acquired data can be used to calculate reflectance values and attenuation coefficients. Field measurements using this method usually require significant costs and can be challenging to perform in a temporal and spatial analysis. Therefore, remote sensing can monitor the optical conditions of larger water bodies, where conventional monitoring tends to be limited (Palmer et al., 2015).

Another method to determine the attenuation coefficient is using the Secchi disk depth. The Secchi disk is a circular instrument with a diameter of approximately 30 cm, painted with black and white colors and attached to a string of a certain length. Determining the Secchi disk depth is simple, which involves submerging the Secchi disk into the water and noting the depth at which the disk is just no longer visible. This depth is considered the Secchi disk depth value, which is closely related to the brightness and clarity of the water. Tillman (2000) and Goncalo et al. (2020) developed empirical formulas to obtain attenuation coefficient values from the Secchi disk depth.

The estimation of attenuation coefficient values can be performed using remote sensing data. The attenuation coefficient (Kd490) at a wavelength of 490 can be calculated using empirical algorithms based on the ratio relationship between the blue and green band reflectance values (Austin, Petzold., 1986); (J.L. Mueller, 2000); (Lee et al., 2005). Mueller (2000) developed an algorithm for estimating the attenuation coefficient using the water-leaving radiance (Lw) values from SeaWiFS imagery. Lee et al. (2005) further developed the algorithm based on the reflectance values in SeaWiFS imagery. The estimation of attenuation coefficient values using remote sensing has evolved by applying the algorithm developed by Lee et al. (2005) to Landsat 8 imagery, which has higher spatial resolution than SeaWiFS (Adi et al., 2013); (Prasetyo et al., 2018). Studies on estimating attenuation coefficient values using remote sensing in Indonesia have been conducted using Landsat 8 imagery in Panggang Island, Karang Lebar dan Air Island, in Kepulauan Seribu Regency. (Prasetyo et al., 2018).

The attenuation coefficient indicates the brightness of water quality and the extent of electromagnetic wave attenuation in the water column (Ambarwulan, 2012). One of the benefits of remote sensing technology in the marine environment is the ability to extract information about water depth, especially in shallow waters, using visible satellite imagery known as Satellite Derived Bathymetry (SDB).

This study aims to estimate the distribution of the attenuation coefficient (Kd) values from Sentinel 2A satellite imagery, analyze the relationship between the diffuse attenuation coefficient (Kd) values from Sentinel 2A satellite imagery and the diffuse attenuation coefficient values obtained from the Secchi disk depth, and also analyze the range of diffuse attenuation coefficient for a good estimation of shallow water depth. Estimating the attenuation coefficient values through remote sensing can be used as a preliminary study for estimating water depth or identifying the bottom coverage of shallow water columns.

2. Methods

2.1. Study Area

This research was conducted in Pulau Panggang, Karang Lebar, and Pulau Air in the Seribu Islands, DKI Jakarta. Field data collection for Secchi Disk Depth and seawater sample was conducted from August 7^{th}-10^{th} to August 2022. Sea water samples were taken to analyze the value of Total Suspended Solid (TSS) in the reseach area. The equipment included a handheld GPS, water sample bottles, data recording forms, and a laptop with ArcGIS, SNAP, QGIS, and Microsoft Office software. The materials used consisted of Sentinel Satellite imagery with a spatial resolution of 10m, water depth data, and Secchi disk depth.

2.2. Data Collection

In this research, data were collected from both field measurements and secondary sources. The secondary data used in the study are attenuation coefficient data acquired from April 22nd to May 1st, 2016, by Budhi Agung Prasetyo in collaboration with the National Institute of Aeronautics and Space (LAPAN), which is now known as the National Research and Innovation Agency (BRIN).

Secchi disk depth was collected using a Secchi disk to obtain Secchi depth data, which will be used to calculate the attenuation coefficient values using an algorithm developed by (Castillo-ram et al., 2020). The relationship between the attenuation coefficient values obtained from the Secchi depth and the estimated values from satellite imagery will be examined.

