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The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel 2A-MSI in coastal waters of Semarang, Indonesia

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Abstract:	The chlorophyll-a (Chl-a) plays an important role in aquatic ecology and biogeochemical cycling, and is a key indicator of trophic state in the environment. The MSI Sentinel-2A BoA offers a unique opportunity to investigate its concentration in the BKT river front, due to its high spatial resolution at B2, B3, B4, and B8. The generated Chl-a algorithm was derived from a linear regression model between in-situ data and reflectance. The results of this study show that the performance of the algorithm that has been generated has accuracy based on the RMSE, bias, MAPE, and R2 values of 2.44 mg/m3, -0.83, 23.92%, and 0.61, respectively. The seasonal variation of Chl-a in the waters of the BKT River was obtained by applying the equation to the BOA reflectance values of the cloud-free Sentinel-2 images representing each month in 2021. Maximum (minimum) Chl-a occurs in December (September) which can reach 11.92 µg/L (7.06 µg/L). Rainfall, wind speed, sunshine and air temperature data were used to analyze the temporal variation of surface Chl-a. The seasonal variation of Chl-a follows the variation in air temperature and sunshine. High (low) air temperature and length of sunshine cause high (low) Chl-a in the BKT River waters. The exposure of the length of the sun causes an increase in temperature that can inhibit the process of photosynthesis and reduce Chl-a. On the other hand, the high wind speed affects the increase of Chl-a in the area away from the river mouth, which is related to the mixing process. According to the criteria of Chl-a concentration in the sea, BKT waters are eutrophic (>6 µg/L), so it is necessary to be concerned about the possibility of algae blooming
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Dear Editor of Regional Studies In Marine Science

We would like to submit an original research article entitled "The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel 2A-MSI in coastal waters of Semarang, Indonesia" for consideration by the Regional Marine Science Study.

We confirm that this work is original and has not been published elsewhere, and is not currently being considered for publication elsewhere.

Chlorophyll-a (Chl-a) plays an important role in aquatic ecology and its biogeochemical cycles, as well as a key indicator of the trophic state in the environment. In this study we first show the temporal variation of Chl-a in the waters off the Banjir Kanal Timur (BKT) River, Semarang, Indonesia, after developing a chl-a algorithm using Sentinel-2A images. The development of algorithm is based on 93 matching data, consisting of in-situ chl-a as truth chla and placed satellite measurements.

We believe this manuscript deserves to be published by Regional Studies In Marine Science.

We have no conflict of interest to disclose.

Thank you for your consideration of this manuscript.

Sincerely,

Lilik Maslukah

The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel 2A-MSI in coastal waters of Semarang, Indonesia

Lilik Maslukah*, Anindya Wirasatriya, Yusuf Jati, Dwi Haryo Ismunarti, Rikha Widiaratih

Highlights

1. Estimating chlorophyll from high spatial resolution (10m) Sentinel 2A imagery
2. The chlorophyll-a algorithm using Sentinel-2 images for the coastal water off Banjir Kanal Timur (BKT) River, Semarang, Indonesia is Chl-a (μg/L) = 〚10〛 **^((2.743-0.725*(log(B2*c))-0.625*(log(B3*c))+1.623*(log(B4*c))+0.809*(log(B8*c)))** with the Root Mean Square Error, bias, MAPE and R^2 of 2.44 mg/m3, -0.83, 23.92%, and 0.61 respectively.
3. The Maximum (minimum) Chl-a occurs in December (September) which can reach 11.92 ug/L (7.06 ug/L)
4. According to the criteria of Chl-a concentration in the sea, BKT waters are eutrophic, so it is necessary to be concerned about the possibility of algae blooming.

The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel 2A-MSI in coastal waters of Semarang, Indonesia

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Abstrak

Chlorophyll-a (Chl-a) plays an important role in aquatic ecology and its biogeochemical cycles, as well as a key indicator of the trophic state in the environment. The Sentinel-2A MSI BoA offers a unique opportunity to investigate its concentration in coastal due to its high spatial resolution (10-60 m). The spatial resolution of 10m at four bands (blue, green, red, and near-infrared) was used to monitor Chl-a from the front of BKT, one of the estuaries in the north coastal waters of Java. The generating of the Chl-a algorithm was derived from the linear regression model between in-situ data and reflectance from BoA Sentinel-2A. A total of 43 water samples were collected to build the algorithm and 50 of the water samples were used for validation. The collection of water samples was conducted on 21 August 2021. The in-situ Chl-a was obtained through the trichromatic method using a spectrophotometer. The results of this study show that the performance of the algorithm that has been generated has accuracy based on the RMSE, bias, MAPE, and R^2 values of 2.44 mg/m^3, -0.83, 23.92%, and 0.61, respectively. The seasonal variation of Chl-a in the waters of the BKT River was obtained by applying the equation to the BOA reflectance values of the cloud-free Sentinel-2 images representing each month in 2021. Maximum (minimum) Chl-a occurs in December (September) which can reach 11.92 µg/L (7.06 µg/L). Rainfall, wind speed, sunshine and air temperature data were used to analyze the temporal variation of surface Chl-a. The seasonal variation of Chl-a follows the variation in air temperature and sunshine. High (low) air temperature and length of sunshine cause high (low) Chl-a in the BKT River waters. The exposure of the length of the sun causes an increase in temperature that can inhibit the process of photosynthesis and reduce Chl-a. On the other hand, the high wind speed affects the increase of Chl-a in the area away from the river mouth, which is related to the mixing process. According to the criteria of Chl-a concentration in the sea, BKT waters are eutrophic (>6 µg/L), so it is necessary to be concerned about the possibility of algae blooming.

Keywords: Coastal algorithm, chlorophyll-a, visible-NIR band, Sentinel-2MSI

Introduction

Phytoplankton holds significant ecological importance within the marine ecosystem owing to its capacity for photosynthesis, a metabolic process that facilitates the synthesis of organic compounds utilizing light energy and carbon dioxide (Rost et al., 2008; Abbas et al, 2021; Aranha et al, 2022). Phytoplankton possesses chlorophyll-a within its cellular structure and plays a crucial role in ecological systems, serving as a fundamental component of the aquatic life cycle and serving as the primary source of energy within oceanic food webs. Chlorophyll-a is a crucial factor in assessing water quality due to its regulatory role in biological processes occurring within coastal waters (Ogashawara et al., 2021; Tran et al., 2023). The determination of chlorophyll-a distribution within a given area is typically achieved through the implementation of field sampling techniques, which are subsequently complemented by laboratory-based analyses (Abbas et al., 2019; Maslukah et al., 2019). Nevertheless, this approach proves to be ineffective and inefficient due to its prolonged duration, elevated expenses, and restricted geographical reach (Duan et al., 2010; Ogashawara et al., 2021; Aranha et al., 2022). In order to address these concerns, a number of remote sensing techniques have been devised for the purpose of monitoring chlorophyll-a (Ouma et al., 2020;). Remote sensing methods show promise for monitoring chlorophyll-a levels in a given area due to their extensive coverage and ability to provide periodic observations (Maslukah et al., 2019; Ouma et al, 2020). The utilization of ocean color data within the visible and near-infrared (VNIR) wavelength bands facilitates the estimation of chlorophyll-a levels (Ouma et al. 2020). The acquisition of chlorophyll-a data from these satellites necessitates the utilization of an algorithm that is heavily reliant on the band and spectral resolution capabilities offered by the satellite (Ogashawara et al., 2021).

The quantification of chlorophyll-a in reservoirs has been extensively studied, and multiple algorithms have been devised for this purpose. These algorithms encompass different approaches, such as utilizing two bands (red and near-infrared) as demonstrated by O'Reilly et al. (2019) and Tran et al. (2023), as well as employing a single band, as explored by Bramich et al. (2020). The aforementioned phenomenon is similarly observed in marine regions, where algorithms are employed to calculate the ratio between blue and green color bands (Tilstone et al., 2021; Tran et al., 2023). In the expanse of open ocean waters, the presence of colored dissolved organic matter (CDOM) and suspended particulate matter is limited to relatively small quantities (Nelson and Siegel 2002). Additionally, the concentration of chlorophyll-a in these waters is comparatively lower than that observed in coastal regions. Estuarine regions, characterized by terrestrial influence, exhibit heightened optical complexity as a result of the absorption caused by CDOM and non-algal particles (Ouma et al, 2020; Tran et al., 2023). The optical properties of water are significantly influenced by the presence of turbid coastal waters characterized by high concentrations of CDOM and suspended non-phytoplanktonic particles (Lewis &Arrigo, 2020). The aforementioned intricate aquatic conditions diminish the efficacy of the band ratio algorithm in estimating Chl-a concentration. This is because the signal of the blue band declines below the detection threshold as a result of substantial absorption by phytoplankton (Soja-Wozniak, 2020).

There is a need to further develop ocean color sensors and refine algorithms for the retrieval of chlorophyll-a (Chl-a) in coastal waters. This is crucial for effectively monitoring the temporal and spatial fluctuations of phytoplankton blooms. This study employed the Sentinel-2 satellite to examine the fluctuations in chlorophyll-a levels adjacent to the Banjir Kanal Timur (BKT) river. The European Space Agency launched the Sentinel-2 satellite in 2015, which operates in a polar orbit. The Sentinel-2 satellite possesses a superior spatial resolution of 10 meters for the visible-Nir band, in comparison to the Landsat-8 Image, which exhibits a spatial resolution of 30 meters for bands 1 to 9 (Ouma et al, 2020). The utilization of multi-spectral sensors with high radiometric resolution, such as the Sentinel-2A Multispectral Instrument (MSI), is highly advantageous for the monitoring and evaluation of Chl-a levels in intricate coastal waters (Gohin et al., 2020).

In the context of Indonesia, prior research has relied on existing algorithms. However, the present study aims to develop a novel algorithm for estimating chlorophyll-a levels in Sentinel-2 images. Additionally, the accuracy of this algorithm will be assessed through a validation process. Additionally, the algorithm that has been acquired is subsequently utilized on other images in order to capture the temporal fluctuations of chlorophyll-a in the vicinity of the BKT River. This study represents the inaugural investigation into the seasonal fluctuations of chlorophyll-a levels in the BKT River, employing the Sentinel-2 algorithm.

The BKT river is a flood control system situated in the eastern region of Semarang city. The length of this river is approximately 14.50 kilometers. The BKT River originates from the Penggaron river and follows a course through the Pucang Gading outlet, Kedung Mundu river drainage outlet, Candi river, Bajak river, Kartini pump drainage, and the extensive rice field / Sambirejo pump drainage before ultimately discharging into the Java Sea. The direction of the river's current originating from an upstream source will exert a significant impact on the introduction of both organic and non-organic substances resulting from soil erosion and the discharge of solid and liquid waste. This, in turn, can have implications for the overall quality of the water. During the rainy season, sediment originating from terrestrial sources is introduced into the marine environment at an elevated pace, resulting in heightened turbidity within the estuarine system. According to Utama et al. (2021), the research findings elucidated that the concentration of suspended solids in the vicinity of the BKT estuary amounted to 290 mg/L during the rainy season and 60 mg/L during the dry season (Hutasuhut et al., 2022). In addition to exhibiting high turbidity, the frontal region of the river mouth is characterized as a eutrophic zone, as evidenced by the presence of chlorophyll-a concentrations. Specifically, during the dry season, the average chlorophyll-a concentration in this area is reported to be 12.67 µg/L, as documented by Maslukah et al. (2019). Conversely, in the wet season, the average chlorophyll-a concentration increases to 18.06 µg/L, as reported by Maslukah et al. (2020). According to the classification proposed by Hakanson and Bryan (2008), BKT waters can be categorized as being in eutrophic conditions. Temporal and continuous monitoring is necessary to observe and analyze the dynamics that take place.

In the vicinity of the BKT River and the coastal waters of Semarang, numerous scholars have employed remote sensing techniques to assess the dispersion of chlorophyll-a. This has been achieved through the utilization of MODIS (Maslukah et al., 2021) and Landsat 8 images (e.g., Subiyanto, 2017; Qonita et al., 2019). According to Maslukah et al. (2021), there is still an underestimation in the monitoring of chlorophyll-a using the MODIS level 3 satellite. The limitation in spatial resolution (4 km) and the algorithm designed for MODIS specifically caters to open ocean conditions. This algorithm relies solely on the blue to green band ratio, rendering it inappropriate for estuaries and coastal regions due to their distinct optical characteristics that deviate significantly from those of the open ocean (case 1). However, Subiyanto (2017) has conducted chlorophyll-a estimation using a higher resolution satellite (Sentinel-2). It is worth noting that this study lacks validation and relies on Landsat algorithms derived from different water bodies.

Hence, the reliability of their chlorophyll-a estimations is subject to doubt. Furthermore, while the researchers successfully obtained the spatial distribution of chlorophyll-a, their analysis failed to account for temporal fluctuations In their study, Qanita et al. (2019) conducted an analysis on the efficacy of Sentinel 2, utilizing the Case 2 Regional Processor on SNAP software, in the BKB River (specifically, the West Canal Flood area). However, the obtained chlorophyll-a concentration was found to be lower than the measurements obtained through field observations. The coefficient of determination (R2) value for this comparison was determined to be 0.1825. This observation suggests that the BKB River possesses distinct attributes that render the algorithm unsuitable for application in the coastal waters of Semarang. Therefore, the development of a novel algorithm is imperative for the estimation of chlorophyll-a levels in the BKT estuary front, as well as in other turbid waters.

The utilization of ocean color remote sensing in turbid regions (case 2) presents significant challenges due to the unique characteristics exhibited by each coastal area. Hence, an algorithm formulated for a specific domain may lack generalizability to other domains. This study presents the development of an algorithm utilizing Sentinel-2 imagery for the estimation of chlorophyll-a concentrations in the coastal region of Semarang City, with a specific focus on the BKT estuary. The BKT river holds significant prominence within Semarang, a highly populous city in Indonesia characterized by intense human engagement. In order to advance scientific understanding and monitoring capabilities, it is imperative to undertake the development of chlorophyll-a algorithms for additional regions within Indonesia in the future. The geographical coordinates of the study site are depicted in Figure 1.

The current research is centered around evaluating the reaction of each spectral band to the measured concentration of chlorophyll-a. The objective is to create a novel algorithm for accurately quantifying chlorophyll-a levels in turbid and shallow coastal waters, specifically in the vicinity of the BKT estuary. This will be achieved by utilizing data from the Sentinel-2A MSI. The second objective pertains to the utilization of algorithms for the purpose of observing spatial-temporal variations.

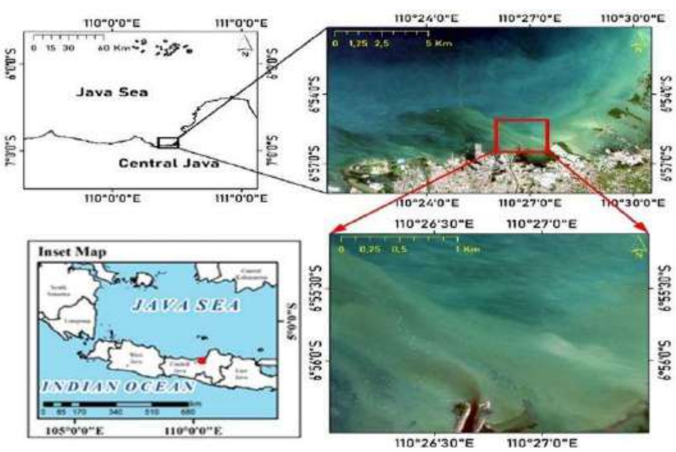


Figure 1. The research site is located in the vicinity of the BKT river estuary in Semarang, Indonesia.

