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A Robust Algorithm for Estimating Total Suspended Solids (TSS) Using Sentinel-2: Case Study in Coastal Waters of Teluk Awur, Jepara, Indonesia

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Abstract

Total suspended solids (TSS) is an important parameter of water quality, so regular monitoring is necessary to prevent further marine pollution due to TSS. Remote sensing is one of the most effective and efficient methods to monitor TSS with cost-effective operations. The Sentinel-2 satellite is freely available to users with high spectral and spatial resolution (10m, 20m, 60m). Dynamic changes in coastal waters and their characteristics cause TSS retrieval algorithms built from available imagery having less optimal results in other water regions. This research aims to develop an empirical TSS algorithm model that specifically applies to the coastal waters of Teluk Awur, Jepara. The algorithm was developed using an empirical method through correlation between spectral values of Sentinel-2 imagery and in situ TSS values. Water sampling was conducted at 110 stations with a depth of 0.5 m on 22 July 2023 simultaneously collocated with Sentinel-2 image recording. Half of the data was used for algorithm tuning and the other half used for validation. The best regression analysis is found in the red band (B4) and the model is linear. The relatively good performance is shown by the coefficient of determination (R^2) of 0.45, RMSE (3.40 mg.L^{-1}), and MAPE (10.76%). The resulting algorithmic model was TSS (mg.L^{-1}) =817.213(B4)-0.959. This study shows that Sentinel-2 MSI images for TSS retrieval in the coastal waters of Teluk Awur could be applicable and the red band (B4) can be used for mapping TSS concentrations in the surrounding study area.*

Keywords: *Algorithm, Suspended Solid, Sentinel-2, Teluk Awur, Remote Sensing*

Introduction

The coastal waters of Teluk Awur are situated in the region of Jepara Regency and the coastline has been degraded due to abrasion processes (Ibrahim *et al.,* 2021). The high rate of land conversion for residential, tourism, agriculture, and aquaculture farms may contribute to the increase in suspended materials that empty the waters (Kwong *et al.,* 2022). Total Suspended Solid (TSS), consists of biotic and abiotic suspended materials. In high concentrations, TSS causes the water column to become more turbid (Wirasatriya *et al.,* 2023), thereby reducing the penetration of sunlight into the water and causing disruption in the aquatic ecosystem (Wang *et al.,* 2017; Yu *et al.,* 2019). TSS in waters could be derived from internal coastal sources, such as; the result of abrasion and resuspension processes of bottom sediments and the result of photosynthesis processes, and external sources, such as; sediment input from land which is carried by river flow or water run-off and human activities at upstream region (Ciancia *et al.,* 2020). As one of the determining parameters of water quality, it is necessary to monitor TSS concentration.

The coastal water quality with high concentration of TSS continues to deteriorate, due to the increasing turbidity and input of pollutants. On the other hand, the presence of seagrass meadows, mangroves, and corals in the coastal waters of Teluk Awur, playing an ecologically important role, requires suitable water quality to support the ecosystem's health (Whitfield, 2017). Thus, continuous monitoring of water quality, especially TSS is important, which can also be used as a basis for future decision-making in coastal management, either for aquaculture or conservation areas (Maslukah *et al.,* 2023). Based on the Indonesian Government Regulation No. 22 of 2021, it is stated that if the TSS value exceeds (>20 mg.L^{-1}), the waters are classified into a polluted water for the designation of environmental cultivation, conservation, and tourism.

Analyzing TSS concentration is usually performed through sampling and laboratory analysis. However, such field samplings are often considered

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insufficient (Doxaran *et al.,* 2014), as they are time- and cost-consuming (Saberioon *et al.,* 2020). The method of aquatic remote sensing offers an efficient proxy for its monitoring at local, regional, and global scales (Liu *et al.,* 2017; Saberioon *et al.,* 2020). This approach utilized spectral values or reflectance remote sensing (Rrs/λ), which carries information on the optical properties of the near-surface constituents of water, including TSS. Coastal waters have significantly higher constituents of chlorophyll-a (Chl-a), TSS, and colored dissolved organic matter (CDOM). These are the substances that actively influence the optical properties of water (Katlane *et al.,* 2020; Ngoc *et al.,* 2020) and are continuously changing at spatial and temporal scales.

