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Suspended Sediment Analysis of Changes in Mangrove Forest Area Using Sentinel-2 Imagery at Citarum River Estuary, Muara Gembong District, Bekasi Regency

Analisis Sedimen Tersuspensi terhadap Perubahan Luas Hutan Mangrove menggunakan Citra Sentinel-2A di Muara Sungai Citarum, Kecamatan Muara Gembong, Kabupaten Bekasi

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Abstract

This study investigates the distribution of suspended sediments and the dynamics of mangrove forest areas in the Citarum River Estuary, Muara Gembong District, Bekasi Regency, over three observation periods: 2018, 2021, and 2024. The research employs a survey method with an associative approach. Suspended sediment samples were collected using a simple random sampling technique at eight designated locations within the estuary. The analysis of suspended sediment distribution utilized Sentinel-2A satellite imagery, with the Wirasatriya algorithm identified as the most effective for this purpose. The findings indicate an increase in the total area of suspended sediments over time, measuring 1,134.92 hectares in 2018, 1,244.74 hectares in 2021, and 1,254.38 hectares in 2024. Additionally, there was a notable shift in sediment concentration patterns, with low-concentration sediments (63.19%) dominating in 2018, while medium concentrations (100–220 mg/L) became more prevalent in 2021 (43.90%) and 2024 (47.65%). Mangrove forest areas were classified using a supervised classification method integrated with the random forest algorithm. The results revealed a continuous increase in mangrove forest cover during the study period, with a 20.01% expansion between 2018 and 2021, followed by an additional 30.65% growth from 2021 to 2024. Correlation analysis demonstrated a strong association between suspended sediment distribution and changes in mangrove forest area, with a correlation coefficient of 0.814 and a determination coefficient of 0.662. These findings highlight the interconnected dynamics of sediment distribution and mangrove forest development in the estuarine environment.

Keywords: Suspended sediment, Mangrove Forest Area, Sentinel-2A

Abstrak

Penelitian bertujuan untuk mengetahui sebaran sedimen tersuspensi dan perubahan luas hutan mangrove di Muara Sungai Citarum serta hubungan keduanya dari tahun 2018, 2021, dan 2024. Penelitian berlokasi di Muara Sungai Citarum, Kecamatan Muara Gembong, Kabupaten Bekasi. Metode penelitian yaitu metode survei dengan pendekatan asosiatif. Pengambilan sampel sedimen tersuspensi menggunakan teknik simple random sampling pada delapan titik lokasi di Muara Sungai Citarum. Analisis algoritma sedimen tersuspensi menggunakan Citra Sentinel-2A akuisisi tahun 2024 didapatkan algoritma terbaik yaitu algoritma Wirasatriya. Hasil sebaran luas sedimen tersuspensi memiliki total luas pada tahun 2018 yaitu 1134,92 ha, tahun 2021 yaitu 1244,74 ha dan tahun 2024 yaitu 1254,38 ha. Luas sebaran konsentrasi sedimen tersuspensi cenderung bergeser ke konsentrasi sedang yaitu 100-220 mg/l. Sebaran sedimen tersuspensi tahun 2018 didominasi kelas rendah (63,19%), tahun 2021 didominasi kelas sedang (43,90%), dan tahun 2024 didominasi kelas sedang (47,65%). Klasifikasi mangrove menggunakan klasifikasi terbimbing dengan metode random forest. Perubahan luas hutan mangrove Muara Sungai Citarum cenderung meningkat setiap tahun pengamatan. Penambahan luas periode tahun 2018 ke 2021 meningkat sebesar 20,01% dan periode tahun 2021 ke 2024 meningkat sebesar 30,65%. Hasil uji korelasi menunjukkan hubungan sangat kuat antara sedimen tersuspensi dengan perubahan luas mangrove dengan nilai korelasi 0,814 dan koefisien determinasi 0,662. Temuan ini menyoroti dinamika yang saling berhubungan antara distribusi sedimen dan perkembangan mangrove di lingkungan muara.

Kata kunci: Sedimen tersuspensi, Mangrove, Sentinel-2A

1. Introduction

The Citarum River, which is one of the largest rivers, has the potential to be used as a place for human activities that produce waste (Paramita & Ningrum, 2020). According to Prihatno & Setiyadi (2021), the Citarum River is one of the rivers prone to environmental problems due to waste discharge and increased erosion resulting from land conversion. The issue of forest conversion covers an area of 6,543 Ha with an erosion rate of 31.4% in the upper reaches of the Citarum River (Paramita & Ningrum, 2020). Transport of waste and erosion material increases the rate of sediment export towards river mouths by more than 100 tonnes/km^2 each year (Marvin & Pranoto, 2019). According to Hidayah & Apriyanti (2020), the sedimentation growth of the Citarum River reached 48.5 m/year, which increased the land area by 75 m/year. Eroded material carried by streams from upstream to the estuary can be described through the concentration of suspended sediment, an indicator of floating material that can be deposited or suspended in the waters (Rodríguez-Martínez et al., 2021). Suspended sediment material that flows will gradually accumulate into the estuary, where there is a risk of forming mud deposits through the sedimentation process