Data and Methods

Satellite data : The satellite data employed in this study consisted of the Sentinel-2 level 2A image, which encompassed the coastal region of Semarang City. The Sentinel-2 image at level 2A has undergone geometric and radiometric corrections, resulting in reflectance values derived from the Bottom of the Atmosphere (BOA). This image is equipped with twelve multi-spectral bands, spanning a range of wavelengths from 443 nm to 22,202 nm (Gatti & Bertolini, 2015). In the present investigation, a novel approach was devised to assess chlorophyll-a concentration. This approach integrates elements from the methodology proposed by Moutzouris-Sidiris and Topouzelis (2021), which employs the blue to green band ratio, as well as the green and red band ratio introduced by Ha et al. (2017). Additionally, insights from Chen et al. (2017) regarding the near-infrared (NIR) band and Aranha et al. (2021) concerning the visible band were incorporated into the combined method. This research investigates the application of visible (blue, green, red) NIR bands, with a spatial resolution of 10 meters, for the analysis of chlorophyll-a levels in the BKT River. An analysis was conducted to establish a chlorophyll-a algorithm for the region adjacent to the BKT River by comparing the visible and NIR bands with in-situ chlorophyll-a measurements. Therefore, in order to derive the seasonal fluctuations of chlorophyll-a, our algorithm was implemented on Sentinel-2 images that accurately represent each month of the year 2020.

Meteorological data

The meteorological data regarding daily rainfall and wind speed were collected from the Achmad Yani International Airport's Meteorological Station. The data collected on a daily basis were subsequently aggregated to form monthly averages. The data can be accessed through the official website of the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) at https://dataonline.bmkg.go.id/home.

Sample collection and analysis

A total of 100 field samples were collected. The sampling procedure took place on August 21, 2021, between the hours of 08:00 and 11:00 a.m., aligning with the specific date and time of the Sentinel-2 data acquisition over Semarang City (refer to Figure 3). It is worth mentioning that the sampling area under consideration exhibited characteristics of eastern monsoon conditions. Analysis of meteorological data revealed that the recorded wind speed ranged from 2.19 to 2.40 meters per second.

Water samples of 500 mL were collected from the near surface, with a depth range of ±30 cm. The spectrometric method was employed to conduct the chlorophyll analysis, utilizing three wavelengths (trichromatic). The suspension was extracted using a solvent consisting of 90% acetone. The filtration process employed filter paper made from cellulose nitrate with a pore size of 0.45 um, specifically sourced from Millipore Merck. The chlorophyll-a concentration in water samples was determined using the calculation formula prescribed by the American Public Health Association (APHA) method, as described in the studies conducted by Maslukah et al. (2019) and Maslukah et al. (2021).

In order to refine the chlorophyll-a algorithm, a dataset was generated comprising of match-up data. This dataset included in-situ chlorophyll-a measurements as the ground truth, along with corresponding satellite observations obtained from collocated locations. In order to ensure the representation of the sampling distribution, the match-up positions for algorithm tuning and validation were evenly distributed across the study area. Out of the total 100 match-ups, we allocated 50 for the purpose of tuning and the remaining 50 for validation. In both subsets, the exclusion of outlier data was implemented. The figure provided, Figure 3, displays the positions of the stations used for tuning and validation purposes. The initial analysis involved evaluating the correlation (r) between the overall concentration data and the visible-NIR band's Rrs. Subsequently, a total of 42 match-ups were employed to develop the chlorophyll-a algorithm for Sentinel-2A, while an additional 43 match-ups were utilized for the purpose of validation. Table 1 displays the statistical data pertaining to in-situ chlorophyll-a for the purposes of algorithm tuning and validation.

Table 1. Statistics on in situ Chlorophyll-a used for algorithm tuning and validation.

Data	n	average (µg/L)	Min (µg/L)	Max (µg/L)	St . Dev (µg/L)
Tunning	44	9.49	2.15	17.27	3.47
Validation	43	8.75	3.5	14.52	2.90

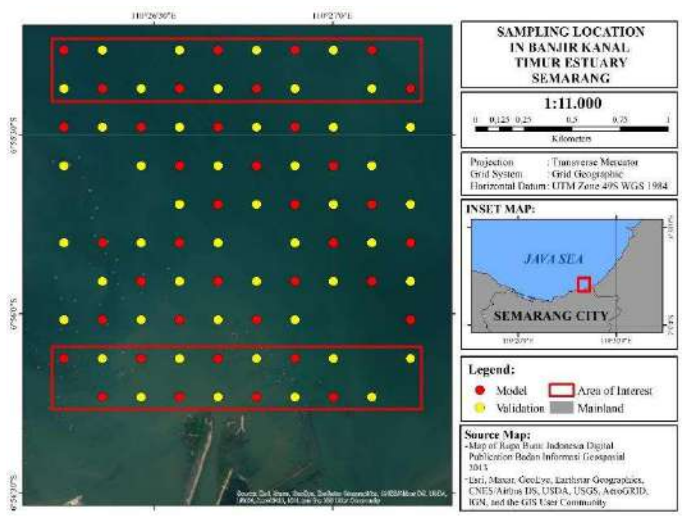


Figure 3. Location of sampling for match-up model (●) dan validation (●). The red rectangle (□) denotes (inshore and offshore) the regions in closest proximity to and furthest distance from the river's mouth.

The algorithm assessment

The evaluation of the algorithms derived from this study encompassed three statistical techniques, namely the determination coefficient (R2) as reported by Shaik et al. (2021) and Moutzouris-Sidiris and Topouzelis et al. (2021), the root mean square error (RMSE), the mean absolute percentage error (MAPE), and the bias, as discussed by Watabene et al. (2017) and Ciancia et al. (2020). The mathematical equations employed for the evaluation of algorithms are derived from formulas 1, 2, 3, and 4, correspondingly.

$$R^2 = \left[\frac{N\ x\ \sum_{i=1}^{N}(Chla_i,meas)\ x\ Chla_{i,retr}) - \sum_{i=1}^{N} Chla_{i,meas}\ x\ \sum_{i=1}^{N} Chla_{i,retr}}{\sqrt{\left[N\ x \sum_{i=1}^{N}(Chla_i,meas)^2 - (\sum_{i=1}^{N}(Chla_i,meas)^2\right]\left[N\ x\ \sum_{i=1}^{N}(Chla_{i,retr})^2 - (\sum_{i=1}^{N} Chla_{i,retr})^2\right]}}\right]^2 \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(Chla_i,meas - Chla_{i,retr})^2}{N}} \quad (2)$$

$$\text{MARE} = \frac{100\%}{N}\ x\ \sum_{i=1}^{N}\frac{|(Chla_i,meas - Chla_{i,retr})|}{Chla_{i,meas}} \quad (3)$$

$$\text{BIAS} = \frac{1}{N}\ x\ \sum_{i=1}^{N}(Chla_{i,retr} - Chla_{i,measure}) \quad (4)$$

where $Chla_i,meas$ and $Chla_i,retr$ refer to the measured (in-situ) and retrieved (estimated) Chl-a respectively; and N is the total number of samples.

In order to establish the chlorophyll-a algorithm, the initial step involves assessing the correlation between the visible - near-infrared (blue/B2, green/B3, red/B4, and NIR/B8) spectral bands and Chl-a observations. The resulting coefficients obtained are 0.675, 0.661, 0.697, and 0.698, respectively (as shown in Table 2). Table 2 demonstrates that all Rrs exhibit significant correlations with the observed chlorophyll-a levels. To develop the new algorithm, we utilized Rrs Nir, red, green, and blue wavelengths to estimate the concentration of chlorophyll-a in the BKB offshore region. According to Aranha et al. (2022), bodies of water characterized by a prevalence of phytoplankton exhibit two distinct peaks of absorption in the electromagnetic spectrum. Specifically, one peak is observed in the blue region at approximately 440 nm, while the other peak is located in the red region at around 670 nm. The green band, characterized by a wavelength range of 560 nm, exhibits a high reflectance of chlorophyll owing to its low absorption coefficient. Furthermore, the existence of phytoplankton is distinguished by its maximum reflection at 700 nm, specifically within the near-infrared spectrum (Matthews et al., 2012). Given the intricate nature of the region under investigation, the study incorporated an examination of the utilization of four bands on Sentinel-2 satellites, each possessing an equivalent spatial resolution of 10 meters.

Table 2. The correlation of Chl-a in situ with band of B2, B3, B4, and B8

		B2	B3	B4	B8
Chl-a	Pearson Correlation	.698**	.697**	.661**	.675**
	Sig. (2-tailed)	.000	.000	.000	.000
	N	84	84	84	84

A model was constructed employing multiple regression analysis to derive estimations of chlorophyll-a levels in the BKB River. The calculated coefficient of determination (R^2) is 0.45, The statistical significance of this relationship is supported by a p-value of less than 0.05. The equation representing this relationship is consistent with formula 5.

$$\textbf{Chl-a} = 10^{(2.743-0.725*(log(B2*c))-0.625*(log(B3*c))+1.623*(log(B4*c))+0.809*(log(B8*c))} \quad (5)$$

Where c : 0.036/B8; B2; B3; B4; B8 (reflektan band biru, hijau, merah dan dekat merah).

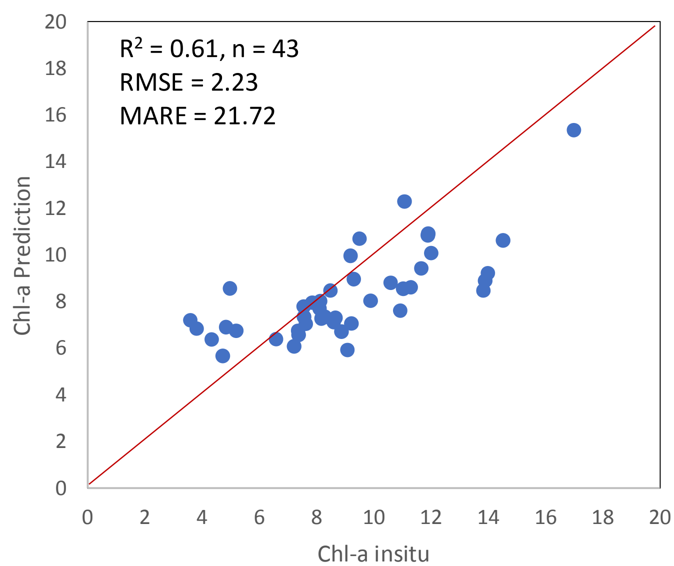


Figure 4. Validation of chlorophyll-a from eq. (5) with observed chlorophyll-a (observation).

Hence, the equation (5) can be employed for the estimation of chlorophyll-a levels off BKT River. Figures 5 and 6 depict the spatial and temporal distribution, respectively.

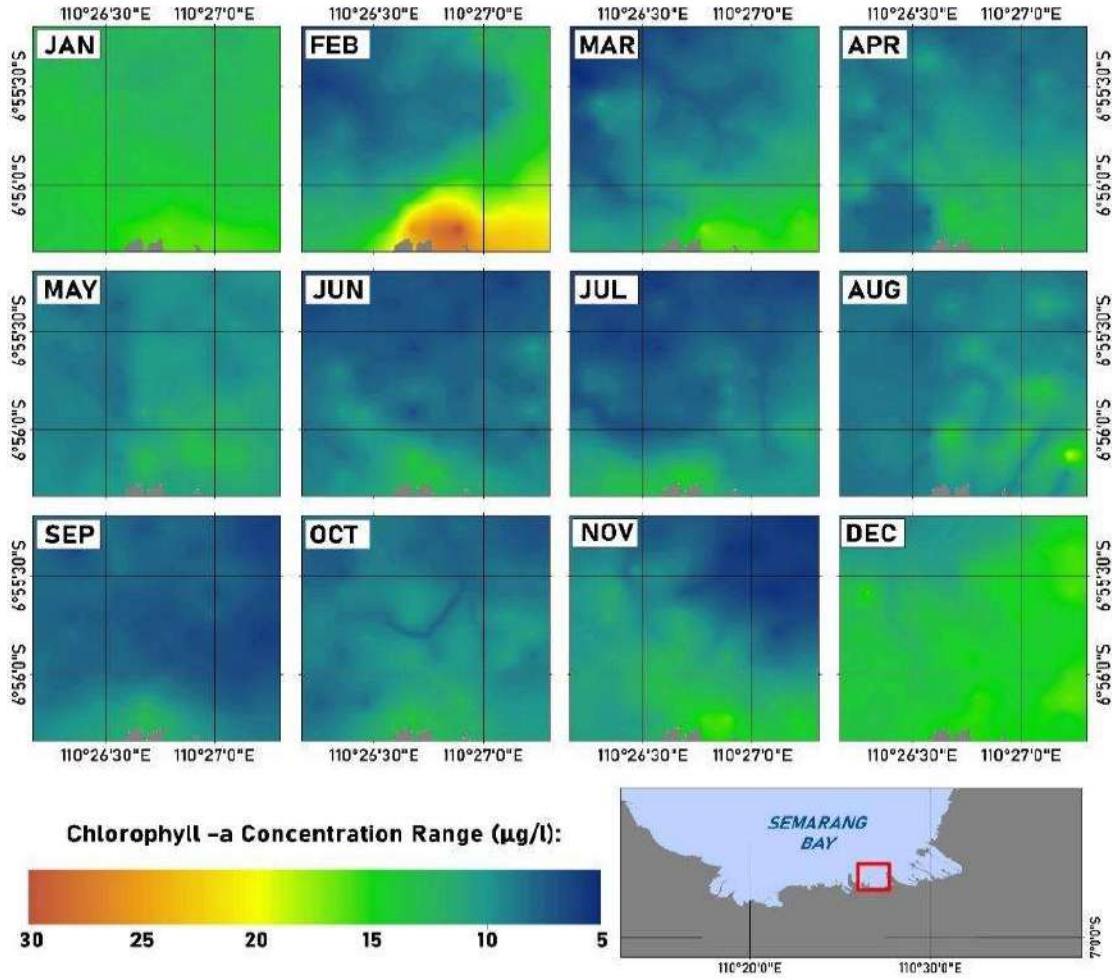
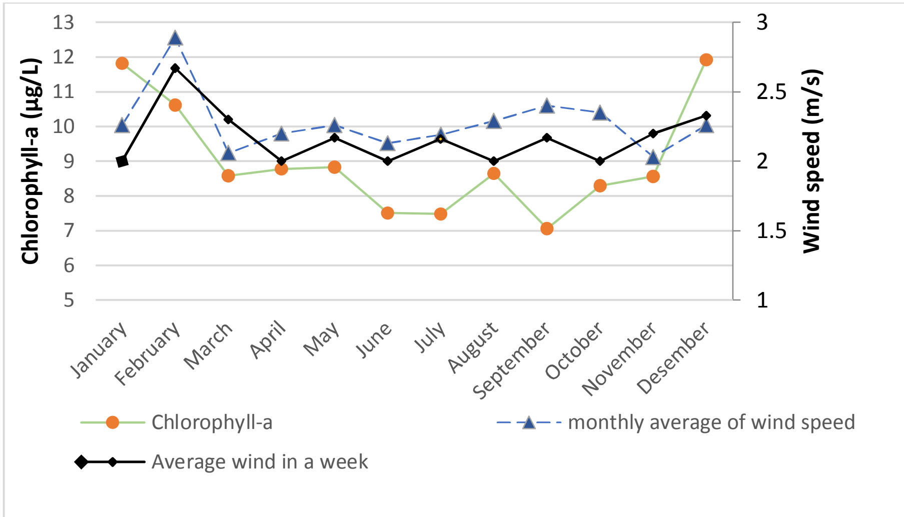


Figure 5. Distribution of Chl-a (a) 3 January 2021 (b) 27 February 2021 (c) 14 March (d) 23 April 2021 (e) 13 May 2021 (f). June 22, 2021 (g). 27 July 2021 (h) 21 August 2021 (I) 10 September 2021 (j) 10 October 2021 (k). November 4, 2021 (l). December 14, 2021 estimated from Sentinel-2 imagery using eq. (5). The BKT Semarang estuary, depicted with a red box



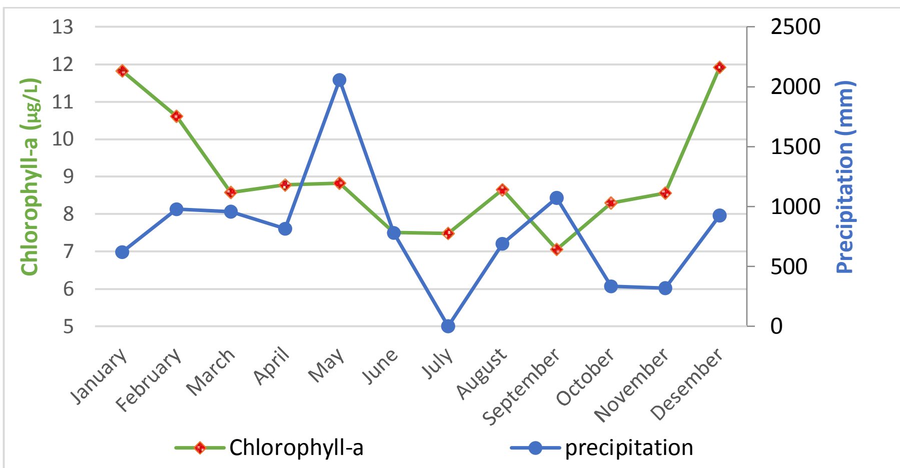


Figure 6. Temporal variation of Chl-a with wind speed (a) and precipitation (b) based on Sentinel imagery on 3 January 2021, 27 February 2021, 14 March 2021, 23 April 2021, 13 May 2021, 22 June 2021, 27 July 2021, 21 August 202, 10 September 2021, 10 October 2021, 4 November 2021, 14 December 2021.