Once a good coefficient of determination (>60-70%) is achieved between in-situ measurements of diffuse attenuation coefficient and estimates using Sentinel-2 imagery, the estimation of diffuse attenuation coefficients in the waters around Pulau Panggang will be carried out. Shallow water depth estimation at the research location will be conducted using the Satellite Derived Bathymetry (SDB)

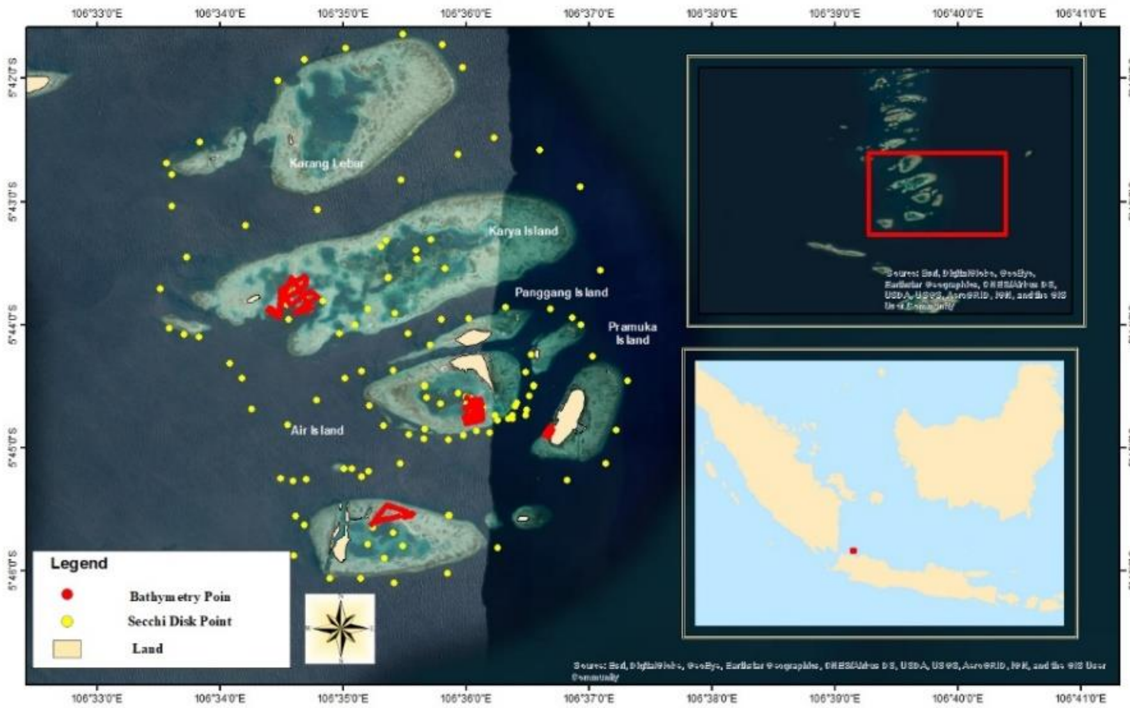

Figure 1 Map of The Study

method.with the Random Forest algorithm. Statistical analysis (R^2 and RMSE) will be employed to assess the accuracy of the depth estimation. The attenuation coefficient estimation and shallow water depth estimation result will be overlaid to determine the range of attenuation coefficient values at different depths with good accuracy.

2.3. Estimating attenuation coefficients using Sentinel 2A imagery

In the research location, attenuation coefficient measurements were conducted using a spectroradiometer in April 2016 by Prasetyo et al. (2018). The attenuation coefficient data obtained from these measurements were used to verify the calculation results of attenuation coefficients using Landsat imagery (30-meter spatial resolution), resulting in a good correlation with correlation coefficients ranging from 0.6 to 0.7. In this study, Sentinel 2A imagery was selected due to its higher spatial resolution of 10 meters for estimating diffuse attenuation coefficients. The chosen Sentinel image closely matched the data acquisition time using the spectroradiometer. The selected image was a Sentinel 2 level 1C image that underwent radiometric correction using Sen2Cor to obtain reflectance values. Subsequently, the reflectance values were used to estimate the attenuation coefficients using algorithms proposed by Lee et al. (2005), Werdel (2009), Zhang and Fell (2007), and Tiwari et al. (2018). The calculated results from the algorithms were then regressed against the attenuation coefficient values obtained from field data collected by Prasetyo et al. (2018).