Mangroves are vegetation that can grow well in muddy areas and are influenced by sea tides (Apriliyani et al., 2020). Mangroves are often found in coastal areas with muddy soil and are protected from waste (Ely et al., 2021). Mangroves are essential for safeguarding coastlines, absorbing carbon, and providing ecosystems (Friess et al., 2019). The various roles and benefits of mangroves are stipulated in Law No. 27 of 2007 concerning the Management of Coastal Areas and Small Islands to maintain mangroves so they are not destroyed for unsustainable purposes.

According to Decree Number 92/UM/54 of 1954 by the Indonesian Minister of Agriculture, the Muara Gembong mangrove forest is protected. Increasing economic needs prompted the Bekasi Regent's proposal to designate mangrove forests as production forests, which was finally determined through Minister of Forestry Decree Number SK.475/Menhut-II/2005 by the Minister of Forestry on 16 December 2015 (Pamungkas et al., 2020). The designation of mangroves as production forests initiated the massive conversion of mangrove forests and became one of the factors in changing mangrove forests. Changes in the Muara Gembong mangrove forest in 2003 experienced shrinkage at a rate of 255.22 ha/year, leaving an area of 379 ha (Pamungkas et al., 2020). In 10 years, namely 2009-2019, the Muara Gembong mangrove forest experienced a reduction of 18%, an increase of 66%, and 16% of the mangrove forest area remaining. The fluctuating changes in the area of mangrove forests every year are accompanied by the dynamic conditions of the Citarum River Estuary (Maulani et al., 2021).

Estimating changes in mangrove forest areas and the distribution of suspended sediment is essential for managing and monitoring mangrove ecosystems designated as production forests. This study utilizes remote sensing as a multi-temporal method to generate spatial information on phenomena occurring within specific timeframes efficiently. This research aims to analyze the distribution of suspended sediment and changes in mangrove forest area in the Citarum River Estuary in 2018, 2021, and 2024 using Sentinel-2A imagery and to identify the relationship between the two.

2. Material and Method

2.1. Time and Place

Using an associative survey method, the research was conducted in Muara Sungai Citarum, Pantai Bahagia Village, Muara Gembong District, Bekasi Regency. This method gathers data to analyze the relationship between two variables from a sampled population (Sugiyono, 2018; Nasution & Sari, 2020).

2.2. Methods

The research utilized field data in the form of water samples from the Citarum River Estuary and secondary data from Sentinel-2A MSI Level 2A images accessed via the ESA Copernicus website (dataspace.copernicus.eu). Sentinel-2A images with <30% cloud cover were acquired for April 5, 2018, April 24, 2021, and May 3, 2024. Field tools included 250 ml sample bottles, cooler boxes, and GPS, while image processing utilized laptops with Google Earth Engine (GEE), Sentinel Application Platform (SNAP), and Quantum GIS (QGIS) software. The sampling locations were determined using the simple random sampling method, where each population element has an equal chance of being selected (Firmansyah, 2022). A total of eight sampling points are shown in Figure 1.

Figure 1. Map of sampling location points

2.3. Procedures

2.3.1. Sampling

Sampling at the Citarum River Estuary was conducted using a 250 mL bottle at the water surface. The coordinates listed on the Navionics Global Positioning System (GPS) were taken at each sampling location. The water samples that have been collected are then given a number label according to the sampling location. River water samples were taken to the Bekasi City Environmental Service Laboratory (DLH) for suspended sediment measurements using the SNI 6989.3.2019 gravimetric method (Arifudin et al., 2020).

2.3.2. Image Processing

Sentinel-2A image processing is carried out to obtain information on the distribution of suspended sediments and the extent of mangrove forests, where the distribution of suspended sediments using SNAP software with four algorithms used to estimate suspended sediment concentrations including the Budhiman Algorithm (2004), Parwati Algorithm (2006), Laili Algorithm (2015), and Wirasatriya Algorithm (2020).

Table 1. Suspended sediment algorithm

Algorithm	Equality
Budhiman (2004)	$TSS = 8{,}1429 * exp(23{,}704 * 0{,}94 * RrsB4)$
Parwati (2006)	$TSS = 3{,}328 * \exp(34{,}009 * (RrsB4))$
Laili (2015)	$TSS = 31{,}42 * \left(\frac{Log(RrsB2)}{Log(RrsB4)}\right) - 12{,}719$
Wirasatriya (2020)	$TSS = (1956{,}2 * RrsB4) - 50{,}056$

Reclassify is used to divide the distribution area of suspended sediment concentrations based on classes, referring to the Decree of the Minister of the Environment No. 1 in 2010.