The highest concentration was observed in December, reaching a value of 11.92 µg/L, while the lowest concentration was recorded in September, with Chl-a concentration of 7.06 µg/L. The observed pattern in this study diverges from the findings of Wirasatriya et al. (2019), who utilized MODIS imagery to examine the area adjacent to the northern coast of Java. Wirasatriya et al. (2019) reported that the pattern reached its maximum in June and January. It is important to note that the previous study analyzed data over a longer time span of 10 years, encompassed a significantly larger regional area, and employed a lower image resolution of 4 km. Shabrina et al. (2018) also demonstrated distinct variations in seasonal dynamics during the summer period (March-August 2015 and 2016), with the highest concentration of Chl-a observed in the month of June. The finding suggests that the temporal patterns of each region exhibit distinct variations.

High TSS concentrations in estuaries cause disturbances in the photosynthesis process, which results in low phytoplankton biomass. The results of Wirasatriya et al. (2022) explained that the river is the main contributor of TSS and wind affects its distribution pattern, which will influence the temporal dynamics of chlorophyll-a. To investigate this, in this study, we divided two areas, near and off the river, which are given a red box in Figure 1, and the time series are shown in Fig. 7 & Fig. 8 and the correlation results are shown in Table 4.

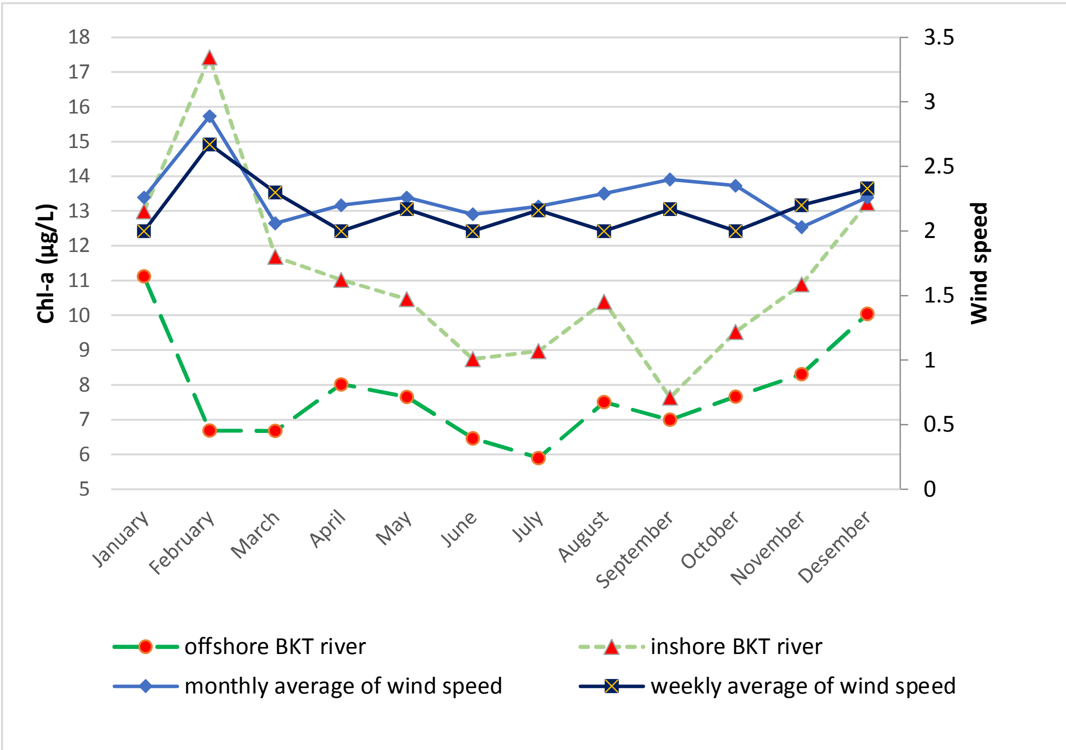


Figure 7. Time series Chl-a in offshore dan inshore BKT river and wind speed

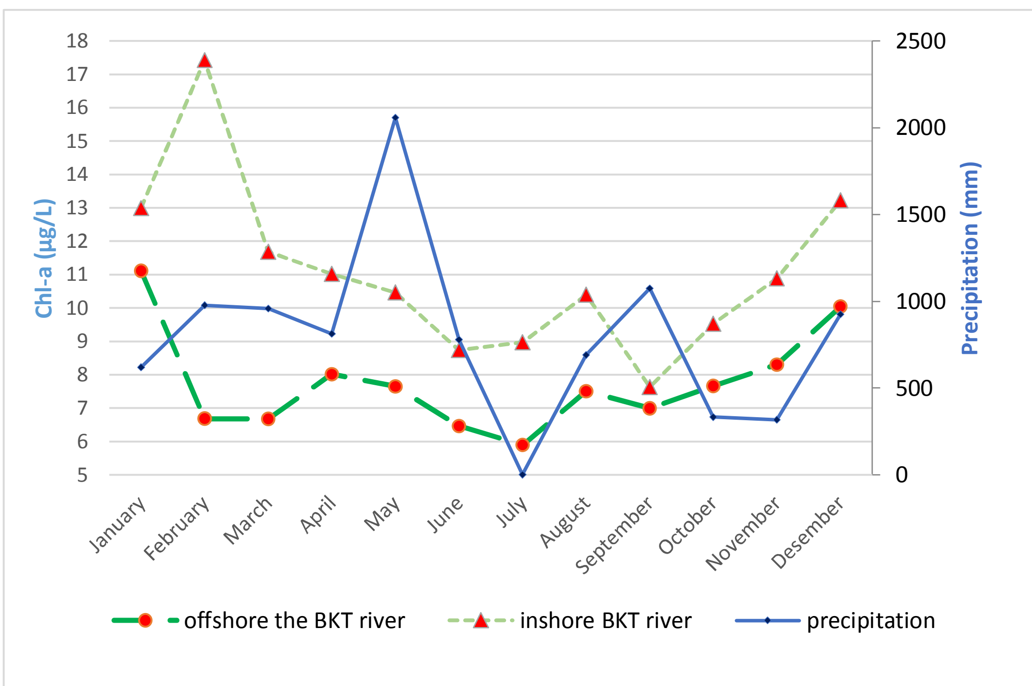


Figure 8. Time series of Chl-a in offshore dan inshore BKT river and precipitation

Figure 7 illustrates that, on the whole, the patterns exhibit similarity, except for the month of February. The region adjacent to the estuary exhibits the highest amount in February, whereas the vicinity near the estuary demonstrates the lowest value. This variation is associated with the recorded monthly mean wind. The region adjacent to the estuary is characterized by a moderate degree of sediment input. The presence of sunlight reaching the depths of the water facilitates the flourishing of phytoplankton in these regions, as opposed to the adjacent coastal waters.

Table 4. The Pearson correlations of chlorophyll-a with climatological data

	Chl-a_near	Chl-a_far	Average_Wind_montly	Average_wind_weekly	Aver_Rain_weekly	Aver_Rain_montly	average_temp_air	Aver_SS
Chl-a	.786**	.797**	.298	.344	.022	.128	-.682*	-.803**
Chl-a inshore	1	.319	-.113	-.191	-.016	.031	-.325	-.646*
Chl-a offshore	.319	1	.590*	.715**	-.128	.141	-.833**	-.753**

Seasonal dynamics of Chlorophyll-a

The island of Java is part of the maritime continent, so its climate is influenced by the Asian (Australian) monsoon which brings humid (dry) air, and causes the rainy season (Alifdini et al., 2021). The rainy season occurs from December to February, while the dry season is from June to August. From March to May and from September to November are known as the first and second transition seasons, respectively. Figure 8 depicts the temporal fluctuations of chlorophyll-a levels in the BKT River. The images depicting the rainy season, first transition, dry season, and second transition are observed during the months of January and February, April and May, July and August, and October and November, respectively.

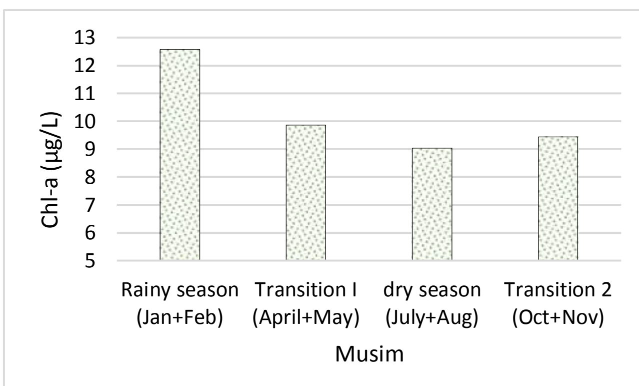


Figure 8. Seasonal variation of chlorophyll in 2021 during the rainy season (January and February), first transition (April and May), dry season (July and August), and second transition (October and November).

According to the data presented in Figure 8, it is evident that the peak concentration of chlorophyll-a is observed during the rainy season. During the rainy season, a notable elevation in the concentration of chlorophyll-a, reaching up to 12 µg/L (approximately mg/m^3), was observed in the vicinity of the BKT river. However, this concentration then decreased in the subsequent season. In the second transition, the presence of chlorophyll-a originating from the BKT Semarang River has resulted in a rise of 0.42 µg/L. According to the findings of Maslukah et al. (2021), the chlorophyll-a concentrations in Semarang waters were observed to be higher during the rainy season (February) compared to the dry season (July), as indicated by the insitu (field measurement) data. Therefore, in order to examine potential factors contributing to the temporal fluctuations of chlorophyll-a, we conducted a comparative analysis between chlorophyll-a levels and various meteorological variables including precipitation, wind speed, average air temperature, and duration of solar irradiation. These data were obtained from a neighboring meteorological station located at Ahmad Yani airport in Semarang. The variation in chlorophyll-a levels is influenced by terrestrial factors, particularly precipitation. Increased and prolonged precipitation can lead to higher runoff discharge in rivers, resulting in the transportation of additional nutrients from terrestrial areas. This influx of nutrients promotes the growth of phytoplankton (Maslukah et al., 2021). According to Hutasuhut et al. (2021), the velocity of wind can induce water currents that have the potential to initiate resuspension processes, leading to the liberation of nutrients from the sedimentary layer. Additional climatological factors, such as air temperature and duration of irradiation, play a role in influencing the variability of chlorophyll-a in the BKT River. The findings pertaining to the relationships among climatological parameters are depicted in Figure 6 and summarized in Table 4.

The data presented in Table 4 demonstrates that air temperature and solar radiation have a negative correlation with chlorophyll-a concentration. The findings of this study diverge from those presented by Aranha et al. (2021) in a tropical reservoir, wherein they observed a decline in chlorophyll-a concentrations during periods of minimal solar radiation. According to a study conducted by Shabrina et al. (2018), the concentration of chlorophyll-a in the northern waters of Central Java during the rainy season is influenced by the levels of sunlight and temperature. Nevertheless, the degree of correlation was not evaluated in this study.

It was observed that wind had a positive impact, although the correlation was not statistically significant ($p>0.05$). Wirasatriya et al. (2022) discovered a noteworthy pattern within the waters of South Sulawesi. In the northern region, it was observed that the wind exerted a significant impact on the rise of chlorophyll-a concentrations. However, in the southern region, a distinct pattern emerged, wherein elevated levels of Chl-a were observed under conditions characterized by weakened wind speeds. This is related to sediment resuspension and influences the proliferation of phytoplankton. However, this analysis contains no field measurement data, which is a limitation. The responses of the optical properties captured by the imagery are substantially related to the water conditions, which may impact the analysis of the chlorophyll data captured by the imagery. In turbid regions, Maslukah et al. (2022) discovered that chlorophyll-a concentrations in coastal waters derived from imagery data were underestimated.

Discussion

Prior research has indicated that the waters adjacent to the Banjir Kanal Timut (BKT) exhibit elevated levels of chlorophyll-a concentrations (Maslukah et al., 2019; Maslukah et al., 2021), indicating a state of eutrophication in terms of trophic status. Moreover, the escalation of industrial activities and population density has led to a consequential impact on the quality of estuarine waters. This is primarily due to the substantial influx of nutrients from land, resulting in an adverse influence on the growth and development of phytoplankton. The estimation of phytoplankton biomass can be derived by assessing the concentration of chlorophyll-a, a predominant green pigment within phytoplankton, as indicated by Munandar et al. (2023). The presence of a significant amount of chlorophyll-a serves as an indicator that can be utilized to assess alterations in water quality (Ciancia et al., 2020; Shaik et al., 2021; Saberioon et al., 2020). Hence, the assessment of environmental degradation can be conducted by observing alterations in the concentration of chlorophyll-a. Long-term field measurements are characterized by high costs, significant time requirements, and substantial financial investments (Ogashawara et al., 2021; Aranha et al., 2022). The application of remote sensing presents a viable approach for addressing this issue.

The BKT river estuary exhibits a relatively constrained spatial extent in comparison to the expansive waters of the open ocean. Utilizing high-resolution satellites is a more advantageous approach for monitoring the variability of chlorophyll-a. Hence, the focus of this research lies in the utilization of the Sentinel-2 MSI, renowned for its frequent revisits and possession of a red edge spectral band at a wavelength of 705 nm. According to Warren et al (2019), this particular sensor demonstrates suitability for the purpose of monitoring water quality in both coastal and inland waters. The reflectance values utilized in this study were obtained from the BOA, which had undergone calibration using the Sen2Core. The algorithm employed in our study builds upon prior research by incorporating four bands with a resolution of 10 meters (as denoted by formula 5). Each of these bands is multiplied by the ratio of the Near-Infrared (Nir) band (Rrs 705). Warrena et al. (2019) conducted a study in which they examined three separate spectral ratios: Rrs444/Rrs560, Rrs490/Rrs560, and Rrs704/Rrs665. However, their findings did not yield satisfactory results for both marine and inland areas.