The hypothesis proposed is that the calculated attenuation coefficients from the Sentinel 2A imagery will exhibit a good correlation coefficient (r = 0.6-0.7), thereby allowing for further analysis of the distribution of attenuation coefficients for different temporal periods, such as in 2021, corresponding to field data acquisition.

2.4. The relationship between the diffuse attenuation coefficient (Kd) values derived from Sentinel 2A satellite imagery and the diffuse attenuation coefficient values obtained from Secchi disk depth

The relationship between diffuse attenuation coefficient (Kd) values derived from Sentinel 2A satellite imagery and the diffuse attenuation coefficient values obtained from Secchi disk depth can be explored through statistical analysis. By comparing the Kd values derived from Sentinel 2A imagery with the Kd value obtained from Secchi disk depth measurements, it is possible to assess the correlation between these two variables (Lee et al., 2018).

The analysis can involve calculating correlation coefficients to quantify the strength and direction of the relationship. It is important to note that the success of establishing a relationship between Kd values from Sentinel 2A imagery and Secchi disk depth relies on the availability and quality of the data, as well as the specific characteristics of the study area.

Field data collection for Secchi disk depth measurements using a stratified approach to represent different depth types. Eighty-seven (87) sample points were obtained During the field observations, and the attenuation coefficient values from Secchi depth (Zsd) were calculated. Determining the Secchi disk depth involved submerging a plate into the seawater and observing until the depth at which the Secchi disk was no longer visible. The obtained depth was recorded and subsequently used to calculate the attenuation coefficient value using an algorithm. The algorithm utilized an empirical equation divided based on the Secchi disk depth for calculating the attenuation coefficient (Castillo-ram et al., 2020).

$Kd = \frac{1.16}{Zsd^{0.62}}$; Zsd < 2.20 m ....(1)

Kd = exp((0.15 - log Zsd x 0.62) x $\frac{1.68-\log Zsd}{0.89}$ + (-0.48 – Log Zsd x Log Zsd x 0.72) x $\frac{1.68-\log Zsd}{0.89}$

; 2.20 < Zsd < 5.37 ....(2)

$Kd = \frac{0.62}{Zsd^{0.72}}$; Zsd > 5.37 ....(3)

Note :
Zsd = Secchi Disk Depth

2.5. The relationship between the attenuation coefficient values and the accuracy level of estimating shallow water depths

A higher attenuation coefficient generally indicates higher light absorption and scattering in the water column, reducing visibility and difficulties in accurately estimating shallow water depths. In such cases, the depth estimation accuracy may be lower due to the limited light penetration and various optical properties in the water.

Conversely, a lower attenuation coefficient implies less light absorption and scattering, allowing for better visibility and potentially higher accuracy in estimating shallow water depths. In these situations, light can penetrate deeper into the water column, making it easier to observe and estimate the depths accurately.

It is important to note that the factors besides the attenuation coefficient influence the accuracy level of estimating shallow water depths. Factors such as water clarity, presence of suspended particles, bottom reflectance, and instrument precision can also affect depth estimation accuracy. Therefore, a comprehensive analysis considering these factors is necessary to fully understand the relationship between the attenuation coefficient and shallow water depth estimation accuracy.

One key to improving the accuracy of estimating water constituent values in shallow coastal waters is to understand and comprehend the bio-optical properties of the specific shallow water environment. The diffuse attenuation coefficient (Kd) indicates water clarity, quality, and the extent of attenuation that occurs on the electromagnetic waves in the water column (Ambarwulan, 2012).

Mapping water depth using ships and echo sounders require high costs and time to provide depth information for large areas with full coverage. Satellite Derived Bathymetry (SDB) technology efficiently provides depth information in shallow water areas with full coverage and a relatively large spatial extent. This study uses a non-linear regression method, specifically Random Forest, which is chosen as it is suitable for multispectral-based Sentinel 2A imagery. (Manessa et al., 2016); (Dewi et al., 2016). The depth estimation process requires depth data will be divided into training and testing data. The depth data used was acquired from single-beam echo sounders in July 2021 by the National Geospatial Information Agency (BIG). The accuracy of depth estimation using the random forest model will be evaluated based on statistics such as the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE) to assess the quality of measurement and estimation data.