High-resolution satellites, such as Sentinel-2 have the advantage of carrying 13 spectral channels ranging from visible, near-infrared (NIR) to shortwave infrared, with a better spatial resolution of 10, 20, and 60 m and a temporal resolution of 2 to 5 days. Therefore, Sentinel-2 is a more efficient and effective alternative in terms of monitoring and mapping the TSS concentration (Saberioon *et al.,* 2020; Hafeez *et al.,* 2022). Detecting TSS through a remote sensing approach in Teluk Awur coastal waters has been conducted previously by Subardjo *et al.,* (2020) using Landsat 8 imagery and Maslukah *et al.,* (2023) using Sentinel-2. However, the resulting data has a relatively high bias. Many factors, such as the type of dominating suspension (phytoplankton or in-organic sediment), bathymetric conditions, and the type of sediment can affect the result of spectral value. Thus, the use of previously developing algorithms is not always universally applicable (Kutser *et al.,* 2018; Premkumar *et al.,* 2021; Milenia *et al.,* 2022).

For this reason, regional and local-based algorithms are needed to derive a more accurate model of local water TSS assessment. To develop them, it is necessary to calibrate in situ TSS values with remote sensing reflectance (Rrs). The characteristics of suitable spectral values are required in improving algorithms based on empirical methods (Ngoc *et al.,* 2020). Several researchers have applied the red band (B4) in calibrating TSS algorithms, such as Wu et al. (2015); Caballero et al. (2018); Priyaa and Jena (2021); and Wirasatriya *et al.* (2023) and some other researchers used it the visible blue, green, and near infrared (NIR) bands (Lyu *et al.,* 2021). Therefore, this study aims to analyze the best algorithm for using visible spectral bands of blue (B2), green (B3), red (B4), and NIR bands including B5, B6, B7, and B8 by the single band method.

Materials and Methods

Seawater samples were collected on 22 July 2023 at 110 station points, sampling time coincided with Sentinel-2A imagery acquisition (Figure 1). A total of 500 mL of seawater was collected at a depth of 0.5 meters for TSS analysis, using the gravimetric method: (1) seawater was filtered with Whatman GF/F (0.45 μm) (pre-dried and pre-weighed) (2) The supernatant was dried for 2 h at 110ºC and reweighed after incubation in a desiccator, and (3) TSS was obtained by dividing the difference in weight before and after filtration by the volume of seawater.

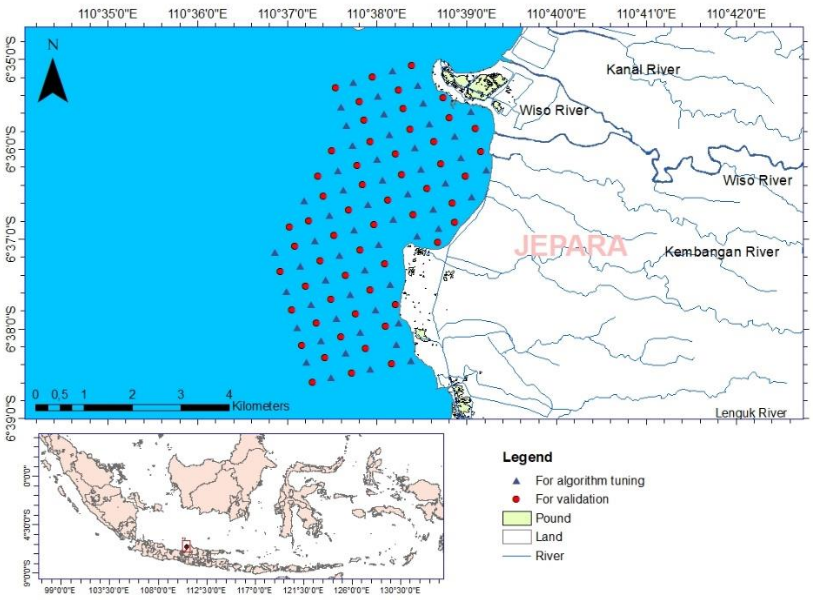


Figure 1. Location of Research in the Coastal Waters of Teluk Awur Jepara, Central Java, Indonesia