The algorithm, denoted as formula 5, was subsequently verified using the observed chlorophyll-a levels, as depicted in Figure 4. The bias observed in the study was determined to be -0.82 mg/m3, indicating a slight underestimation of the estimated chlorophyll-a compared to the observed chlorophyll-a levels. The study conducted by Moutzouris-Sidiris and Topouzelis (2021) investigated the application of different algorithms in case 1 and 2 waters within the Mediterranean Sea. The findings revealed the presence of diverse bias values, both positive and negative. In a study conducted by Maslukah et al. (2022), Sentinel-3 imagery was utilized to assess the chlorophyll-a concentration in the western coastal waters of Semarang Bay. The researchers found that the chlorophyll-a concentration derived from the imagery exhibited a significant disparity compared to the observation data. Specifically, the imagery displayed a bias value of 3.43, indicating a consistent overestimation of chlorophyll-a levels. The observed range of chlorophyll-a concentration in the imagery spanned from 0.70 to 9.07 mg/m3. Nevertheless, the RMSE pertaining to the estimated chlorophyll-a concentration is recorded as 2.23 mg/m3, while the mean absolute relative error stands at 21.72%. This finding suggests that the algorithm used to estimate the chlorophyll-a levels from the BKT River is still yielding results that are relatively accurate. The algorithm under consideration exhibits superior performance compared to the algorithm proposed by Aranha et al. (2021), as the latter demonstrated a relative mean error of 28%. In contrast to the findings of Maslukah et al. (2022), which reported a significantly lower percentage of relative error at 1.19%. The study conducted by Maslukah et al. (2022) exhibits several limitations. Firstly, the sample size is relatively small, consisting of only nine participants. Consequently, this limited sample may introduce potential biases in the findings. Additionally, the resulting bias in the study, measured at 3.5 mg/m^3, is relatively high.

The algorithm obtained is subsequently utilized to estimate the temporal and spatial variations. The present study demonstrates that temporal fluctuations exhibit a discernible seasonal pattern, wherein alterations in precipitation levels lead to subsequent modifications in river discharge. The westerly monsoon prevailing in Indonesia induces elevated wind velocities, thereby influencing the process of sediment resuspension. River discharge and resuspension are two mechanisms that have the potential to impact nutrient inputs into the water column, consequently influencing the growth of phytoplankton. The biomass of phytoplankton can be assessed by measuring chlorophyll-a concentrations.

Trophic status in front off The BKT river

The determination of water's trophic status can be achieved by assessing the concentration of chlorophyll-a. According to Hakanson and Bryann (2008), oligotrophy is characterized by chlorophyll-a concentrations below 2 mg/m^3 in aquatic environments. Mesotrophic conditions are indicated by chlorophyll-a concentrations ranging from 2 to 6 mg/m3, while eutrophic conditions are associated with concentrations between 6 and 20 mg/m3. Hypertrophic conditions, on the other hand, are defined by chlorophyll-a concentrations exceeding 20 mg/m3. According to the classification utilized, the coastal waters of BKT fall within the eutrophic classification. According to the findings of Maslukah et al. (2021), the trophic conditions of the Semarang coastal waters, which encompass the BKB and BKT estuaries, were determined based on field observations of chlorophyll-a concentration data and chlorophyll analysis from images. Based on empirical data, coastal waters can be classified as eutrophic or mesotrophic based on the levels of chlorophyll-a derived from satellite imagery. However, the findings of this study indicate that both samples exhibited eutrophic conditions. The issue at hand is closely tied to the limited spatial resolution of MODIS, which must not be conflated with observational data obtained from a localized region. According to the findings of Maslukah et al. (2019), the study elucidated that the concentration of chlorophyll-a in the vicinity of the BKT estuary exhibits significant fluctuations within a range of approximately ± 500m, with variations in concentration ranging from 1 to 10 mg/m3. The MODIS image data is acquired by sampling each pixel at a spatial resolution of 4 x 4 km.

Conclusion

In this study, the seasonal spatial and temporal distribution of near-surface chl-a concentrations in Semarang coastal waters in 2020 is described using visible and NIR band reflectance data from Sentinel 2 imagery. This study includes the use of a new empirical model based on Sentinel 2 observed in 2020 and taken from Semarang coastal waters specifically (BKT river front). In addition, the relationship between chl-a concentration and climatological factors such as rainfall, length of sunshine wind and tidal conditions was studied. Thus, we tuned an algorithm based on the blue, green, red, and Nir bands and obtained the following formula:

$$\textbf{Chl-a} = 10^{(2.743-0.725(logB2*c)-0.625(logB3*c)+1.623(logB3)+0.809(logB8*c)}$$

where c=0.04/B8. The algorithm's validation results indicated that the Root Mean Square Error, Mean Absolute Percentage Error, and bias were 2.44 µg/L, 23.92%, and -0.83 µg/L, respectively. The study revealed that there was a greater degree of spatial variation in chlorophyll-a concentrations towards the mouth of the river compared to the offshore region. This study reveals that the temporal fluctuations in the area of the outer estuary are primarily driven by variations in wind speed rather than precipitation-related factors. The other climatological factors that exerted a significant influence were the air temperature and the duration of solar radiation (SS), exhibiting a negative correlation.

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Conflict of Interest: The authors declare no conflict of interest

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Lilik Maslukah

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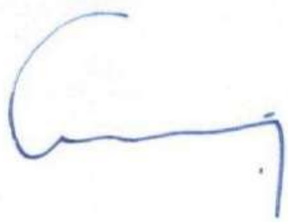

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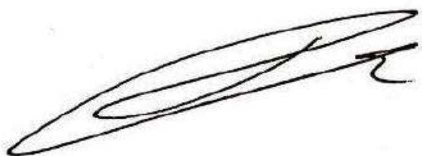

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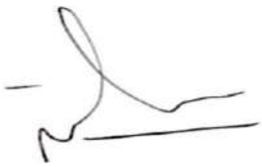

Rikha Widiaratih

Decision on submission to Regional Studies in Marine Science

From: Regional Studies in Marine Science (em@editorialmanager.com)

To: lilik_masluka@yahoo.com

Date: Sunday, January 21, 2024 at 09:28 PM GMT+7

Manuscript Number: **RSMA-D-23-01718**

The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel 2A-MSI in coastal waters of Semarang, Indonesia

Dear Dr Maslukah,

Thank you for submitting your manuscript to Regional Studies in Marine Science.

I have completed my evaluation of your manuscript. The reviewers recommend reconsideration of your manuscript following major revision and modification. I invite you to resubmit your manuscript after addressing the comments below. Please resubmit your revised manuscript by **Feb 20 2024 11:59:59:000PM**.

When revising your manuscript, please consider all issues mentioned in the reviewers' comments carefully: please outline every change made in response to their comments and provide suitable rebuttals for any comments not addressed. Please note that your revised submission may need to be re-reviewed.

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Regional Studies in Marine Science values your contribution and I look forward to receiving your revised manuscript.

Kind regards,

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Associate Editor

Regional Studies in Marine Science

Editor and Reviewer comments:

Reviewer #1: 1) General comments
This paper addresses the issue of high spatial resolution for remotely estimating Chla in BKT. This manuscript used the empirical algorithm to accurately monitor Chla with MAPE of 23.92%. Generally, the subject of the manuscript is interesting, and the manuscript approach is acceptable. I think the manuscript needs to be improved significantly before publication.
2) Specific comments
1. There is a massive problem with details throughout the manuscript, please be careful when writing!
Highlight
2. There's no need to list the formulas, just the empirical model.
3.Root Mean Square Error and MAPE? Just say it produces robustness.
4.Why are the words the same as in the summary? Is there an attitude that is wrong?

Abstract
5. What is the Abstrak?
6.Measurements of chlorophyll a are not necessary in the abstract.
Introduction:
7.Why not use the abbreviation Chl-a?
8.There's no need to say Sentinel-2A, just Sentinel-2, unless you've done a Sentinel-2A to Sentinel-2B comparison.
9.Empirical algorithms don't need to be considered as new unless you show accuracy with other algorithms
10. It's nice to be able to describe the BKT study, but there's no need to overstate this study. If the authors really wanted to describe this, why didn't they consider doing a comparison of different algorithms for different satellites of BKT?
11. For the entire article, use MSI instead of Sentinel-2A
12.Table 2, why is there no scatterplot for modelling? For modelling this is the most important!

Regional Studies in Marine Science

The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel-2 MSI in coastal waters of Semarang, Indonesia

--Manuscript Draft--

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	Heru Nur Krisna, BSc
Abstract:	In aquatic ecology, Chlorophyll-a (Chl-a) plays a pivotal role in biogeochemical cycles, as well as a key indicator for the trophic state in the environment. Taking advantage of the high spatial resolution of The Sentinel-2 images, we investigate the spatial-temporal distribution of Chl-a in the coastal waters of Semarang, Indonesia. With a spatial resolution of 10m, blue, green, red, and near-infrared bands of Sentinel-2 images were used to monitor Chl-a in the waters off the Banjir Kanal Timur (BKT) River, one of the estuaries in the north Semarang. The generation of the Chl-a algorithm was derived from the linear regression model between in-situ data and reflectance from BoA Sentinel-2. A total of 43 water samples were collected to build the algorithm and 43 of the water samples were used for validation. Considering the passing time of Sentinel-2 at the equator, the collection of water samples was conducted on 21 August 2021 at 9.00-11.00 local time. The results show that the performance of the algorithm generated in this study has high accuracy as denoted by the RMSE, bias, MAPE, and R2 values of 2.47 mg/m3, -0.63, 23.52%, and 0.44, respectively. For the seasonal variation, the highest (lowest) concentration of Chl-a is observed in December (September), with values reaching 11.92 μg/L (7.06 μg/L). The seasonal fluctuation of Chl-a depends on air temperature and sunshine duration. High (low) air temperature and long (short) duration of solar exposure result in increased (decreased) Chl-a concentrations in the BKT River's waters. Conversely, the elevated wind velocity only impacts the rise of Chl-a in the region far from the river estuary, which is associated with the mixing process. BKT waters is categorized as eutrophic conditions, with a concentration exceeding 6 μg/L. Therefore, it is important to be concerned about the possibility of algae blooming.
Suggested Reviewers:	Ulung Jantama Wisha, PhD candidate of PhD, University of the Ryukyus Faculty of Science Graduate School of Engineering and Science ulungjantama@gmail.com His expertise is water quality
	Riza Yuliratno Setiawan, Dr Lecturer, Gadjah Mada University Faculty of Agriculture riza.y.setiawan@ugm.ac.id His Experties is Remote sensing
	Widodo Setyo Pranowo, Prof National Research and Innovation Agency Republic of Indonesia widodo.pranowo@gmail.com His Experties is dynamical of coastal oceanography

Response to Reviewers:	General Comment: 1.General comment : This paper addresses the issue of high spatial resolution for remotely estimating Chla in BKT. This manuscript used the empirical algorithm to accurately monitor Chla with MAPE of 23.92%. Generally, the subject of the manuscript is interesting, and the manuscript approach is acceptable. I think the manuscript needs to be improved significantly before publication. Response: Thank you for considering our manuscript with the title "The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel-2 MSI in the coastal waters of Semarang, Indonesia" Thank you for the suggestions to improve the article and we have revised it. 2.Specific comments 1.There is a massive problem with details throughout the manuscript, please be careful when writing! Highlight Response: Thank you for your comment. we have rechecked our manuscript carefully. We eliminated a few paragraphs (the 3th, 6th, and 7th paragraph) in the Introduction of earlier manuscripts by considering that we didn't evaluate with an earlier algorithm in this research. 2.There's no need to list the formulas, just the empirical model. Response: We change the term of the algorithm to become an empirical model. 3.Root Mean Square Error and MAPE? Just say it produces robustness. Response: In this research, we use RMSE and MAPE as accuracy tools from the empirical model produced. 4.Why are the words the same as in the summary? Is there an attitude that is wrong? Abstract Response: The abstract content has been revised. 5.What is the Abstrak? Response: The term abstrak already changed with the abstract. 6.Measurements of chlorophyll a are not necessary in the abstract. Response: The sentences about using the spectrometer have been deleted in the abstract. 7.Why not use the abbreviation Chl-a? Response: The term Chorophyll-a has been changed with Chl-a in the entire manuscript. 8.There's no need to say Sentinel-2A, just Sentinel-2, unless you've done a Sentinel-2A to Sentinel-2B comparison. Response: We have changed the term of Sentinel-2A to Sentinel-2 MSI. 9.Empirical algorithms don't need to be considered as new unless you show accuracy with other algorithms Response: In the introduction, the need for a new empirical algorithm has been removed, since we didn't do the comparison. This answer is also connected to point 1. 10.It's nice to be able to describe the BKT study, but there's no need to overstate this study. If the authors really wanted to describe this, why didn't they consider doing a comparison of different algorithms for different satellites of BKT? Response: We eliminated a few paragraphs (the 3th, 6th, and 7th paragraph) in the Introduction of earlier manuscripts by considering that we didn't evaluate with an earlier algorithm in this research. This item has been explained with point 9. 11.For the entire article, use MSI instead of Sentinel-2A Response: We have changed the term of Sentinel-2A to Sentinel-2 MSI. 12.Table 2, why is there no scatterplot for modelling? For modelling this is the most important! Response: Table 2 has been revised to a scatter plot and has been shown in Figure 3.

The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel 2A-MSI in coastal waters of Semarang, Indonesia

Lilik Maslukah*, Anindya Wirasatriya, Yusuf Jati, Dwi Haryo Ismunarti, Rikha Widiaratih

Highlights

1. Estimating chlorophyll from high spatial resolution (10m) Sentinel 2A imagery
2. The chlorophyll-a algorithm using Sentinel-2 images for the coastal water off Banjir Kanal Timur (BKT) River, Semarang, Indonesia is Chl-a (µg/L) = $10^{((2.743-0.725*(\log(B2*c))-0.625*(\log(B3*c))+1.623*(\log(B4*c))+0.809*(\log(B8*c)))}$ with the Root Mean Square Error, bias, MAPE and R^2 of 2.47 mg/m3, -0.63, 23.52%, and 0.44 respectively.
3. The Maximum (minimum) Chl-a occurs in December (September) which can reach 11.92 ug/L (7.06 ug/L)
4. According to the criteria of Chl-a concentration in the sea, BKT waters are eutrophic, so it is necessary to be concerned about the possibility of algae blooming.

The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel-2 MSI in the coastal waters of Semarang, Indonesia

Lilik Maslukah[1*], Anindya Wirasatriya[1], Yusuf Jati Wijaya[1], Dwi Haryo Ismunarti[1], Rikha Widiaratih[1], Heru Nur Krisna[2]

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Abstract

In aquatic ecology, Chlorophyll-a (Chl-a) plays a pivotal role in biogeochemical cycles, as well as a key indicator for the trophic state in the environment. Taking advantage of the high spatial resolution of The Sentinel-2 images, we investigate the spatial-temporal distribution of Chl-a in the coastal waters of Semarang, Indonesia. With a spatial resolution of 10m, blue, green, red, and near-infrared bands of Sentinel-2 images were used to monitor Chl-a in the waters off the Banjir Kanal Timur (BKT) River, one of the estuaries in the north Semarang. The generation of the Chl-a algorithm was derived from the linear regression model between in-situ data and reflectance from BoA Sentinel-2. A total of 43 water samples were collected to build the algorithm and 43 of the water samples were used for validation. Considering the passing time of Sentinel-2 at the equator, the collection of water samples was conducted on 21 August 2021 at 9.00-11.00 local time. The results show that the performance of the algorithm generated in this study has high accuracy as denoted by the RMSE, bias, MAPE, and R^2 values of 2.47 mg/m^3, -0.63, 23.52%, and 0.44, respectively. For the seasonal variation, the highest (lowest) concentration of Chl-a is observed in December (September), with values reaching 11.92 µg/L (7.06 µg/L). The seasonal fluctuation of Chl-a depends on air temperature and sunshine duration. High (low) air temperature and long (short) duration of solar exposure result in increased (decreased) Chl-a concentrations in the BKT River's waters. Conversely, the elevated wind velocity only impacts the rise of Chl-a in the region far from the river estuary, which is associated with the mixing process. BKT waters is categorized as eutrophic conditions, with a concentration exceeding 6 µg/L. Therefore, it is important to be concerned about the possibility of algae blooming.