Table 2. Suspended sediment category

Category	Concentration Range (mg/L)
Low	0-100
Medium	100-220
High	220-350

Sentinel-2A image processing to calculate the area of mangrove forests using GEE software with color composites using a combination of NIR, SWIR, and Red bands (8, 11, 4), and the classification used is guided classification (Jia et al., 2019; Dimyati et al., 2022). Guided classification using ee.Classifier.smileRandomForest for the random forest method.

2.4. Data Analysis

The analysis uses a correlation test to determine the strength of the relationship between suspended sediment distribution data and changes in the area of mangrove forests in the Citarum River Estuary in 2018, 2021, and 2024.

2.4.1. Suspended Sediment

The accuracy test uses Normalized Mean Absolute Error (NMAE) and Root Mean Square Error (RMSE). NMAE aims to determine the absolute error of the algorithm's estimated values with in-situ data (Mukhtar, 2023). RMSE aims to determine deviations in values between algorithm estimation data and in-situ data. The NMAE and RMSE equations are as follows.

$$NMAE(\%) = \frac{1}{n}\sum\frac{x-y}{y_{max}}\ x\ 100\%$$

Description:

x	= Image processing result value	ymax	= Maximum field measurement value
y	= Field measurement result value	N	= Number of samples

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(X_{observasi} - X_{estimasi})^2}{N}}$$

Description:

$X_{estimasi}$ = Value of image processing result
$X_{observasi}$ = Value of field measurement result
N = Number of samples

2.4.2. Changes in the Mangrove Forest Area

Supervised classification of Sentinel-2A images using the random forest method was carried out by testing the accuracy of the confusion matrix. According to Rahmawati et al. (2022), the confusion matrix equation is as follows.

$$\text{Producer's Accuracy} = \frac{xii}{x_{+i}}\ x\ 100\% \qquad \text{Overall Accuracy} = \frac{\sum_{i=1}^{r} xii}{N}\ x\ 100\%$$

$$\text{User's Accuracy} = \frac{xii}{x_{i+}}\ x\ 100\% \qquad \text{Kappa Coefficient} = \frac{N\ \sum_{i=1}^{r} Xii - \sum_{i=1}^{r}(X_{i+}X_{+i})}{N^2 - \sum_{i=1}^{r}(X_{i+}X_{+i})}$$

Description:

N = Number of pixels
Xi+ = Number of pixels in row-i
X+i = Number of pixels in the column-i
Xii = The diagonal value of the ith row and ith column of the contingency matrix

2.4.3. Relationship between Suspended Sediment with Changes in Mangrove Forest Area

Correlation analysis was carried out to determine the strength of the relationship between the distribution of suspended sediment and changes in mangrove forest areas using the Product Pearson Moment correlation test. According to Marwoto et al. (2021), the Product Pearson Moment correlation test equation is as follows.

$$r_{xy} = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{(n\sum x^2 - (\sum x)^2)(n\sum y^2 - (\sum y)^2)}}$$

Description:

r_xy = Correlation value
x = Suspended sediment value
y = Value of changes in mangrove forest area
n = The number of samples

The correlation test results are in the form of an r value with a value of $-1 \leq r \leq 1$ where the relationship is very low, namely the value 0.00 – 0.19, the low relationship is the value 0.20 – 0.39, the relationship is medium, namely the value 0.40 – 0, 59, a strong relationship, namely a value of 0.60 – 0.79, and a very strong relationship, namely a value of 0.80 – 1.00 (Bayudana et al., 2022).

3. Result and Discussion

3.1. Suspended Sediment

Based on the graph in Figure 2, all algorithms' suspended sediment concentration values are consistently lower than the in-situ concentration values. Despite these differences, the distribution patterns of the lowest and highest values among the algorithms are similar, occurring at sampling point 7 and sampling point 2, respectively. In contrast, the in-situ measurements indicate the lowest concentration at sampling point 5 and the highest at sampling point 6. The uniformity in the highest and lowest values in the image processing results can be attributed to the algorithms relying on the same remote sensing reflectance (Rrs) values for each pixel, resulting in similar value patterns.