The reflectance data of Sentinel-2 was processed using SNAP software. In this study, we used Sentinel-2 MSIL2A-type images. Gatti and Bertolini (2015) explained that the reflectance values used are Bottom of Atmosphere type, so in this study, both geometric correction and radiometric correction could be neglected (Esa, 2015). Otherwise, the sentinel-2 was processed through cropping, resampling, and reprojection (González *et al.,* 2022).

Tuning algorithm for TSS estimation

Sentinel-2 has two bands in the blue region, centered at 443 nm (B1) and 490 nm (B2); one band in the green region (B3, centered at 560 nm); one band in the red region (B4, centered at 665 nm) and five bands in the NIR region (B5/705 nm, B6/740 nm, B7/783 nm, B8/842 nm, and B8a/856 nm), respectively. In previous studies, many TSS retrieval algorithms have been developed using the red band (664.5 nm). However, in this study, other visible bands will be simulated based on the NIR, following protocol proposed by Liu *et al*. (2017) and Prekumar *et al*. (2016), namely at B5, B6, B7, and B8. The new TSS equation was generated using an empirical method, through the establishment of a linear regression equation between in situ data and reflectance using a single-band method. A total of 50% of *in situ* TSS and reflectance data were used to build the model and the other for validation. The algorithm for TSS was analyzed using regression equations of various forms (linear, exponential, power, and logarithmic) generated from the relationship between Rrs and *in situ* data (Liu *et al.,* 2017; Sukmono *et al.,* 2023).

Validation of TSS algorithm

Testing the performance of the resulted model was based on the bias value, Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE) and Bias (Equations 1, 2, and 3) (Ciancia *et al.,* 2020).

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{n}(TSS_{predicted} - TSS_{insitu})^2} \quad ..... (1)$$

Mean Absolute Error (MAPE)

$$MAPE = (\frac{1}{N}) \sum_{i=1}^{n}[\frac{TSS_{predicted} - TSS_{in\ situ}}{TSS_{predicted}}] \times 100 ..... (2)$$

Bias

$$Bias = \frac{1}{N} \sum_{i=1}^{n}(TSS_{predicted} - TSS_{in\ situ} \quad ..... (3)$$

Result and Discussion

The analysis showed that the TSS concentration ranged from 13.86 to 45.80 mg.L^{-1}. According to the classification by Yu *et al.* (2019), the water type of Teluk Awur coastal water is classified as moderate. This indicates that although the water in the area has not reached the level of severe pollution, there has been a significant increase in pollutant content compared to clean or lightly polluted waters. Moderate pollution conditions usually occur due to a combination of several types of pollutants in higher concentrations but have not yet reached massively damaging levels. Furthermore, the reflectance values used in this study are B2-B8, with the statistical values presented in Table 1.

Tuning algorithm of TSS

In this study, a model for determining TSS from sentinel imagery was developed through the relationship between in situ data and Rrs for each band (B2-B8), the results of which are shown in Table 2. Considering Table 2, the correlation band (r) >0.5 was selected to be developed as a candidate model for the TSS retrieval algorithm in B3, B4, and B5. Regression model development uses linear, power, exponential, and logarithmic equations. The overall results are shown in Table 3.

Furthermore, a validation was performed on the bands with R^2> 0.35, namely B4 and B5, the results of which are shown in Table 4. Table 4 shows that the validation with the best RMSE was achieved for band 4, using the linear equation with an RMSE of 3.40 mg.L^{-1}. However, B5 (linear) also represents a good model algorithm with an RMSE of 3.44 mg.L^{-1} (Figure 2).