Keywords: Coastal algorithm, Chlorophyll-a, visible-NIR band, Sentinel-2 MSI

Introduction

Phytoplankton holds significant ecological importance within the marine ecosystem owing to its capacity for photosynthesis, a metabolic process that facilitates the synthesis of organic compounds utilizing light energy and carbon dioxide (Rost et al., 2008; Abbas et al, 2021; Aranha et al, 2022). Phytoplankton possesses Chl-a within its cellular structure and plays a crucial role in ecological systems, serving as a fundamental component of the aquatic life cycle and serving as the primary source of energy within oceanic food webs. Chl-a is a crucial factor in assessing water quality due to its regulatory role in biological processes occurring within coastal waters (Ogashawara et al., 2021; Tran et al., 2023). The determination of Chl-a distribution within a given area is typically achieved through the implementation of field sampling techniques, which are subsequently complemented by laboratory-based analyses (Abbas et al., 2019; Maslukah et al., 2019). Nevertheless, this approach proves to be ineffective and inefficient due to its prolonged duration, elevated expenses, and restricted geographical reach (Duan et al., 2010; Ogashawara et al., 2021; Aranha et al., 2022). In order to address these concerns, a number of remote sensing techniques have been devised for the purpose of monitoring Chl-a (Ouma et al., 2020;). Remote sensing methods show promise for monitoring Chl-a levels in a given area due to their extensive coverage and ability to provide periodic observations (Maslukah et al., 2019; Ouma et al, 2020). The utilization of ocean color data within the visible and near-infrared (VNIR) wavelength bands facilitates the estimation of Chl-a levels (Ouma et al. 2020). The acquisition of Chl-a data from these satellites necessitates the utilization of an algorithm that is heavily reliant on the band and spectral resolution capabilities offered by the satellite (Ogashawara et al., 2021).

The quantification of Chl-a in reservoirs has been extensively studied, and multiple algorithms have been devised for this purpose. These algorithms encompass different approaches, such as utilizing two bands (red and near-infrared) as demonstrated by O'Reilly et al. (2019) and Tran et al. (2023), as well as employing a single band, as explored by Bramich et al. (2020). The aforementioned phenomenon is similarly observed in marine regions, where algorithms are employed to calculate the ratio between blue and green color bands (Tilstone et al., 2021; Tran et al., 2023). In the expanse of open ocean waters, the presence of colored dissolved organic matter (CDOM) and suspended particulate matter is limited to relatively small quantities (Nelson and Siegel 2002). Additionally, the concentration of Chl-a in these waters is comparatively lower than that observed in coastal regions. Estuarine regions, characterized by terrestrial influence, exhibit heightened optical complexity as a result of the absorption caused by CDOM and non-algal particles (Ouma et al, 2020; Tran et al., 2023). The optical properties of water are significantly influenced by the presence of turbid coastal waters characterized by high concentrations of CDOM and suspended non-phytoplanktonic particles (Lewis &Arrigo, 2020). The aforementioned intricate aquatic conditions diminish the efficacy of the band ratio algorithm in estimating Chl-a concentration. This is because the signal of the blue band declines below the detection threshold as a result of substantial absorption by phytoplankton (Soja-Wozniak, 2020).

The BKT river is a flood control system situated in the eastern region of Semarang city. The length of this river is approximately 14.50 kilometers. The BKT River originates from the Penggaron river and follows a course through the Pucang Gading outlet, Kedung Mundu river drainage outlet, Candi river, Bajak river, Kartini pump drainage, and the extensive rice field / Sambirejo pump drainage before ultimately discharging into the Java Sea. The direction of the river's current originating from an upstream source will exert a significant impact on the introduction of both organic and non-organic substances resulting from soil erosion and the discharge of solid and liquid waste. This, in turn, can have implications for the overall quality of the water. During the rainy season, sediment originating from terrestrial sources is introduced into the marine environment at an elevated pace, resulting in heightened turbidity within the estuarine system. According to Utama et al. (2021), the research findings elucidated that the concentration of suspended solids in the vicinity of the BKT estuary amounted to 290 mg/L during the rainy season and 60 mg/L during the dry season (Hutasuhut et al., 2022). In addition to exhibiting high turbidity, the frontal region of the river mouth is characterized as a eutrophic zone, as evidenced by the presence of Chl-a concentrations. Specifically, during the dry season, the average Chl-a concentration in this area is reported to be 12.67 µg/L, as documented by Maslukah et al. (2019). Conversely, in the wet season, the average Chl-a concentration increases to 18.06 µg/L, as reported by Maslukah et al. (2020). According to the classification proposed by Hakanson and Bryan (2008), BKT waters can be categorized as being in eutrophic conditions. Temporal and continuous monitoring is necessary to observe and analyze the dynamics that take place.

The utilization of ocean color remote sensing in turbid regions (case 2) presents significant challenges due to the unique characteristics exhibited by each coastal area. Hence, an algorithm formulated for a specific domain may lack generalizability to other domains. This study presents the development of an algorithm utilizing Sentinel-2 imagery for the estimation of Chl-a concentrations in the coastal region of Semarang City, with a specific focus on the BKT estuary. The BKT river holds significant prominence within Semarang, a highly populous city in Indonesia characterized by intense human engagement. In order to advance scientific understanding and monitoring capabilities, it is imperative to undertake the development of Chl-a algorithms for additional regions within Indonesia in the future. The geographical coordinates of the study site are depicted in Figure 1.

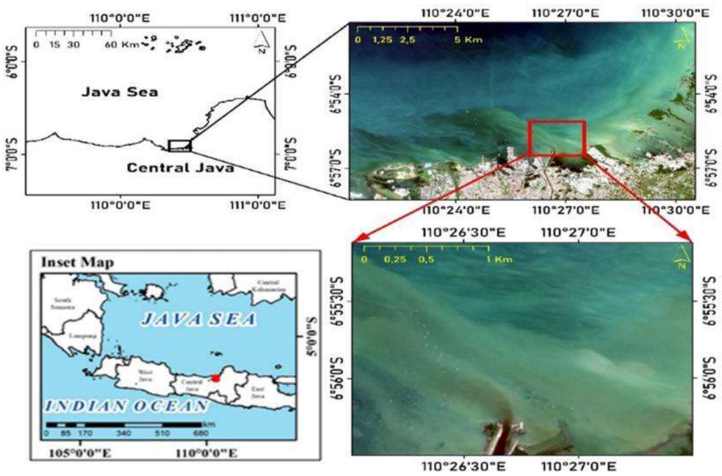

Figure 1. The research site is located in the vicinity of the BKT river estuary in Semarang, Indonesia.

The Sentinel-2 satellite possesses a superior spatial resolution of 10 meters for the visible-Nir band, in comparison to the Landsat-8 Image, which exhibits a spatial resolution of 30 meters for bands 1 to 9 (Ouma et al, 2020). The utilization of multi-spectral sensors with high radiometric resolution, such as the Sentinel-2 Multispectral Instrument (MSI), is highly advantageous for the monitoring and evaluation of Chl-a levels in intricate coastal waters (Gohin et al., 2020).

In the context of Indonesia, prior research has relied on existing algorithms. Subiyanto (2017) has estimated Chl-a using the Sentinel-2 satellite. However, this research lacks validation and relies on Landsat algorithms derived from different water bodies. This research aims to develop a new algorithm to estimate Chl-a levels on Sentinel-2 imagery. Additionally, the accuracy of this algorithm will be assessed through a validation process and the algorithm that has been acquired is subsequently utilized on other images to capture the temporal fluctuations of Chl-a in the vicinity of the BKT River. This study represents the inaugural investigation into the seasonal fluctuations of Chl-a levels in the BKT River, employing the Sentinel-2 algorithm. The current research is centered around evaluating the reaction of each spectral band to the measured concentration of Chl-a. The objective is to create a novel algorithm for accurately quantifying Chl-a levels in turbid and shallow coastal waters, specifically in the vicinity of the BKT estuary. This will be achieved by utilizing data from the Sentinel-2 MSI. The second objective pertains to the utilization of algorithms to observe spatial-temporal variations.

Data and Methods

Satellite data: The satellite data employed in this study consisted of the Sentinel-2 image, which encompassed the coastal region of Semarang City. The Sentinel-2 image has undergone geometric and radiometric corrections, resulting in reflectance values derived from the Bottom of the Atmosphere (BOA). This image is equipped with twelve multi-spectral bands, spanning a range of wavelengths from 443 nm to 22,202 nm (Gatti & Bertolini, 2015). In the present investigation, a novel approach was devised to assess Chl-a concentration. This approach integrates elements from the methodology proposed by Moutzouris-Sidiris and Topouzelis (2021), which employs the blue to green band ratio, as well as the green and red band ratio introduced by Ha et al. (2017). Additionally, insights from Chen et al. (2017) regarding the near-infrared (NIR) band and Aranha et al. (2021) concerning the visible band were incorporated into the combined method. This research investigates the application of visible (blue, green, red)-NIR bands, with a spatial resolution of 10 meters, for the analysis of Chl-a levels in the BKT River. An analysis was conducted to establish a Chl-a algorithm for the region adjacent to the BKT River by comparing the visible and NIR bands with in-situ Chl-a measurements. Therefore, in order to derive the seasonal fluctuations of Chl-a, our algorithm was implemented on Sentinel-2 images that accurately represent each month of the year 2020.

Meteorological data

The meteorological data regarding daily rainfall and wind speed were collected from the Achmad Yani International Airport's Meteorological Station. The data collected on a daily basis were subsequently aggregated to form monthly averages. The data can be accessed through the official website of the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) at https://dataonline.bmkg.go.id/home.

Sample collection and analysis

A total of 100 field samples were collected. The sampling procedure took place on August 21, 2021, between the hours of 08:00 and 11:00 a.m., aligning with the specific date and time of the Sentinel-2 data acquisition over Semarang City (refer to Figure 3). It is worth mentioning that the sampling area under consideration exhibited characteristics of eastern monsoon conditions. Analysis of meteorological data revealed that the recorded wind speed ranged from 2.19 to 2.40 meters per second.

Water samples of 500 mL were collected from the near surface, with a depth range of ±30 cm. The spectrometric method was employed to conduct the chlorophyll analysis, utilizing three wavelengths (trichromatic). The suspension was extracted using a solvent consisting of 90% acetone. The filtration process employed filter paper made from cellulose nitrate with a pore size of 0.45 um, specifically sourced from Millipore Merck. The Chl-a concentration in water samples was determined using the calculation formula prescribed by the American Public

Health Association (APHA) method, as described in the studies conducted by Maslukah et al. (2019) and Maslukah et al. (2021).

In order to refine the Chl-a algorithm, a dataset was generated comprising of match-up data. This dataset included in-situ Chl-a measurements as the ground truth, along with corresponding satellite observations obtained from collocated locations. In order to ensure the representation of the sampling distribution, the match-up positions for algorithm tuning and validation were evenly distributed across the study area. Out of the total 100 match-ups, we allocated 50 for the purpose of tuning and the remaining 50 for validation. In both subsets, the exclusion of outlier data was implemented. The figure provided, Figure 2, displays the positions of the stations used for tuning and validation purposes. The initial analysis involved evaluating the correlation (r) between the overall concentration data and the visible-NIR band's Rrs. Subsequently, a total of 43 match-ups were employed to develop the Chl-a algorithm for Sentinel-2A, while an additional 43 match-ups were utilized for the purpose of validation. Table 1 displays the statistical data pertaining to in-situ Chl-a for the purposes of algorithm tuning and validation.

Table 1. Statistics on in situ Chl-a used for algorithm tuning and validation.

Data	n	average (μg/L)	Min (μg/L)	Max (μg/L)	St . Dev (μg/L)
Tunning	43	9.49	2.15	17.27	3.47
Validation	43	8.75	3.5	14.52	2.90

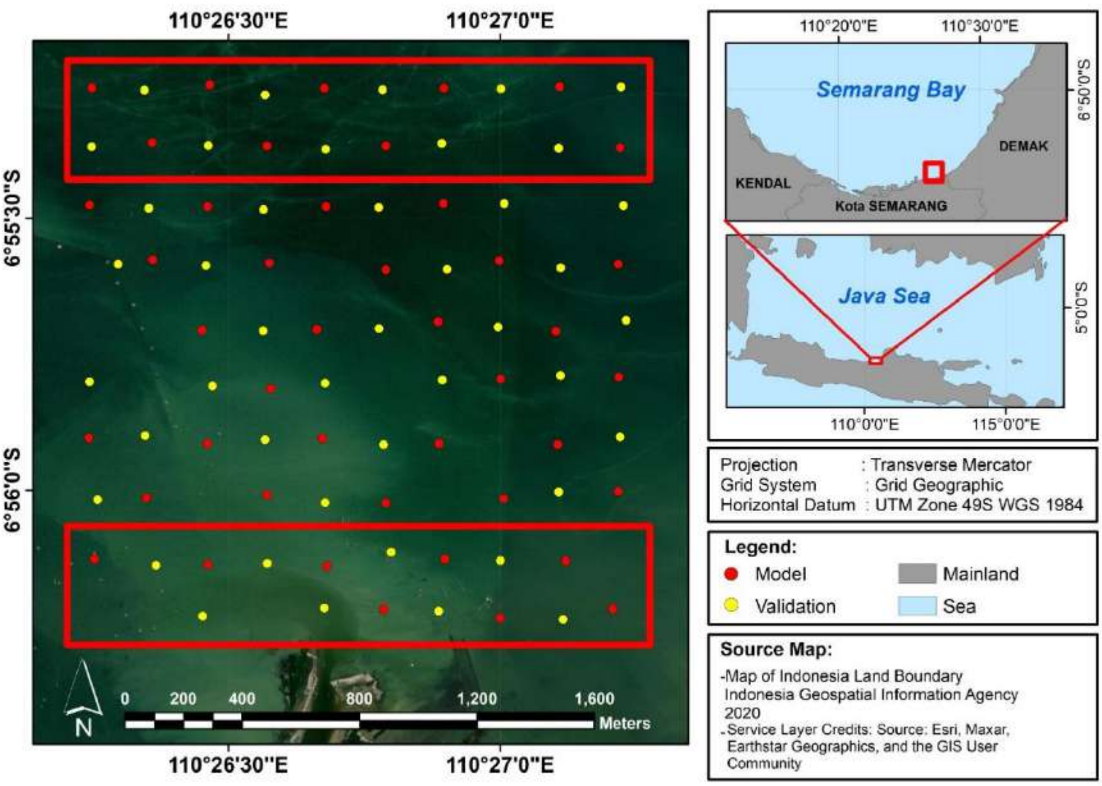

Figure 2. Location of sampling for match-up model (●) dan validation (●). The red rectangle (□) denotes (inshore and offshore) the regions in closest proximity to and furthest distance from the river's mouth.

The algorithm assessment

The accuracy test of the algorithms developed in this research is based on three statistical techniques, namely the coefficient of determination (R^2) as reported by Shaik et al. (2021) and Moutzouris-Sidiris and Topouzelis et al. (2021), the root mean square error (RMSE), the mean absolute percentage error (MAPE), and the bias, as discussed by Watabene et al. (2017) and Ciancia et al. (2020). The mathematical equations employed for the evaluation of algorithms are derived from formulas 1, 2, 3, and 4, correspondingly.

$$R^2 = \left[\frac{N\ x\ \sum_{i=1}^{N} (Chla_i, meas)\ x\ Chla_{i,retr}) - \sum_{i=1}^{N} Chla_{i,meas}\ x\ \sum_{i=1}^{N} Chla_{i,retr}}{\sqrt{\left[N\ x \sum_{i=1}^{N} (Chla_i, meas)^2 - (\sum_{i=1}^{N} (Chla_i, meas)^2\right] \left[N\ x\ \sum_{i=1}^{N} (Chla_{i,retr})^2 - (\sum_{i=1}^{N} Chla_{i,retr})^2\right]}} \right]^2 \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (Chla_i, meas - Chla_{i,retr})^2}{N}} \quad (2)$$

$$\text{MAPE} = \frac{100\%}{N}\ x\ \sum_{i=1}^{N} \frac{|(Chla_i, meas - Chla_{i,retr})|}{Chla_{i,meas}} \quad (3)$$

$$\text{BIAS} = \frac{1}{N}\ x\ \sum_{i=1}^{N} (Chla_{i,retr} - Chla_{i,meas}) \quad (4)$$

where $Chla_i, meas$ and $Chla_i, retr$ refer to the measured (in-situ) and retrieved (estimated) Chl-a respectively; and N is the total number of samples.