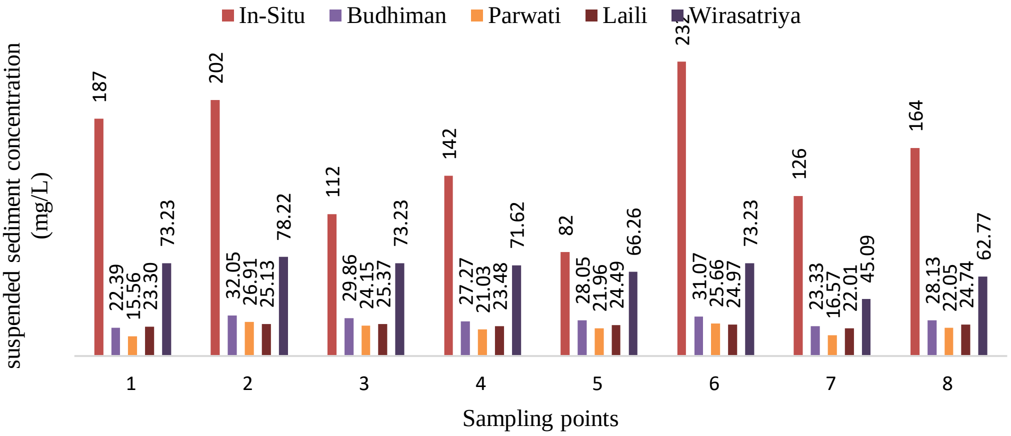

Figure 2. Comparison of suspended sediment concentration (mg/L)

The average concentration of suspended sediments across the study area is 155.8 mg/L. Among the algorithms, the Budhiman algorithm yields an average concentration of 31.41 mg/L, ranging from 24.07 mg/L to 35.10 mg/L. The Parwati algorithm produces a slightly lower average of 26.20 mg/L, ranging from 17.38 mg/L to 30.91 mg/L. The Budhiman and Parwati algorithms demonstrate comparable differences between their lowest and highest values, at 11.03 mg/L and 13.53 mg/L, respectively. These similarities stem from their reliance on a red band reference and the use of exponential regression equations (Mukhtar, 2023). The Laili algorithm results in an average concentration of 22.26 mg/L, with a narrower range of 20.79 mg/L to 22.91 mg/L. This limited range is due to the algorithm's simple regression equation, which incorporates a blue and red bands ratio.

In contrast, the Wirasatriya algorithm produces an average concentration of 67.91 mg/L, with a broader range of 45.09 mg/L to 78.22 mg/L. Notably, the values obtained from the Wirasatriya algorithm are closer to the in-situ measurements than those derived from the other algorithms. This algorithm is based on a red band reference and employs a simple linear regression equation, contributing to its improved alignment with in-situ data.

The differences between the suspended sediment values derived from image processing using various algorithms and the field-observed data can be attributed to the following factors: Algorithms are often optimized for use in water bodies with specific characteristics that match the location and temporal conditions under which the algorithm was developed (Afgatiani et al., 2020). Furthermore, three models predict suspended sediment values: empirical, theoretical, and semi-analytic (Afgatiani et al., 2023). Another factor is the discrepancies between the temporal sampling and Image Acquisition times.

3.2. In-Situ Suspended Sediment

The results of the In-situ suspended data are shown in Table 3.

Table 3. In-situ Suspended Sediment Concentration

Points	Coordinate (Degree)		Time	In-situ suspended sediment concentration (mg/L)
	Long	Lat		
1	106.9945	-5.9380	13.45	187
2	106.9923	-5.9392	13.03	202
3	106.9899	-5.9401	13.37	112
4	106.9886	-5.9419	13.10	142
5	106.9867	-5.9409	13.32	82
6	106.9869	-5.9432	13.15	232
7	106.9838	-5.9386	13.26	126
8	106.9844	-5.9421	13.18	164

3.3. Field Suspended Sediment Measurements

The results of field measurements for suspended sediment concentrations, as presented in Table 6, indicate that the lowest concentration was observed at sampling point 5 (82 mg/L), while the highest concentration occurred at sampling point 6 (232 mg/L). According to the classification of suspended sediment concentrations outlined in the Minister of Environment Decree No. 1 of 2010, the concentration at sampling point 5 falls within the low category, and the concentration at sampling point 6 is classified as high. The remaining sampling points fall into the medium category, with concentrations ranging from 100–220 mg/L.

3.4. Suspended Sediment Algorithm Accuracy

The accuracy test results using RMSE and NMAE for in situ and Sentinel-2A data are shown in Table 4.

Table 4. NMAE and RMSE values of suspended sediment algorithm

Algorithm	NMAE (%)	RMSE (mg/L)
Budhiman	41,79	107,05
Parwati	44,04	111,66
Laili	44,63	115,33
Wirasatriya	27,31	74,44

The results indicate a positive correlation between NMAE and RMSE values, where higher NMAE values correspond to higher RMSE values. NMAE measures the average absolute difference between field and image data, while RMSE represents the root mean square difference, typically yielding higher values (Rusdy et al., 2022). NMAE is preferred for model accuracy comparisons across diverse datasets (Mukhtar et al., 2021), while RMSE quantifies deviations between predicted and observed values (Azka et al., 2018). High NMAE and RMSE values may result from a limited number of field samples, leading to less precise accuracy calculations.