Table 1. Descriptive statistics of in situ TSS and various reflectance values of Sentinel-2 for algorithm tuning and validation

Band	Σ sample	Minimum	Maximum	Mean	St. Dev.
B2	112	0.0460	0.0860	0.0666	0.0079
B3	112	0.0549	0.1004	0.0759	0.0092
B4	112	0.0231	0.0708	0.0335	0.0066
B5	112	0.0188	0.0619	0.0267	0.0056
B6	112	0.0078	0.0278	0.0135	0.0023
B7	112	0.0087	0.0253	0.01466	0.0022
B8	112	0.0057	0.0278	0.01139	0.0023
In situ	110	13.86	45.8	26.75	5.89

The results of the one-way ANOVA test showed that the in situ TSS, the predicted TSS of B4 and B5, have no significant difference (p>0.05). However, from the results of previous studies, the use of the red band (B4) is the most commonly used (Parwati *et al.,* 2014; Sukmono *et al.,* 2023). Liu *et al*. (2017) also explained that the use of B4 for TSS provides good performance. It should be noted that to determine TSS with higher concentrations, the use of longer wavelength bands is recommended ((Liu *et al.,* 2017). Considering that the TSS in this study has a moderate value, the use of B4 and B5 is more appropriate. The validation of TSS from B4 and B5 versus in situ TSS is shown in Figure 2 and the distribution pattern in Figure 3. The descriptive results of in situ TSS, predicted TSS of B4 linear, and predicted TSS of B5 linear are shown in Table 5.

Coastal waters are shallow and dynamic and consist of many types of organic and inorganic materials, which will affect the optical properties of the water. Therefore, the existing algorithms are not directly applicable because the bands used are not appropriate with the character of the water in the

Table 2. The correlation of in situ data to various bands of Sentinel-2

		B2	B3	B4	B5	B6	B7	B8
In situ Data	Correlation	0.356**	0.0.528**	0.703**	0.649**	0.332*	0.398**	0.237
	Sig. (2-tailed)	0.008	0.000	0.000	0.000	0.013	0.003	0.081
	N	55	55	55	55	55	55	55

Note: *. Correlation is significant at the 0.05 level (2-tailed); **. Correlation is significant at the 0.01 level (2-tailed).

Table 3. The regression models of B3, B4, and B5 using linear, power, exponential, and logarithmic

Band	Types of regression	R^2	Algorithm retrieval of TSS (mg.L^{-1})
B3	Linier (TSS=a*(B3)+c)	0.28	TSS = 422.454*(B3) - 5.548
	Power (TSS=c*B3^a)	0.26	TSS = 566.101*(B3)^1.198
	Exponent (TSS=c*exp(B3*a))	0.27	TSS = 7.64*exp(B3*15.908)
	Logarithmic (TSS=a*ln(B3)+ c)	0.27	TSS = 31.645*Ln(B3)+8108.335
B4	Linier (TSS=a*(B4)+c)	0.49	TSS = 817.213*(B4) - 0.959
	Power (TSS=c*B4^a)	0.47	TSS = 1019.246*(B4)^1.082
	Exponent (TSS=c*exp(B4*a))	0.46	TSS = 9.216*exp(B4*30.345)
	Logarithmic (TSS=a*ln(B4)+ c)	0.49	TSS = 28.682*Ln(B4)+124.256
B5	Linier (TSS=a*(B5)+c)	0.42	TSS = 910.986*(B5) + 2.163
	Power (TSS=c*B5^a)	0.39	TSS = 901.505*(B5)^0.98
	Exponent (TSS=c*exp(B5*a))	0.38	TSS = 10.494*exp(B5*33.312)
	Logarithmic (TSS=a*ln(B5)+ c)	0.42	TSS = 26.402*Ln(B5)+122.536

Table 4. The in situ TSS and predicted TSS from B5 and B4 linearly, exponentially, power, and logarithmic