In order to establish the Chl-a algorithm, the initial step involves assessing the correlation between the visible - near-infrared (blue/B2, green/B3, red/B4, and NIR/B8) spectral bands and Chl-a observations. The resulting coefficients obtained are 0.69, 0.69, 0.65, and 0.65, respectively (as shown in Figure 3). Figure 3 demonstrates that all Rrs exhibit significant correlations with the observed Chl-a levels. To develop the new algorithm, we utilized Rrs Nir, red, green, and blue wavelengths to estimate the concentration of Chl-a in the BKB offshore region. According to Aranha et al. (2022), bodies of water characterized by a prevalence of phytoplankton exhibit two distinct peaks of absorption in the electromagnetic spectrum. Specifically, one peak is observed in the blue region at approximately 440 nm, while the other peak is located in the red region at around 670 nm. The green band, characterized by a wavelength range of 560 nm, exhibits a high reflectance of chlorophyll owing to its low absorption coefficient. Furthermore, the existence of phytoplankton is distinguished by its maximum reflection at 700 nm, specifically within the near-infrared spectrum (Matthews et al., 2012). Given the intricate nature of the region under investigation, the study incorporated an examination of the utilization of four bands on Sentinel-2 satellites, each possessing an equivalent spatial resolution of 10 meters.

Author's Response To Reviewer Comments

Close

Reviewer #1: I wish the authors of this manuscript (especially the first & corresponding authors) might have written the reviewer's response for the first time, since there is even no response to revirewer and any cover letter, so that the content of the response is so sloppy and not rigorous.

The revised manuscript might changed somewhere, however there is not even a specific description of the revised manuscript after the first revision, as well as no Authors' Responses letter to Reviewer's Comments.

The the author's response for the revised manuscript makes it awfully difficult for me to continue my review (especially check the changed text in the revised manuscript) for the second term. For instance, when the author responded to some questions, the author's reply and explanatory content did not even have as many content of the question as I asked.

It is hoped that the authors will take seriously the revision of the manuscript and pay more attention to writing of the reviewer's response, for as much as the publication of academic papers is a very serious matter, and should have occasion for your great patience.

There is no significant revision from this revised manuscript especially accordding to my comments, therefore I maintain my point of view that the lack of significant revision for the objectives of this work makes the paper not robust to be published in Regional Studies in Marine Science.
Response: Thank you very much for your comments. We do apologize for this situation. We think that there is an error in the system so that we cannot get your comments. We only received comments from 1 reviewer that has already been responded and answered point by point. Thus, we missed your comments. In this revised version we tried to follow your suggestion to improve the quality of this manuscript. The revised parts are highlighted in yellow.

To wit:
The author's manuscript lacks a clear hypothesis (not only in abstract, but also in introduction section), strong logic, the connection between paragraphs is not close enough, and it seems chaotic is the biggest shortcoming of this manuscript.
Response: Thank you very much for your comment. We have revised the abstract and introduction by rearranging the story of our research, and emphasized the novelty of this research. Coastal area of Semarang is known as eutrophic waters. Thus continuous monitoring of Chl-a will be beneficial for the management of the impact of the trophic dynamic in the coastal waters of Semarang. Taking the benefit of the continuous monitoring of satellite measurement, the present study provides the assessment of Chl-a off the Banjir Kanal Timur (BKT) River, Semarang, using the proper remote sensing approach.

First, the manuscript lacks a clear hypothesis (not only in abstract, but also in introduction section), especially in the introduction part, thus resulting a lengthy, very descriptive text. The authors should formulate a valid scientific hypothesis, concentrate on a general scientific framework around this new hypothesis. That could be a useful starting point for a good Introduction part.
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Moreover, all abbreviations in each part of the manuscript including the abstract and contents, as well as in the Table and Figure, should be introduced for the first time despite how common or not the abbreviation is.
Response : Thank you very much for your suggestion. It is done.

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Response : Thank you very much for your suggestion. We have carefully checked and added some literatures:
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Re: Decision on submission to Regional Studies in Marine Science

From: Lilik Maslukah (lilik_masluka@yahoo.com)

To: support@elsevier.com

Date: Thursday, March 28, 2024 at 09:36 AM GMT+7

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Thank you very much

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Lilik Maslukah.

> On Wednesday, March 27, 2024 at 06:27:50 PM GMT+7, Regional Studies in Marine Science <em@editorialmanager.com> wrote:
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> Manuscript Number: RSMA-D-23-01718R1
>
> The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel-2 MSI in coastal waters of Semarang, Indonesia
>
> Dear Dr Maslukah,
>
> Thank you for submitting your manuscript to Regional Studies in Marine Science.
>
> I have completed my evaluation of your manuscript. The reviewers recommend reconsideration of your manuscript following major revision and modification. I invite you to resubmit your manuscript after addressing the comments below. Please resubmit your revised manuscript by Apr 17 2024 11:59:59:000PM.
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>
> Regional Studies in Marine Science values your contribution and I look forward to receiving your revised manuscript.

Kind regards,

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Associate Editor

Regional Studies in Marine Science

Editor and Reviewer comments:

Reviewer #1: I wish the authors of this manuscript (especially the first & corresponding authors) might have written the reviewer's response for the first time, since there is even no response to revirewer and any cover letter, so that the content of the response is so sloppy and not rigorous.

The revised manuscript might changed somewhere, however there is not even a specific description of the revised manuscript after the first revision, as well as no Authors' Responses letter to Reviewer's Comments.

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To wit:
The author's manuscript lacks a clear hypothesis (not only in abstract, but also in introduction section), strong logic, the connection between paragraphs is not close enough, and it seems chaotic is the biggest shortcoming of this manuscript.

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Regional Studies in Marine Science

The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel-2 MSI off the Banjir Kanal Timur River, Semarang, Indonesia

--Manuscript Draft--

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Keywords:	coastal algortihm, chlorophyll-a, visible-NIR, Sentinel-2 MSI
Corresponding Author:	Lilik Maslukah, Ph.D Diponegoro University Department of Oceanography Semarang, Central Java INDONESIA
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	Yusuf Jati Wijaya, PhD
	Dwi Haryo Ismunarti, Dr
	Rikha Widiaratih, MSc
	Heru Nur Krisna, BSc
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Suggested Reviewers:	Ulung Jantama Wisha, PhD candidate of PhD, University of the Ryukyus Faculty of Science Graduate School of Engineering and Science ulungjantama@gmail.com His expertise is water quality
	Riza Yuliratno Setiawan, Dr Lecturer, Gadjah Mada University Faculty of Agriculture riza.y.setiawan@ugm.ac.id His Experties is Remote sensing
	Widodo Setyo Pranowo, Prof National Research and Innovation Agency Republic of Indonesia widodo.pranowo@gmail.com

	His Experties is dynamical of coastal oceanography
Response to Reviewers:	Reviewer #1: I wish the authors of this manuscript (especially the first & corresponding authors) might have written the reviewer's response for the first time, since there is even no response to revirewer and any cover letter, so that the content of the response is so sloppy and not rigorous. The revised manuscript might changed somewhere, however there is not even a specific description of the revised manuscript after the first revision, as well as no Authors' Responses letter to Reviewer's Comments. The the author's response for the revised manuscript makes it awfully difficult for me to continue my review (especially check the changed text in the revised manuscript) for the second term. For instance, when the author responded to some questions, the author's reply and explanatory content did not even have as many content of the question as I asked. It is hoped that the authors will take seriously the revision of the manuscript and pay more attention to writing of the reviewer's response, for as much as the publication of academic papers is a very serious matter, and should have occasion for your great patience. There is no significant revision from this revised manuscript especially accordding to my comments, therefore I maintain my point of view that the lack of significant revision for the objectives of this work makes the paper not robust to be published in Regional Studies in Marine Science. Response: Thank you very much for your comments. We do apologize for this situation. We think that there is an error in the system so that we cannot get your comments. We only received comments from 1 reviewer that has already been responded and answered point by point. Thus, we missed your comments. In this revised version we tried to follow your suggestion to improve the quality of this manuscript. The revised parts are highlighted in yellow. To wit: The author's manuscript lacks a clear hypothesis (not only in abstract, but also in introduction section), strong logic, the connection between paragraphs is not close enough, and it seems chaotic is the biggest shortcoming of this manuscript. Response: Thank you very much for your comment. We have revised the abstract and introduction by rearranging the story of our research, and emphasized the novelty of this research. Coastal area of Semarang is known as eutrophic waters. Thus continuous monitoring of Chl-a will be beneficial for the management of the impact of the trophic dynamic in the coastal waters of Semarang. Taking the benefit of the continuous monitoring of satellite measurement, the present study provides the assessment of Chl-a off the Banjir Kanal Timur (BKT) River, Semarang, using the proper remote sensing approach. First, the manuscript lacks a clear hypothesis (not only in abstract, but also in introduction section), especially in the introduction part, thus resulting a lengthy, very descriptive text. The authors should formulate a valid scientific hypothesis, concentrate on a general scientific framework around this new hypothesis. That could be a useful starting point for a good Introduction part. Response: Thank you very much for your comment. We have revised the abstract and introduction by rearranging the story of our research, and emphasized the novelty of this research. Coastal area of Semarang is known as eutrophic waters. Thus continuous monitoring of Chl-a will be beneficial for the management of the impact of the trophic dynamic in the coastal waters of Semarang. Taking the benefit of the continuous monitoring of satellite measurement, the present study provides the assessment of Chl-a off the Banjir Kanal Timur (BKT) River, Semarang, using the proper remote sensing approach. Proper remote sensing approach means that we build our own algorithm for Chl-a assessment off the BKT River using adequate matchups insitu and remote sensing reflectants; and validate the algorithm with the insitu data to ensure the accuracy of the algorithm. In addition, the manuscript lacks sufficient discussion, which is an important part of a research paper, and the results section is somewhat confused with the discussion

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The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel-2 MSI off the Banjir Kanal Timur River, Semarang, Indonesia

Lilik Maslukah[1*], Anindya Wirasatriya[1], Yusuf Jati Wijaya[1], Dwi Haryo Ismunarti[1], Rikha Widiaratih[1], Heru Nur Krisna[2]

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Abstract

In aquatic ecology, Chlorophyll-a (Chl-a) plays a pivotal role in biogeochemical cycles, as well as a key indicator for the trophic state in the environment. Coastal area of Semarang is known as eutrophic waters. Thus continuous monitoring of Chl-a will be beneficial for the management of the impact of the trophic dynamic in the coastal waters of Semarang. Taking the benefit of the continuous monitoring of satellite measurement, the present study provides the assessment of Chl-a off the Banjir Kanal Timur (BKT) River, Semarang, using the proper remote sensing approach. In this study, algorithms were generated according to bands sensitive to Chl-a scattering properties, using multiple regression between in-situ Chl-a and Bottom of Atmospheric (BoA) reflectance from Sentinel-2 with 10 m resolution. A total of 43 water samples were collected to build the algorithm and 43 of the water samples were used for validation during the passing time of Sentinel-2 at the equator i.e., on 21 August 2021 at 9.00-11.00 local time. The results show that the performance of the algorithm generated in this study has high accuracy as denoted by the low RMSE, and MAPE, respectively. For the seasonal variation, the highest (lowest) concentration of Chl-a is observed in December (September), with values reaching 11.92 µg/L (7.06 µg/L). The seasonal fluctuation of Chl-a depends on air temperature and sunshine duration. High (low) air temperature and long (short) duration of solar exposure result in increased (decreased) Chl-a off the BKT River. Conversely, the elevated wind velocity only impacts the rise of Chl-a in the region far from the river estuary, which is associated with the mixing process. BKT waters are categorized as eutrophic conditions, with a concentration exceeding 6 µg/L. These algorithms can provide valuable insights into the health and productivity of coastal ecosystems, aiding in their monitoring and management.

Keywords: Coastal algorithm, Chlorophyll-a, visible-NIR band, Sentinel-2 MSI

Introduction

Phytoplankton holds significant ecological importance within the marine ecosystem owing to its capacity for photosynthesis, a metabolic process that facilitates the synthesis of organic compounds utilizing light energy and carbon dioxide (Rost et al., 2008; Abbas et al., 2019; Aranha et al., 2022). Phytoplankton possesses chlorophyll-a (Chl-a) within its cellular structure and plays a crucial role in ecological systems, serving as a fundamental component of the aquatic life cycle and serving as the primary source of energy within oceanic food webs.

Chl-a is a crucial factor in assessing water quality due to its regulatory role in biological processes occurring within coastal waters (Ogashawara et al., 2021; Tran et al., 2023).

The determination of Chl-a distribution within a given area is typically achieved through the implementation of field sampling techniques, which are subsequently complemented by laboratory-based analyses (Abbas et al., 2019; Maslukah et al., 2019). Nevertheless, this approach proves to be ineffective and inefficient due to its prolonged duration, elevated expenses, and restricted geographical reach (Duan et al., 2010; Ogashawara et al., 2021; Aranha et al., 2022). To address these concerns, several remote sensing techniques have been devised to monitor Chl-a (Ouma et al., 2020;). Remote sensing methods show promise for monitoring Chl-a levels in a given area due to their extensive coverage and ability to provide periodic observations (Maslukah et al., 2019; Ouma et al, 2020). The utilization of ocean color data within the visible and near-infrared (VNIR) wavelength bands facilitates the estimation of Chl-a levels (Ouma et al. 2020). The acquisition of Chl-a data from these satellites necessitates the utilization of an algorithm that is heavily reliant on the band and spectral resolution capabilities offered by the satellite (Ogashawara et al., 2021).

The quantification of Chl-a in reservoirs and lakes has been extensively studied, and multiple algorithms have been devised for this purpose. These algorithms encompass different approaches, such as utilizing two bands (red and near-infrared) as demonstrated by O'Reilly et al. (1998) and Tran et al. (2023), as well as employing a single band, as explored by Bramich et al. (2020). The phenomenon above is similarly observed in marine regions, where algorithms are employed to calculate the ratio between blue and green color bands (Tilstone et al., 2021; Tran et al., 2023). In the expanse of open ocean waters, the presence of colored dissolved organic matter (CDOM) and suspended particulate matter is limited to relatively small quantities (Nelson and Siegel, 2002). Additionally, the concentration of Chl-a in these waters is comparatively lower than that observed in coastal regions. Estuarine regions, characterized by terrestrial influence, exhibit heightened optical complexity as a result of the absorption caused by CDOM and non-algal particles (Ouma et al, 2020; Tran et al., 2023). The optical properties of water are significantly influenced by the presence of turbid coastal waters characterized by high concentrations of CDOM and suspended non-phytoplanktonic particles (Lewis & Arrigo, 2020). Those mentioned above intricate aquatic conditions diminish the efficacy of the band ratio algorithm in estimating Chl-a concentration. This is because the signal of the blue band declines below the detection threshold as a result of substantial absorption by phytoplankton (Soja-Wozniak et al., 2020).

The utilization of ocean color remote sensing in turbid regions (case 2) presents significant challenges due to the unique characteristics exhibited by each coastal area. Hence, an algorithm formulated for a specific domain may lack generalizability to other domains. The Sentinel-2 satellite has a superior spatial resolution of 10 meters for the visible NIR band (Ouma et al., 2020), making it particularly useful for monitoring and evaluating Chl-a levels in complex coastal waters (Gohin et al., 2020).