Table 4 highlights variability among the algorithms. The Laili algorithm shows the highest NMAE (44.63%) and RMSE (115.33 mg/L), reflecting the most significant deviation from in-situ values. Conversely, the Wirasatriya algorithm exhibits the closest alignment to field data, with the lowest RMSE (74.44 mg/L) and an NMAE of 27.31%, meeting the accuracy criterion of ≤30%. Previous studies provide additional findings from the Budhiman algorithm (2004) to yield the best accuracy for 2019 image data at the exact location. Similarly, Mukhtar (2023) identified the Budhiman algorithm as the most accurate for 2021 data in Jakarta Bay. These differences highlight the influence of image acquisition timing on algorithm performance and accuracy in suspended sediment estimation.

3.5. Suspended Sediment Distribution

The distribution of suspended sediment in the Citarum River Estuary for 2018, 2021, and 2024 was derived from Sentinel-2A image interpretation using the Wirasatriya algorithm (2020). Figures 4–6 illustrate that the most dominant sediment concentration is in the 0–100 mg/L range (low category), represented by a light brown color. This low-concentration sediment is primarily distributed in offshore marine areas and certain ponds. Sediments in the 100–220 mg/L range (medium category), depicted in a dominant brown color, are concentrated along coastal zones and the outermost sections of river estuaries. The highest sediment concentration class, 220–350 mg/L (high category), shown in dark brown, is predominantly located in the river estuary flow. The sediment concentration decreases with increasing distance from the coast.

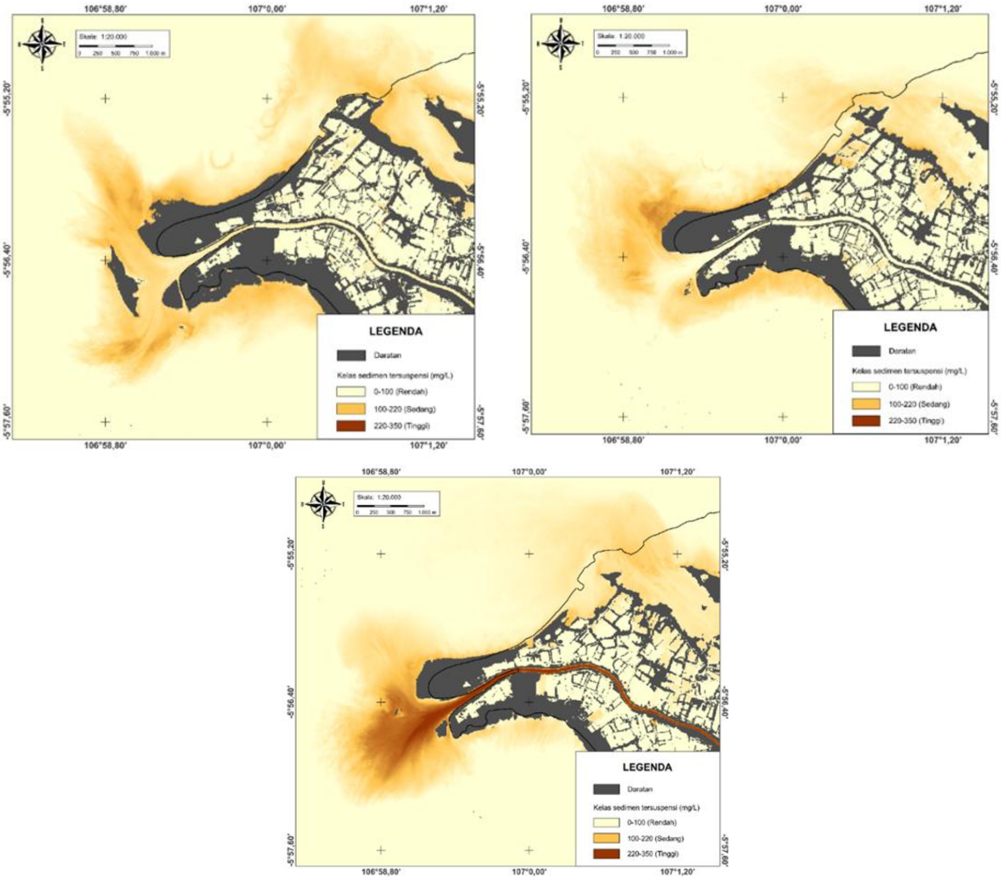

Figure 3. Distribution of Suspended Sediment, a. 2018; b. 2021; c. 2024

In 2018, suspended sediment distribution was dominated by low-category sediments along the river flow and river mouth, with moderate sediments observed near the outer areas of the river mouth and minimal high-category sediments. By 2021, low-category sediments remained dominant, while moderate sediments extended further outside the northern river mouth, with a small portion dispersing northward. In 2024, sediment concentration was significantly increased, with high-category sediments dominating outward from the river mouth. Field observations confirmed extensive sediment deposits along riverbanks and the estuary, aligning with increased sediment concentrations (Adawiah et al., 2021).