The obtained depth estimation data using the SDB method will be analyzed for their corresponding attenuation coefficient values calculated using Sentinel 2A imagery. The expected outcome is to determine the range of attenuation coefficient values that accurately estimate shallow water depths.

3. Result and Discussion

3.1 Estimating the attenuation coefficient using Sentinel 2A imagery

The research area includes the lagoon of Pulau Panggang, Karang Lebar, and the lagoon of Pulau Pramuka. Based on the characteristics of the water conditions, empirical models are applied separately for each lagoon. The lagoon of Pulau Panggang exhibits higher concentrations of Total Suspended Solids (TSS) and chlorophyll-A compared to the lagoon of Karang Lebar, primarily due to anthropogenic activities and aquaculture (Meliani et al., 2019). The diffuse attenuation coefficient (Kd490) values obtained from field measurements by Prasetyo et al. (2018) are compared, and linear regression analysis is performed to assess the relationship between the empirical model's diffuse attenuation coefficient values (Kd490). The results of the linear regression analysis indicate a strong correlation (r = 0.75-0.86) with coefficient of determination (R2 = 0.56-0.74) values, as shown in Table 1.

Table 1 The result of linear regression analysis (R^2) between the coefficient of diffuse attenuation derived from field measurements and empirical model

Lokasi	Algoritma			
	Lee, 2005	Werdel, 2009	Zhang and	Tiwari, 2018

			Fell, 2007	
Pulau Panggang	0.68	0.74	0.68	0.56
Karang Lebar	0.62	0.59	0.62	0.62

Table 2 The result of Root Mean Square Error (RMSE) between the coefficient of diffuse attenuation derived from field measurements and the empirical model

Location	RMSE			
	Lee, 2005	Werdel, 2009	Zhang and Fell, 2007	Tiwari, 2018
Pulau Panggang	0.08	0.09	0.09	0.08
Karang Lebar	0.07	0.08	0.080	0.10

Tables 1 and 2 show the statistical evaluation results between in-situ Kd(490) values and Kd(490) estimates from Sentinel-2 imagery in Panggang Island and Karang Lebar. The Root Mean Square Error (Table 2) values indicate good results. The algorithms (Lee, 2005; Werdel, 2009; and Zhang and Fell, 2007) were developed for clear water conditions, selecting the ratio of the blue band (λ=490) and the green band (λ=555), resulting in a good coefficient of determination and RMSE values for the waters around Panggang Island and Karang Lebar. The algorithm by Tiwari et al. (2018) yielded the lowest coefficient of determination because Tiwari et al. (2018) developed their algorithm in the Red Sea, using the ratio of the red band (λ=443) and the green band (λ=555). The Red Sea waters contain high concentrations of Colored Dissolved Organic Material (CDOM) and low concentrations of chlorophyll-A (Brewin et al., 2015). These characteristics differ from the waters around Panggang Island and its surrounding water. The analysis of seawater samples taken in the field indicates low concentrations of Total Suspended Solid (TSS) concentration (<8mg/L) (Laboratory Analysis, 2022), while the chlorophyll-a in the waters around Panggang Island and Pramuka Island is relatively high due to increased anthropogenic activities that enhance nutrient availability for the growth and development of phytoplankton (Meliani et al., 2019).

Furthermore, based on the statistical analysis results in Table 1 and Table 2, the algorithm developed by Lee et al. (2005) was applied in this study. This algorithm yielded a good coefficient of determination and the lowest RMSE values to determine the attenuation coefficient distribution around the waters of Panggang Island and Karang Lebar. The estimated values of the attenuation coefficient are presented in Figure 2.