		In situ	Linear	Exponential	power	logarithmic
B5	Min	18.48	19.47	19.76	18.54	17.90
	Max	34.86	31.95	31.19	31.57	32.23
	St. Dev.	4.20	3.30	2.99	3.45	3.81
	Average	26.56	25.31	24.64	24.65	25.30
	Bias		-1.25	-1.92	-1.91	-1.26
	RMSE (mg.L^{-1})		3.44	3.71	3.76	3.56
	MAPE (%)		10.22	10.63	11.04	10.86
B4	Min		17.92	18.56	17.29	16.18
	Max		35.00	34.97	34.71	34.67
	St. Dev.		3.79	3.53	3.88	4.18
	Average		25.39	24.73	24.76	25.39
	Bias		-1.22	-1.88	-1.80	-1.17
	RMSE (mg.L^{-1})		3.40	3.68	3.66	3.47
	MAPE (%)		10.76	11.20	11.46	11.19

regional scale. Ruddick *et al.* (2006) explained that band fitting in TSS estimation depends on its concentration. This is different from the open sea, where the algorithm can be applied generally. The improvement of the TSS retrieval algorithm in this study uses Sentinel-2 imagery captured on 22 July 2023 for the coastal waters of Teluk Awur and surrounding areas.

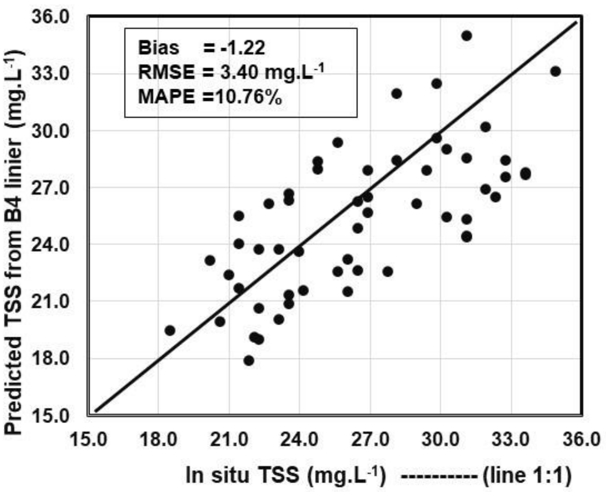
The results show that the Sentinel-2A product can provide sufficient data to efficiently predict and spatially visualize TSS in coastal waters. The red band of Sentinel-2 is acceptable by describing a variation of nearly 50%. Based on the bias values (Table 4), the TSS predictions from all developed equations are negative, which illustrates that the prediction is lower than the actual TSS. This study still has limitations because it only uses Sentinel-2 level 2A reflectance which is not validated against field reflectance. However, this study has successfully described the distribution of TSS in the region and it is the first study developing an algorithmic model for Sentinel-2-based TSS estimation in the coastal waters of Teluk Awur which has been altered by human activities and coastal abrasion (Ibrahim *et al.,* 2023).

The TSS retrieval algorithm generated in this study was analyzed through testing the response of in situ data to reflectance (Rrs) in the visible bands (B2, B3, and B4) and NIR (B5, B6, B7, and B8). Among the models that were developed, B4 showed the best fit for detecting the distribution of TSS in the study area. The application of the red band (B4) in Indonesian waters has also been demonstrated by several studies. Wirasatriya *et al.* (2023) utilized Sentinel-2 red band imagery to develop a new algorithm for determining the distribution of Total Suspended Solids (TSS) in the estuary of the BKB Semarang River. Similarly, Wibisana (2018) employed Landsat 8 red band imagery to assess TSS distribution along Ujung Pangkah Beach, Gresik. Budhiman (2004) used remote sensing techniques for mapping TSM concentrations in the Mahakam Delta through an analytical approach using Landsat imagery. Furthermore, Parwati *et al*. (2014) analyzed TSS extraction algorithms using Landsat 8 red band data in the waters of Berau.