3.6. Suspended Sediment Area

The changes in sediment area were calculated using sediment concentration classes and water area boundaries derived from NDWI masking within the Citarum River Estuary for 2018, 2021, and 2024. The multi-temporal sediment area results, determined using the Wirasatriya algorithm (2020), are summarized in Tables 5

Table 5. Suspended sediment area

Category	2018		2021		2024	
	Area (Ha)	Percentage (%)	Area (Ha)	Percentage (%)	Area (Ha)	Percentage (%)
Low	717,18	63,19	512,28	41,16	513,22	40,91
Medium	417,73	36,81	546,42	43,90	597,68	47,65
High	0,01	0,00	186,04	14,95	143,48	11,44
Total	1134,92	100,00	1244,74	100,00	1254,38	100,00

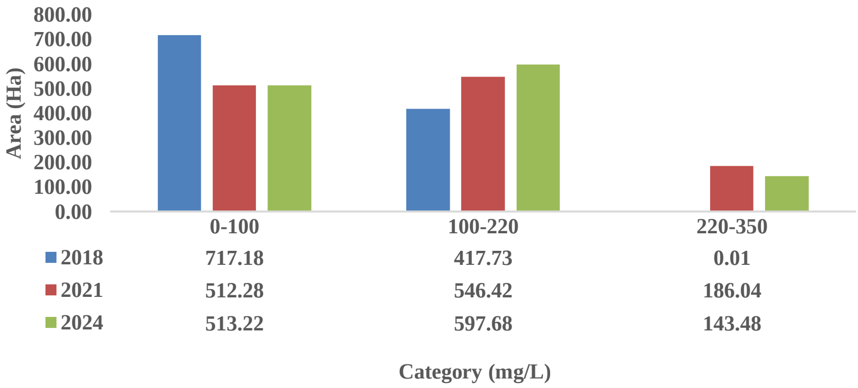

Figure 4. The area of suspended sediment at the Citarum River Estuary in 2018, 2021 and 2024

Based on Table 5, the suspended sediment distribution in 2018 was predominantly in the 0–100 mg/L concentration class (low), covering 63.19% of the total distribution area, equivalent to 1,134.93 hectares. The next largest area was in the 100–220 mg/L concentration class, accounting for 417.73 hectares or 36.81%. In contrast, the 220–350 mg/L concentration class covered only 0.01 ha, representing less than 0.1% of the total distribution area. The suspended sediment distribution in 2021 was primarily concentrated in the 100–220 mg/L (medium) class, comprising 43.90% of the total distribution area or 1,244.74 ha. The 0–100 mg/L (low) class was the next largest, covering 512.28 ha or 41.16%. The smallest area was in the 220–350 mg/L (high) class, which accounted for 186.04 ha or 14.95% of the total distribution area. The suspended sediment distribution 2024 is predominantly in the 100–220 mg/L (medium) concentration class, covering 47.65% of the total area, equivalent to 1,254.38 ha. The next largest area is in the 0–100 mg/L (low) class, accounting for 513.22 ha or 40.91%. The highest concentration class, 220–350 mg/L, occupies the smallest area, with 143.48 ha or 11.44% of the total distribution.

Figure 4 shows fluctuating changes in the area of suspended sediment concentration classes over the observation periods. From 2018 to 2021, the 0–100 mg/L (low) category decreased by 28.57%, followed by a slight increase of 0.18% in 2024, reaching 513.22 hectares. The 100–220 mg/L (medium) category increased significantly by 30.80% from 2018 to 2021 and grew further by 9.38% in 2024, reaching 597.68 hectares. The 220–350 mg/L (high) category surged by 1,860.3% from 2018 to 2021 but decreased by 22.85% in 2024 to 143.48 hectares. The most notable changes occurred between 2018 and 2021, shifting toward medium and high categories. By 2024, the distribution remained similar to 2021, with only minor adjustments, reflecting ongoing sediment accumulation in the Citarum River Estuary.