The Banjir Kanal Timur (BKT) River is one of Semarang's flood control systems located in the eastern part of the city (Fig. 1). This river has a length of ± 14.50 km. The BKT River is the unification of several rivers and canals such as the Penggaron River through the Pucang Gading outlet, Kedung Mundu River drainage outlet, Candi River, Bajak River, Kartini pump drainage and large rice field / Sambirejo pump drainage and empties into the Java Sea.

The upstream flow have a major influence on the input of organic and non-organic materials from soil erosion and solid and liquid waste, which can affect water quality. During the rainy season, sediment from land enters the marine waters at a higher rate and causes the estuary to become more turbid. The results of research by Utama et al. (2021) explained that the suspended solids in front of the BKT estuary reached 290 mg/L in the rainy season and 60 mg/L in the dry season (Hutasuhut et al, 2022). Apart from high turbidity, the front of the river mouth is also a eutrophic area with an average range of chlorophyll-a of 12.67 µg/L in the dry season (Maslukah et al., 2019) and 18.06 µg/L in the wet season (Maslukah et al., 2020). Based on the classification of Hakanson & Bryan (2008), BKT waters are in eutrophic conditions. Thus, temporal and continuous monitoring of Chl-a is required to manage the impact of the trophic dynamic in the coastal waters of Semarang.

The previous monitoring of Chl-a using Sentinel-2 in front of the BKT Semarang estuary was conducted by Subiyanto et al. (2018) following the algorithm used by Nuriya et al. (2016) in the Madura Strait. In the algorithm, the development band is the ratio of the red and NIR (Near Infra Red) bands to the green band. However, this research is still questionable because it is without validation of field data. The use of the NIR band for coastal waters reduces the absorption of colored dissolved organic matter (Gilerson et al., 2010). It was further explained by Yoon et al. (2020) that the empirical algorithm of blue and green bands is more suitable for oligotrophic and mesotrophic coastal waters. Given the absence of a Chl-a estimation algorithm for Sentinel-2, which characterizes the foreshore waters of the BKT river and accommodates the existence of previous studies regarding the bands, this study aims to develop an algorithm for estimating Chl-a levels in Sentinel-2 imagery.

This study examined the response of each spectral band with 10m spatial resolution to field Chl-a concentrations. In addition, statistical analyses and validation techniques were performed to determine the reliability of the algorithm in estimating chlorophyll-a concentrations, which have never been previously investigated. The resulting algorithm was further utilized on other images to capture the spatial-temporal fluctuations of Chl-a around the BKT River. This study is the first investigation into the seasonal fluctuations of Chl-a levels in the BKT River, using the self-built Sentinel-2 algorithm. It is expected that this algorithm can estimate Chl-a concentrations in other eutrophic and shallow waters.

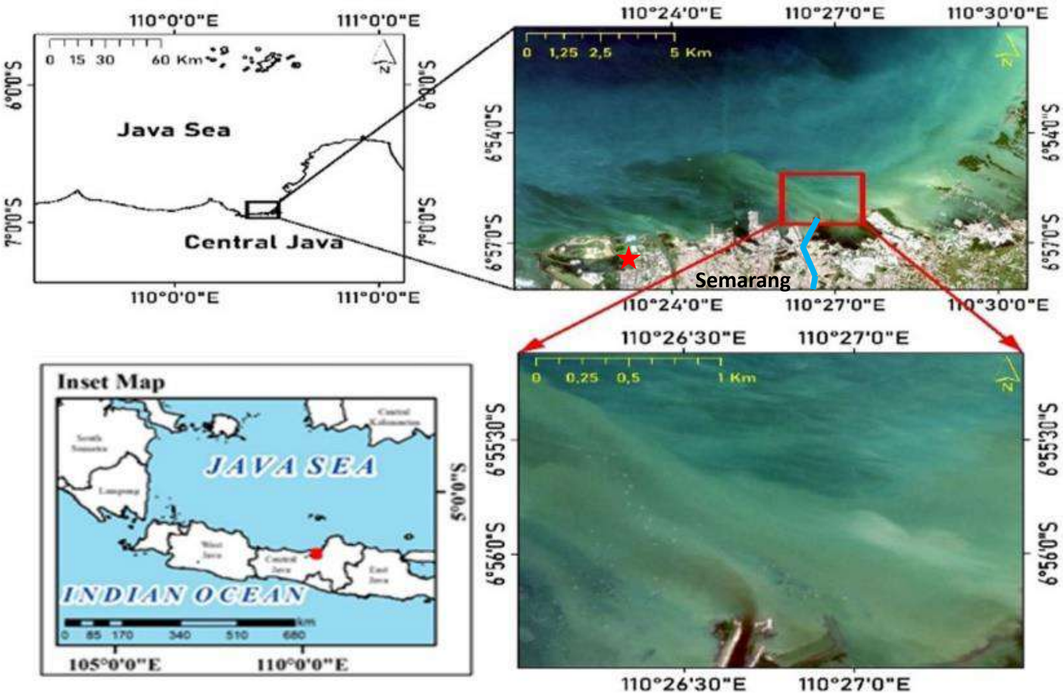

Figure 1. The research site is located in the vicinity of the BKT river estuary (blue line) in Semarang, Indonesia. Red star is a meteorological station used for precipitation data retrieval.

Data and Methods

Satellite data

The satellite data employed in this study consisted of the Sentinel-2 image, which encompassed the coastal region of Semarang City. The Sentinel-2 image has undergone geometric and radiometric corrections, resulting in reflectance values derived from the Bottom of the Atmosphere (BOA). This image is equipped with twelve multi-spectral bands, spanning a range of wavelengths from 443 nm to 22,202 nm (Gatti & Bertolini, 2015). In the present investigation, a novel approach was devised to assess Chl-a concentration. This approach integrates elements from the methodology proposed by Moutzouris-Sidiris and Topouzelis (2021), which employs the blue to green band ratio, as well as the green and red band ratio introduced by Ha et al. (2017). Additionally, insights from Chen et al. (2017) regarding the NIR band and Aranha et al. (2021) concerning the visible band were incorporated into the combined method. This research investigates the application of visible (blue, green, red)-NIR bands, with a spatial resolution of 10 meters, for the analysis of Chl-a levels in the BKT River. An analysis was conducted to establish a Chl-a algorithm for the region adjacent to the BKT River by comparing the visible and NIR bands with in-situ Chl-a measurements. Therefore, in order to derive the seasonal fluctuations of Chl-a, our algorithm was implemented on Sentinel-2 images that accurately represent each month of the year 2020.

Meteorological data

The meteorological data regarding daily rainfall and wind speed were collected from the Achmad Yani International Airport's Meteorological Station (red star at Fig. 1). The data collected on a daily basis were subsequently aggregated to form monthly averages. The data can be accessed through the official website of the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) at https://dataonline.bmkg.go.id/home.

Sample collection and analysis

A total of 100 field samples were collected. The sampling procedure took place on August 21, 2021, between the hours of 08:00 and 11:00 a.m., aligning with the specific date and time of the Sentinel-2 data acquisition over Semarang City (refer to Figure 3). It is worth mentioning that the sampling area under consideration exhibited characteristics of eastern monsoon conditions. Analysis of meteorological data revealed that the recorded wind speed ranged from 2.19 to 2.40 meters per second.

Water samples of 500 mL were collected from the near surface, with a depth range of ±30 cm. The spectrometric method was employed to conduct the chlorophyll analysis, utilizing three wavelengths (trichromatic). The suspension was extracted using a solvent consisting of 90% acetone. The filtration process employed filter paper made from cellulose nitrate with a pore size of 0.45 um, specifically sourced from Millipore Merck. The Chl-a concentration in water samples was determined using the calculation formula prescribed by the American Public Health Association (APHA) method, as described in the studies conducted by Maslukah et al. (2019) and Maslukah et al. (2021).

In order to refine the Chl-a algorithm, a dataset was generated comprising of match-up data. This dataset included in-situ Chl-a measurements as the ground truth, along with corresponding satellite observations obtained from collocated locations. In order to ensure the representation of the sampling distribution, the match-up positions for algorithm tuning and validation were evenly distributed across the study area. Out of the total 100 match-ups, we allocated 50 for the purpose of tuning and the remaining 50 for validation. In both subsets, the exclusion of outlier data was implemented. The figure provided, Figure 2, displays the positions of the stations used for tuning and validation purposes. The initial analysis involved evaluating the correlation (r) between the overall concentration data and the visible-NIR band's Rrs. Subsequently, a total of 43 match-ups were employed to develop the Chl-a algorithm for Sentinel-2A, while an additional 43 match-ups were utilized for the purpose of validation. Table 1 displays the statistical data pertaining to in-situ Chl-a for the purposes of algorithm tuning and validation.

Table 1. Statistics on in situ Chl-a used for algorithm tuning and validation.

Data	n	average (μg/L)	Min (μg/L)	Max (μg/L)	St . Dev (μg/L)
Tunning	43	9.49	2.15	17.27	3.47
Validation	43	8.75	3.5	14.52	2.90

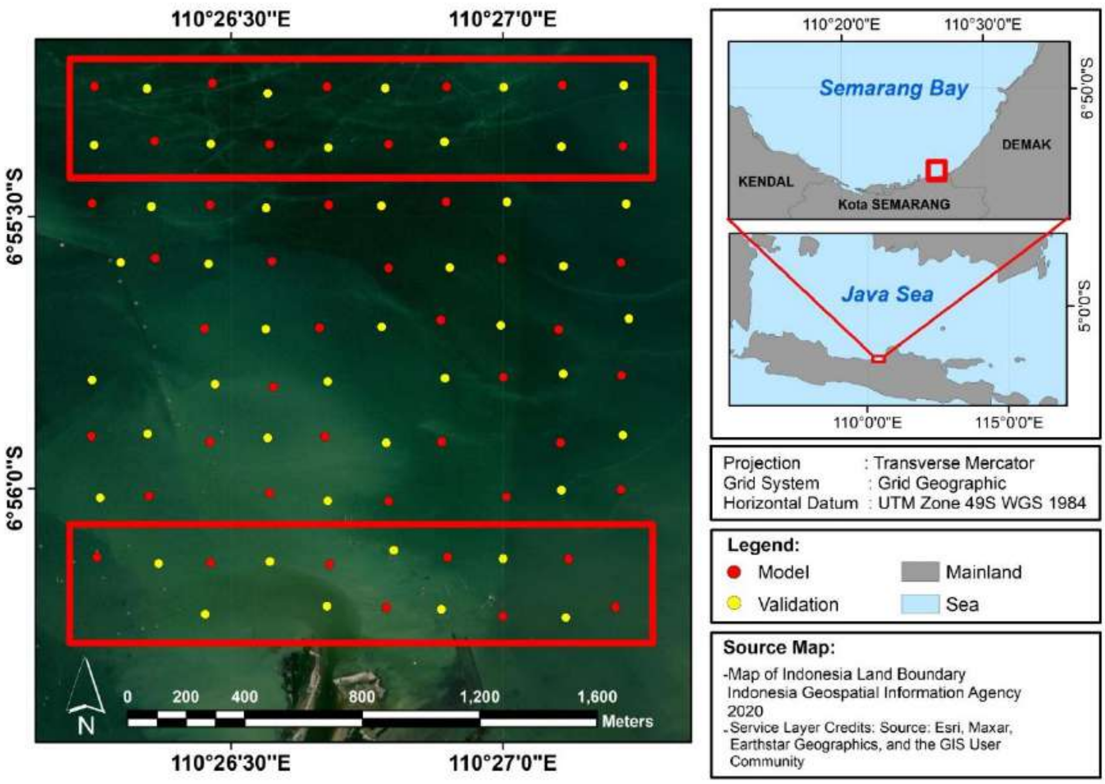

Figure 2. Location of sampling for match-up model (●) dan validation (●). The red rectangle (□) denotes (inshore and offshore) the regions in closest proximity to and furthest distance from the river's mouth.

The algorithm assessment

The accuracy test of the algorithms developed in this research is based on three statistical techniques, namely the coefficient of determination (R^2) as reported by Shaik et al. (2021) and Moutzouris-Sidiris and Topouzelis et al. (2021), the root mean square error (RMSE), the mean absolute percentage error (MAPE), and the bias, as discussed by Watanabe et al. (2018) and Ciancia et al. (2020). The mathematical equations employed for the evaluation of algorithms are derived from formulas 1, 2, 3, and 4, correspondingly.

$$R^2 = \left[\frac{N\ x\ \sum_{i=1}^{N}(Chla_i,meas)\ x\ Chla_{i,retr}) - \sum_{i=1}^{N} Chla_{i,meas}\ x\ \sum_{i=1}^{N} Chla_{i,retr}}{\sqrt{\left[N\ x \sum_{i=1}^{N}(Chla_i,meas)^2 - (\sum_{i=1}^{N}(Chla_i,meas)^2\right] \left[N\ x\ \sum_{i=1}^{N}(Chla_{i,retr})^2 - (\sum_{i=1}^{N} Chla_{i,retr})^2\right]}}\right]^2 \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(Chla_i,meas - Chla_{i,retr})^2}{N}} \quad (2)$$

$$\text{MAPE} = \frac{100\%}{N}\ x\ \sum_{i=1}^{N} \frac{|(Chla_i,meas - Chla_{i,retr})|}{Chla_{i,meas}} \quad (3)$$

$$\text{BIAS} = \frac{1}{N}\ x\ \sum_{i=1}^{N}(Chla_{i,retr} - Chla_{i,meas}) \quad (4)$$

where *$Chla_i$,meas* and *$Chla_i$,retr* refer to the measured (in-situ) and retrieved (estimated) Chl-a respectively; and N is the total number of samples.

Results

Generating Chl-a algorithm

In order to generate the Chl-a algorithm, the initial step involves assessing the correlation between the visible-NIR (blue/B2, green/B3, red/B4, and NIR/B8) spectral bands and Chl-a observations. The resulting coefficients obtained are 0.69, 0.69, 0.65, and 0.65, respectively (as shown in Figure 3). Figure 3 demonstrates that all Rrs exhibit significant correlations with the observed Chl-a levels. To develop the new algorithm, we utilized Rrs NIR, red, green, and blue wavelengths to estimate the concentration of Chl-a in the BKT offshore region. According to Aranha et al. (2022), bodies of water characterized by a prevalence of phytoplankton exhibit two distinct peaks of absorption in the electromagnetic spectrum. Specifically, one peak is observed in the blue region at approximately 440 nm, while the other peak is located in the red region at around 670 nm. The green band, characterized by a wavelength range of 560 nm, exhibits a high reflectance of Chl-a owing to its low absorption coefficient. Furthermore, the existence of phytoplankton is distinguished by its maximum reflection at 700 nm, specifically within the near-infrared spectrum (Matthews et al., 2012). Given the intricate nature of the region under investigation, the study incorporated an examination of the utilization of four bands on Sentinel-2 satellites, each possessing an equivalent spatial resolution of 10 meters.