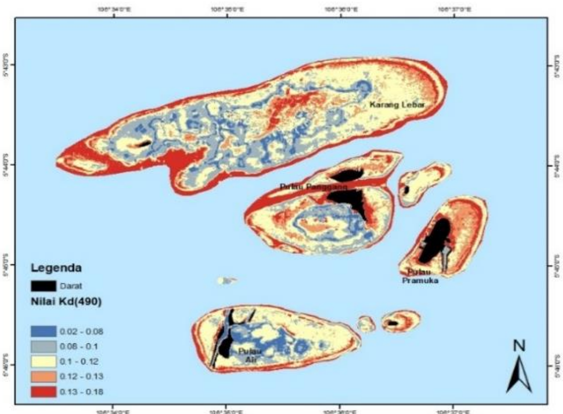

Figure 2 Distribution of Attenuation Coefficient (Kd490) Values in Panggang Island, Karang Lebar, and Pulau Air

The estimated range of attenuation coefficient (Kd) values from Sentinel 2A imagery using the algorithm by Lee et al. (2005) are between 0.02 and 0.18. In this range, Kd < 0.115 m^{-1} is categorized as very clear water, while Kd ≥ 0.115 m^{-1} indicates clear water with increasing turbidity as the value of the attenuation coefficient increases (Saulquin et al., 2013).

The attenuation coefficient values in the waters close to the land on Panggang Island and Pramuka Island are higher than in the lagoon areas that are farther away from the land. It is aligned with the findings of Meliani et al. (2019), stating that these waters have relatively high chlorophyll-A concentrations due to anthropogenic activities resulting from the dense population on Panggang Island and Pramuka Island (Herianto et al., 2023). On the other hand, the attenuation coefficient values in Karang Lebar and Pulau Air tend to be lower, indicating clearer water conditions.

3.2 The relationship between the diffuse attenuation coefficient (Kd) values obtained from Sentinel 2A satellite imagery and the diffuse attenuation coefficient values derived from Secchi disk

The Kd values calculated from Secchi Disk measurements using the algorithm developed by Castillo-ram et al. (2020) represent the attenuation coefficient for Photosynthetically Available Radiation (PAR). PAR refers to the range of wavelengths in sunlight that can penetrate a certain depth in the water column (Meliani et al., 2019). Essentially, the KdPAR values tend to decrease as the Secchi depth increases (Castillo-ram et al., 2020), as depicted in Figure 4

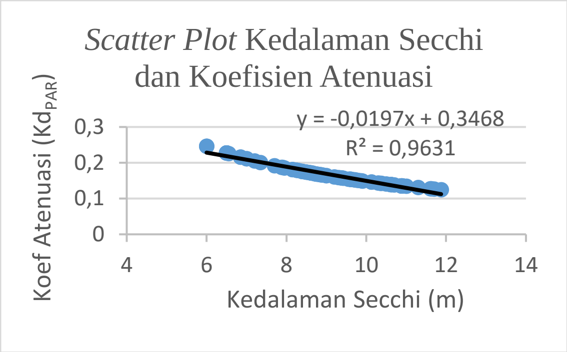

Figure 3 Scatter Plot of Secchi Depth (Zsd) and Attenuation Coefficient (Kd)

It was reported that KdPAR correlates well with Kd values over a wide range of attenuation coefficients (0.03-25 m^{-1}) (Lee et al., 2018). Besides the wide range of Kd values, one of the main factors contributing to this strong correlation is the natural variability of optical components (absorption and scattering) in natural waters. This variability, particularly in the shorter wavelengths (e.g., 400-500nm), which alters the Kd values, also affects the KdPAR values (Lee et al., 2018).

Statistical analysis, including the t-test and determination coefficient (R^2) calculations, was performed on this study's KdPAR and Kd values. The results from the t-test indicate a difference in means, and the R^2 value of 0.207 suggests a relatively low correlation between the two datasets. It happened because of this study restricted range of attenuation coefficient values in this study. The Secchi disk measurements were taken in relatively clear and homogenous water, resulting in a narrow range of Kd values. In contrast, the study by Lee et al. (2018) collected data from various water conditions, such as freshwater lakes (Zhang et al., 2012)), estuaries (Gallegos et al., 2011), and turbid freshwater (Ficek and Zapadka., 2010). These diverse water conditions contributed to a wider range of Kd values due to the varying optical components of the water column, including chlorophyll-a, Colored Dissolved Organic Matter (CDOM), and Total Suspended Solid (TSS). In this study, the laboratory analysis showed homogenous values of TSS (< 8 mg/L) during the Secchi disk measurements (Laboratory Analysis Results, 2022), which likely explains the narrow range of Kd values at the study location.