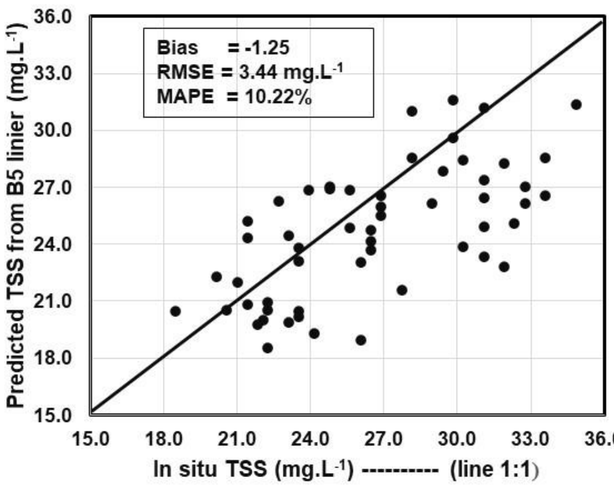
Liu *et al.* (2017) also explained that the red band has a higher value than blue-green for turbid waters. In clearer waters, Rrs is characterized by a peak in the blue region, while in turbid waters there is

Table 5. Descriptive statistic in situ TSS and prediction

	N	Mean	St. Dev.	St. Error	95% Confidence Interval for Mean		Min	Max
					Lower Bound	Upper Bound		
TSS from B4 linier	55	25.33	3.81	0.51	24.31	26.36	17.92	35.00
TSS from B5 linier	55	24.65	3.45	0.46	23.72	25.58	18.54	31.57
TSS from in situ	54	26.43	4.13	0.56	25.32	27.56	18.48	34.86



(a)



(b)

Figure 2. The validation of in situ TSS versus predicted TSS (a) Linear regression of B4 (b) Linear regression of B5