3.7. Mangrove Object Identification

The identification of mangrove areas in Sentinel-2A image data was conducted using band stacking or band composite techniques, specifically combining bands 8 (NIR), 11 (SWIR), and 4 (Red). This band combination leverages the unique sensitivity of each band to specific objects based on their respective wavelengths (Hanan et al., 2020). The composite band differentiates mangrove and non-mangrove areas. Mangrove vegetation is shown in dark orange near coastal regions, water appears as dark blue, while non-mangrove vegetation and settlements are represented by yellow and green, respectively.

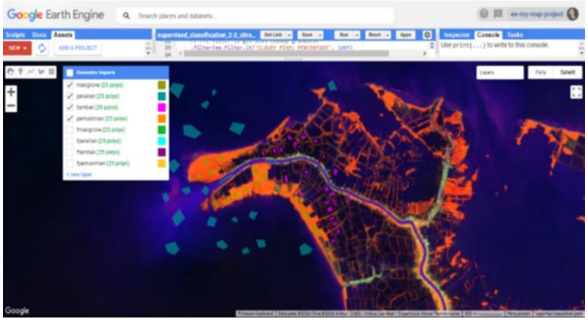

Figure 5. Four class data samples supervised the classification

3.8. Land Cover Classification Accuracy Test

The results of the confusion matrix accuracy test with four classification classes are seen in Table 6. The producer's accuracy, user accuracy and kappa coefficient are found in the confusion matrix.

Table 6. Mangrove land cover classification confusion matrix

Class	Mangrove	Waters	Pond	Settlement	Total (user)
Mangrove	42	0	3	2	47
Waters	1	13	3	1	18
Pond	2	1	13	1	17
Settlement	1	2	2	13	18
Total (producer)	46	16	21	17	100

Table 7. Accuracy of Mangrove Land Cover Classification

Class	Producer's Accuracy (%)		User's Accuracy (%)		Overall Accuracy (%)	Kappa Coefficient (%)
	Accuracy	Omission	Accuracy	Commission		
Mangrove	91,30	8,70	89,36	10,64	81	72,41
Waters	81,25	18,75	72,22	27,78		
Pond	61,90	38,10	76,47	23,53		
Settlement	76,47	23,53	72,22	27,78		

Based on Table 6, land classification using the supervised classification technique achieved an overall accuracy of 81% and a kappa coefficient of 72.41%. These results meet the criteria outlined in BIG Regulation No. 3 of 2014, which requires an overall accuracy of ≥70%. The kappa coefficient, ranging between 0.4 and 0.8, indicates medium accuracy.

3.9. Changes in the Mangrove Forest Area

Figure 6 shows changes in mangrove forest distribution in the Citarum River Estuary over three-year intervals: 2018, 2021, and 2024. Mangrove areas, highlighted in red on the map, are visible along the land, river flow, and estuary. In 2021 and 2024, mangrove forests extended beyond the 2018 land boundary of Pantai Bahagia Village, illustrating significant growth in mangrove forest area during the observed periods.

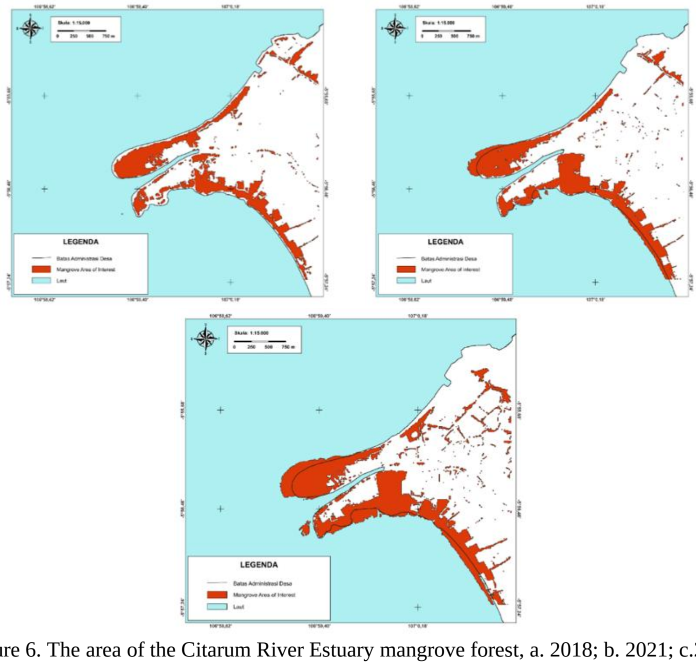

Figure 6. The area of the Citarum River Estuary mangrove forest, a. 2018; b. 2021; c.2024

Table 8. Mangrove forest area in 2018, 2021 and 2024

No	Region	Area (Ha)		
		2018	2021	2024
1	Pantai Bahagia	372,68	337,36	470,93
2	Citarum River Estuary	108,43	130,12	170,01

Table 8 shows changes in mangrove forest area in the Citarum River Estuary, covering Pantai Bahagia Village and Muara Sungai Citarum, from 2018 to 2024: 1. 2018: Pantai Bahagia Village had 372.68 ha of mangrove forests, with 108.43 ha (29.09%) in Muara Sungai Citarum. 2. 2021: The Mangrove Forest area in Pantai Bahagia Village decreased to 337.36 ha, with 130.12 ha (38.57%) in Muara Sungai Citarum. 3. 2024: The total mangrove area increased to 470.93 ha, with 170.01 ha (36.10%) in Muara Sungai Citarum.