3.3 The relationship between the attenuation coefficient values and the accuracy of shallow water depth estimation

The estimation of depth values in Figure 3 was tested for accuracy using in-situ measurements acquired with a single-beam echosounder. The dataset consisted of 16,010 measurement points, with a split of 75% of the data (12,006 points) used as training data and 25% of the data (4,004 points) randomly selected as testing data for accuracy assessment. The results of the analysis, including the determination coefficient (R^2), Root Mean Square Error (RMSE), and Mean Absolute Percentile Error (MAPE), are summarized in Table 3.

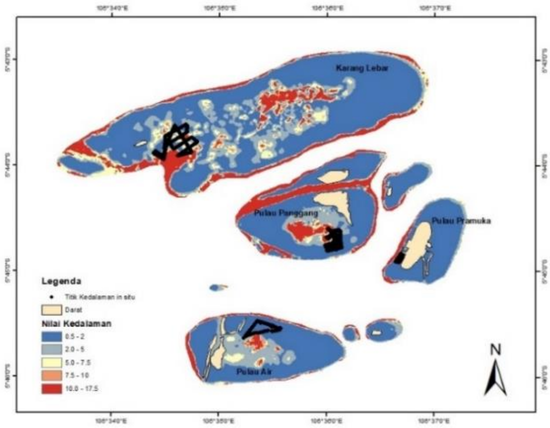

Figure 4 The depth estimation map using Sentinel-2A imagery

Table 3 Statistic analysis for estimating the depth value using The Random Forest algorithm

Depth (m)	R^2	RMSE	MAPE	The number of Data
0-17	0.977	0.381	10.2	4004
0-5	0.917	0.149	10.84	3087
6-10	0.75	1.161	10.4	555
>10	0.79	1.187	4.57	381

Based on the accuracy test results in Table 3, the statistical analysis of depth estimation using the non-linear Random Forest model indicates good accuracy, as evidenced by a coefficient of determination (R^2) value of 0.977 for the analysis of the entire testing dataset. In addition to the overall testing dataset, the data was also separated based on depth to assess the variation in error values within each depth range.

Table 3 shows the depth range of 0-5 meters shows the highest coefficient of determination (R^2) compared to other depth ranges. It is because the 0-5 meter range has good attenuation coefficient values, typically ranging from 0.06 to 0.11, calculated using the algorithm proposed by Lee et al. (2005). These values indicate that the areas within this range have clear water conditions, resulting in accurate depth estimation using the single-beam echosounder (SDB) method.

On the other hand, the depth ranges of 6-10 meters and 11-21 meters have lower R^2 values than the 0-5 meter depth range. Since the water depth increases, more electromagnetic wave energy is absorbed, and less light reaches the seafloor. The attenuation coefficient values for depths greater than 15 meters consistently exceed 0.14 m^{-1}. It is because areas with depths greater than 15 meters tend to have consistently dark colors, indicating reduced reflectance due to the attenuation caused by varying depths, preventing sunlight from reaching the seafloor effectively.

These findings suggest that depth estimation accuracy using the Random Forest model may vary depending on the depth range and the associated attenuation coefficient values, with clearer and shallower areas yielding higher accuracy than deeper areas with higher attenuation coefficients.

4. Conclusion

Sentinel-2 Level 2A imagery can be utilized to estimate the attenuation coefficient values using a combination of the green and blue bands, especially in relatively clear waters such as those around Pulau Panggang, Karang Lebar, and Pulau Air. The range of attenuation coefficient values in the shallow water areas (0-21 meters) around Pulau Panggang and Karang Lebar is between 0.02 and 0.14 m-1.

The correlation between KdPAR and Kd values will exhibit a strong correlation if the resulting range of attenuation coefficient values is sufficiently wide. In the study location, the highest accuracy in-depth estimation was achieved in the depth range of 0-5 meters, with attenuation coefficient values ranging from 0.06 to 0.11 m-1. As the depth increases, the resulting attenuation coefficient values also increase, leading to a decrease in the accuracy of water depth estimation.

Therefore, the success of depth estimation in the study area is influenced by the range of attenuation coefficient values, with higher accuracy observed in shallower depths and lower attenuation coefficients. The Sentinel-2 imagery can be valuable in estimating these coefficients and providing insights into the underwater characteristics of the studied areas.

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