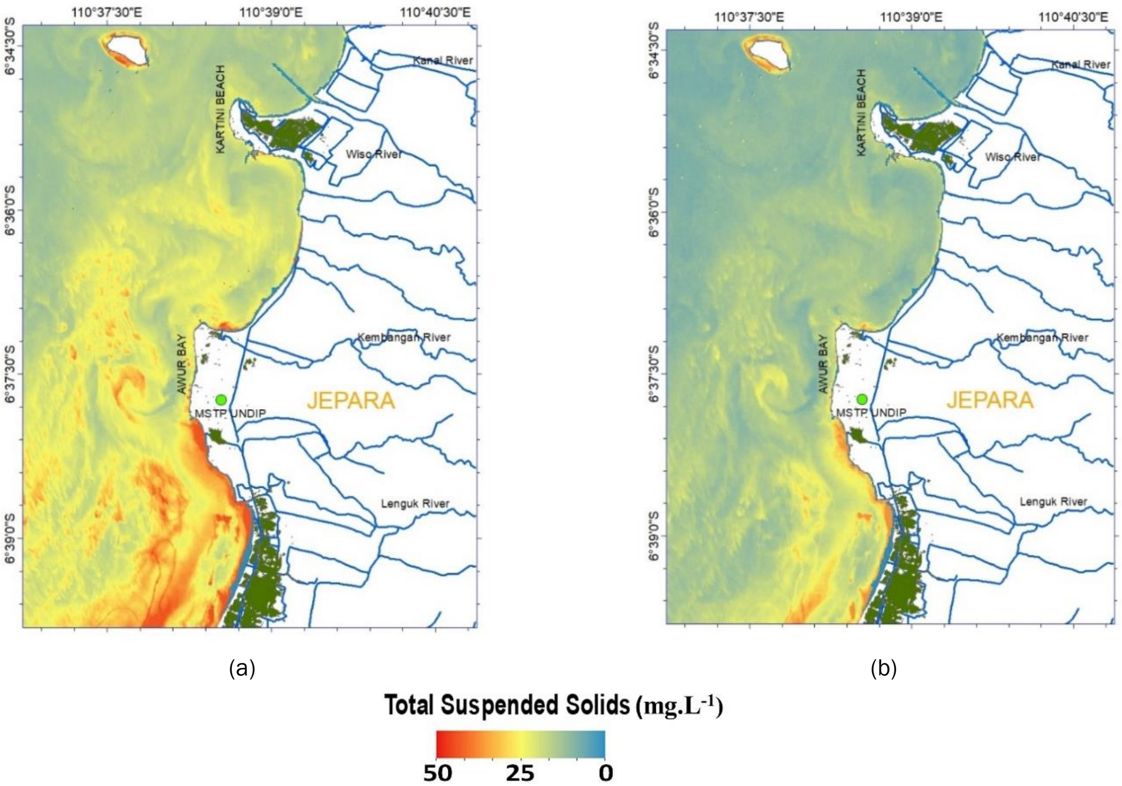


Figure 3. The distribution pattern of TSS using (a) Band 4 (linear) (b) Band 5 (linear)

usually a peak in the green-red region, depending on the dominating type and concentration of suspension (Caballero *et al.,* 2018). Based on the classification of Yu *et al*. (2019), the TSS concentration at the research site is medium, which is shown in the range of 13.86-45.80 mg.L^{-1} (average 26.75 mg.L^{-1}). In contrast to the research of Liu *et al.* (2017) in lake waters found the highest correlation occurred in band 7 which showed TSS values with a wider range, reaching 17.16-294.50 mg.L^{-1} (average 77.75 mg.L^{-1}). While the results of Saberioon *et al*. (2020) the highest correlation was found in band 5 based on a combination of visible and NIR. Ruddick *et al*. (2006) also explained that for high TSS concentrations, the best results are obtained with longer wavelengths (700 nm and above), while for low concentrations, it is more appropriate to use shorter wavelengths (e.g. green wavelength band).

The difference in correlation between in situ TSS and reflectance reflects the characteristics of the coastal waters. Therefore, the algorithms of TSS from other waters are generally not directly applicable (Indeswari *et al.,* 2018; Yu *et al.,* 2019). Constantin *et al*. (2017) explained that each region has unique characteristics so local and regional-based algorithms should be developed. The results of this study can also explain that the NIR band (B5) could be applied for TSS estimation.

In addition to the selection of suitable bands, this study also analyzed the type of regression equation used in the generated algorithm. As a result of the regression equation analysis, the best model performance was found in the linear and logarithmic regression of B4, with a coefficient of determination (R^2=0.49). However, the validation test showed that linear B4 was the best, as indicated by the RMSE (3.40 mg.L^{-1}) and MAPE (10.76%) in the concentration range of 13.86-45.8 mg.L^{-1}. This value is still small compared to the research of Liu *et al*. (2017) on the red band with MAPE = 36.87% and RMSE= 32.38 mg.L^{-1} with a range of 17.16-294.5 mg.L^{-1} using the exponential equation in the red band and Parwati *et al*. (2016) with MAPE reaching 30.32%. In contrast to the research of Chen *et al*. (2015) which explains that the quadratic regression equation in TSS estimation is good, but in this study, it is not performed. However, the linear equation can be preferred because it is a simpler equation, particularly for the waters of Teluk Awur.

Conclusion

Seven bands of Sentinel-2 imagery has been examined for estimating TSS in the waters of Teluk Awur, Jepara. The best algorithm model following the linear regression model is TSS (mg.L^{-1})= 817.213*(B4) - 0.959 which shows the best performance as indicated by the low RMSE, MAPE, and bias values, i.e, 3.4 mg.L^{-1}, 10.76% and -1.23, respectively. Applying this algorithm, the predicted values of TSS on 22 July 2023 in the waters of Teluk Awur ranged from 17.92 to 35 mg.L^{-1} (average 25.33 mg.L^{-1}). This results is similar with the in situ TSS which ranges from 18.48 to 34.86 mg.L^{-1} (average 26.43 mg.L^{-1}). The high sensitivity of band 4 (B4) to detect surface particles in water, such as sediments and organic matter, making it more effective for observing TSS concentrations in surface waters.

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