Research by Metkono et al. (2022) estimated a potential 70 ha of mangroves in Pantai Bahagia Village in 2018, while Pamungkas et al. (2020) reported 300 ha for the same year. Pratama et al. (2022) calculated 464.42 ha using Sentinel-2A imagery. Variations in results are attributed to differences in imaging times and land cover classification methods.

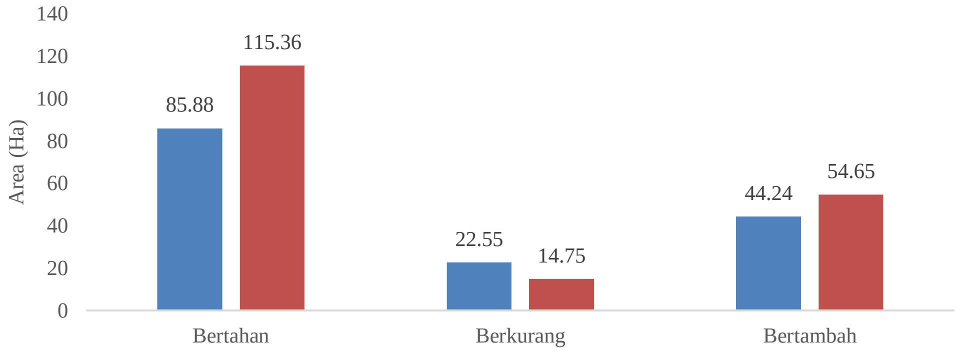

Figure 7. Changes in the area of the Citarum River Estuary mangrove forest in 2018, 2021 and 2024

An analysis of mangrove forest area changes in the Citarum River Estuary from 2018 to 2024 reveals consistent annual increases in coverage. Between 2018 and 2021, the mangrove area in Pantai Bahagia Village expanded by 44.24 ha (20.01%), significantly surpassing the reduction of 22.55 ha (14.50%). This trend continued during 2021–2024, with a more significant increase of 54.65 ha (30.65%), while reductions were notably smaller, totaling 14.75 ha (18.99%). These findings highlight the region's steady recovery and growth of mangrove forests. Overall, the mangrove forest area in the estuary steadily increased across all observation periods. Relationship between suspended sediments and mangrove area changes correlation tests between suspended sediment distribution and mangrove area changes for 2018, 2021, and 2024 are summarized in Table 9.

Table 9. Correlation test and coefficient of determination

Regression Statistics	
Multiple R	0.814
R Square	0.662
Adjusted R Square	0.325
Standard Error	25.663
Observations	3

The correlation test results in Table 9 show a correlation coefficient (r) of 0.814, indicating a very strong relationship between suspended sediment concentration and mangrove forest area. Suspended sediment contributes to land expansion through deposition, creating a suitable habitat for mangrove growth. The coefficient of determination (r^2) is 0.662, meaning suspended sediment accounts for 66.2% of the variation in mangrove forest area, while other factors outside the study influence the remaining 33.8%.

4. Conclusions

The analysis concludes that the distribution of suspended sediment, as measured using the Wirasatriya algorithm, has shifted over time towards medium and high concentration classes. In 2018, low concentrations dominated (63.19%), but medium concentrations became the most prevalent in 2021 (43.90%) and 2024 (47.65%). Additionally, the mangrove forest area in the Citarum River Estuary has shown consistent growth, with an increase of 44.24 hectares (20.01%) from 2018 to 2021 and a further expansion of 54.65 hectares (30.65%) from 2021 to 2024. This growth strongly correlates with suspended sediment, with a correlation coefficient of 0.814. Suspended sediment accounts for 66.2% of the variation in mangrove forest area, while other factors influence the remaining 33.8%.

5. Suggestions

Research related to testing the TSS algorithm in waters is recommended to conduct sampling at an accurate location and time point with the recording time of the image data used so that suspended sediment data that matches the situation in the field is obtained simultaneously. It is also recommended to consider other factors, such as tides, currents, and wind direction, that have the potential to directly affect the distribution of suspended sediments in the waters.

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