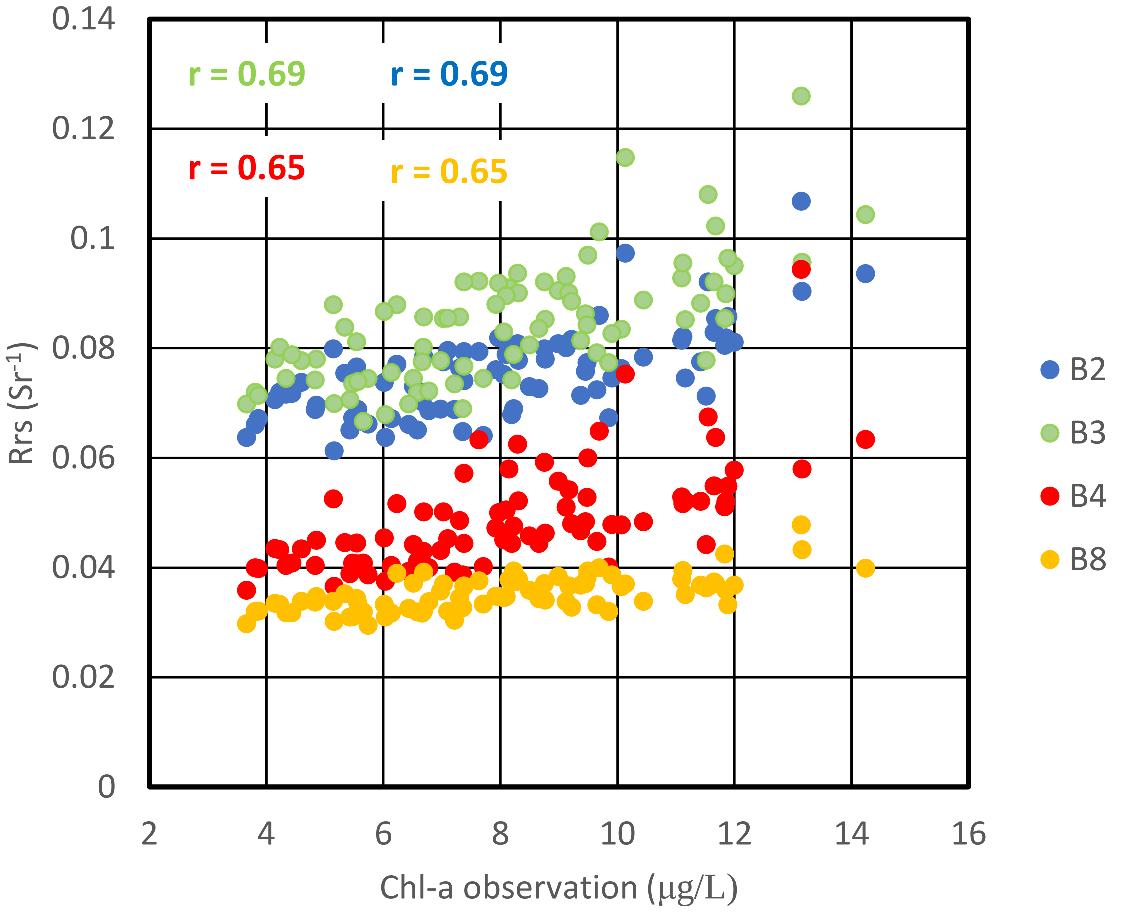

Figure 3. Scatter plot of observed Chl-a versus remote sensing reflectance of the visible-NIR

A model was constructed employing multiple regression analysis to derive estimations of Chl-a levels in the BKT River. The calculated coefficient of determination (R^2) is 0.45, The statistical significance of this relationship is supported by a p-value of less than 0.05. The empirical model produced between the observation and reflectance data is as follows equation 5.

$$\textbf{Chl-a} = \mathbf{10}^{(2.743 - 0.725*(log(B2*c)) - 0.625*(log(B3*c)) + 1.623*(log(B4*c)) + 0.809*(log(B8*c)))} \quad (5)$$

Where c : 0.036/B8; B2; B3; B4; B8 (reflectant blue, green, red and NIR).

The performance of the algorithm model in equation 5 was then tested statistically, which resulted in RMSE, Bias and MAPE values of 2.47 µg/L, -0.63, and 23.52, respectively (Fig 5). The negative bias indicates that estimated Chl-a underestimates the observed Chl-a. Since the RMSE and MAPE are quite small, the Chl-a off the BKT River estimated from the obtained algorithm has a good accuracy. Thus, equation (5) can be used to estimate TSS off the BKT River.

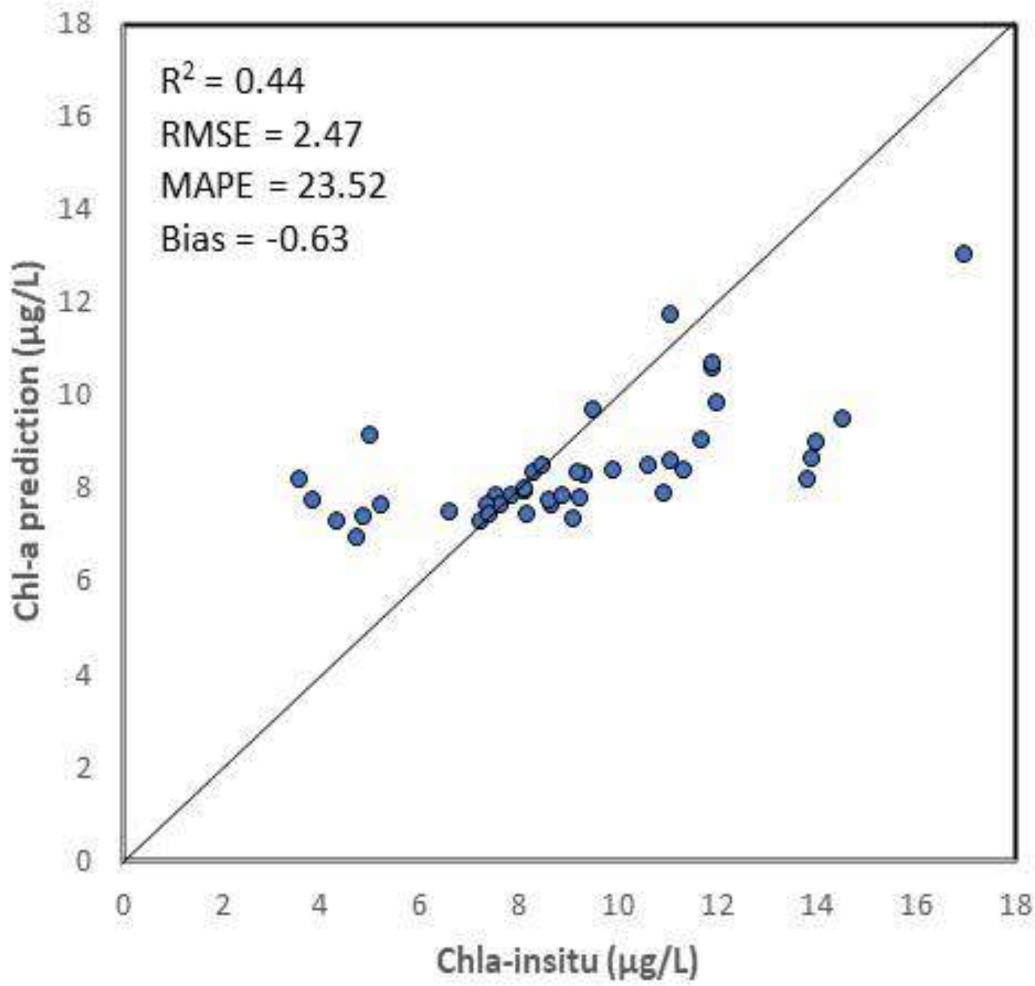

Figure 4. Validation of Chl-a from eq. (5) with observed Chl-a (observation).

Hence, the equation (5) can be employed for the estimation of Chl-a levels off BKT River. Figures 5 and 6 depict the spatial and temporal distribution, respectively.

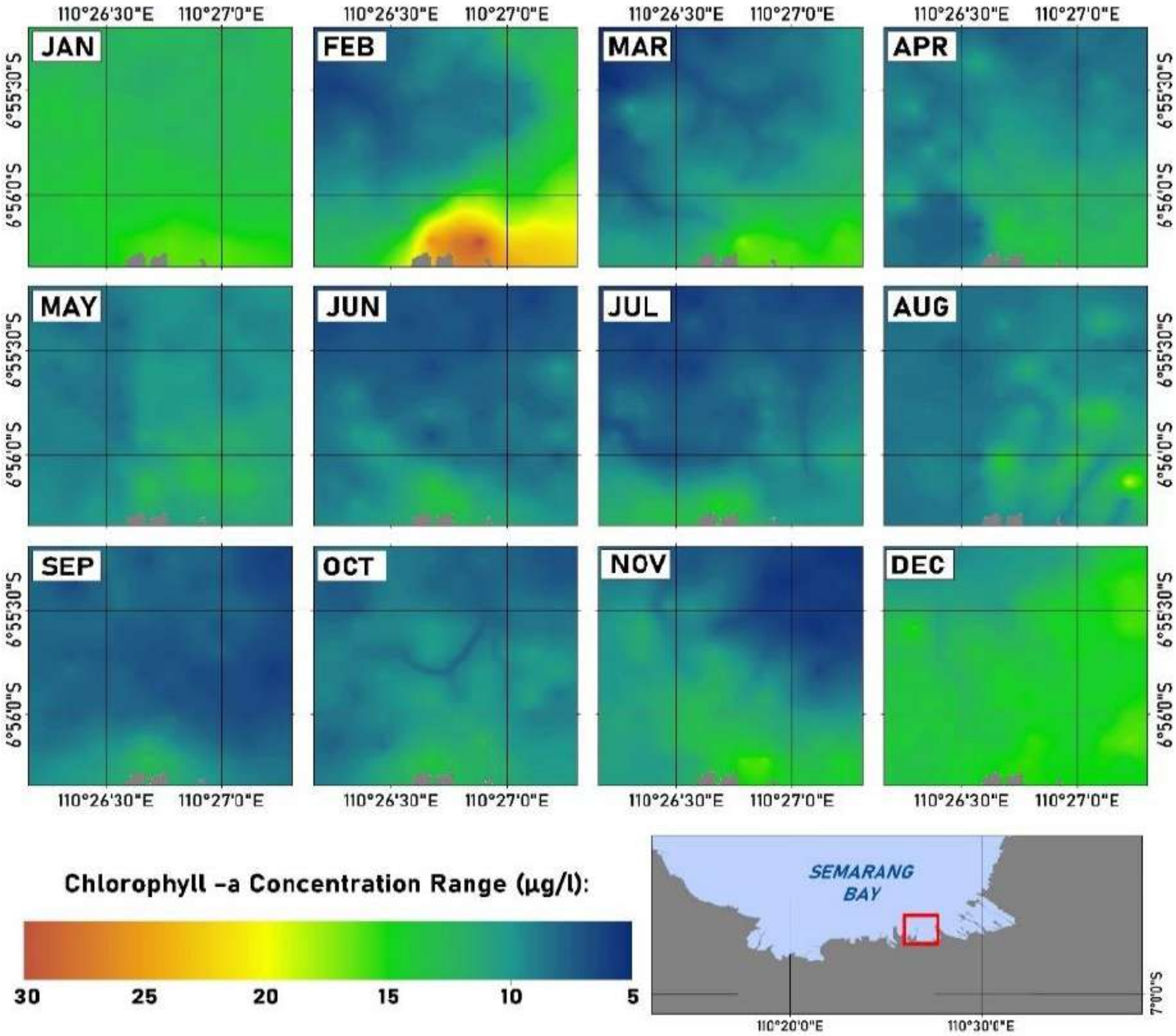

Figure 5. Distribution of Chl-a (a) 3 January 2021 (b) 27 February 2021 (c) 14 March (d) 23 April 2021 (e) 13 May 2021 (f). June 22, 2021 (g). 27 July 2021 (h) 21 August 2021 (I) 10 September 2021 (j) 10 October 2021 (k). November 4, 2021 (l). December 14, 2021 estimated from Sentinel-2 imagery using eq. (5). The BKT Semarang estuary, depicted with a red box

The highest concentration was observed in December, reaching a value of 11.92 µg/L, while the lowest concentration was recorded in September, with Chl-a concentration of 7.06 µg/L. The observed pattern in this study diverges from the findings of Wirasatriya et al. (2019), who utilized MODIS imagery to examine the area adjacent to the northern coast of Java. Wirasatriya et al. (2019) reported that the pattern reached its maximum in June and January. It is important to note that the previous study analyzed data over a longer time span of 10 years, encompassed a significantly larger regional area, and employed a lower image resolution of 4 km. Shabrina et al. (2018) also demonstrated distinct variations in seasonal dynamics during the summer period (March-August 2015 and 2016), with the highest concentration of Chl-a observed in June. The finding suggests that the temporal patterns of each region exhibit distinct variations.

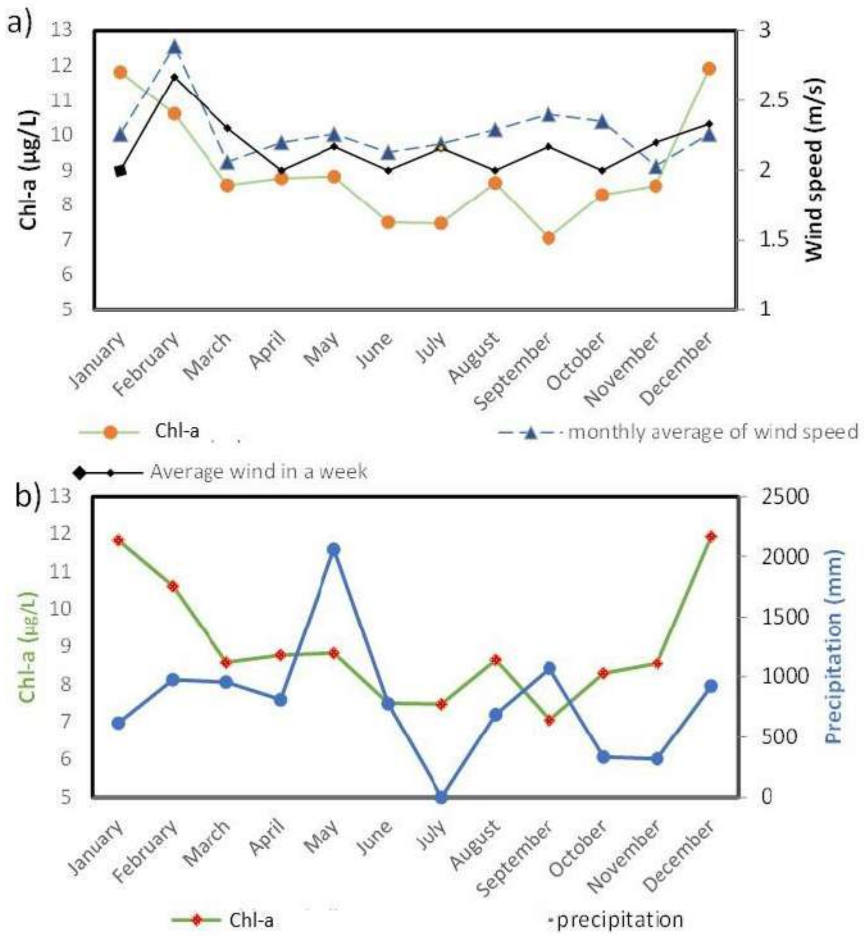

Figure 6. Temporal variation of Chl-a with wind speed (a) and precipitation (b) based on Sentinel imagery on 3 January 2021, 27 February 2021, 14 March 2021, 23 April 2021, 13 May 2021, 22 June 2021, 27 July 2021, 21 August 202, 10 September 2021, 10 October 2021, 4 November 2021, 14 December 2021 for whole study area (Fig. 2).

High Total Suspended Solids (TSS) concentrations in estuaries cause disturbances in the photosynthesis process, which results in low phytoplankton biomass. The results of Wirasatriya et al. (2023) explained that the river is the main contributor of TSS and wind affects its distribution pattern, which will influence the temporal dynamics of Chl-a. To investigate this, in this study, we divided two areas, near and off the river, which are given a red box in Figure 1, and the time series are shown in Fig. 7 & Fig. 8 and the correlation results are shown in Table 2.

Table 2. The Pearson correlations of Chl-a with climatological data

	Chl-a near	Chl-a far	the monthly of wind	the weekly of wind	the weekly of rain	the monthly of rain	Temperature of_ air	sunshine duration (hour)
Chl-a	$.786^{**}$	$.797^{**}$	.298	.344	.022	.128	$-.682^{*}$	$-.803^{**}$
Chl-a inshore	1	.319	-.113	-.191	-.016	.031	-.325	$-.646^{*}$
Chl-a offshore	.319	1	$.590^{*}$	$.715^{**}$	-.128	.141	$-.833^{**}$	$-.753^{**}$

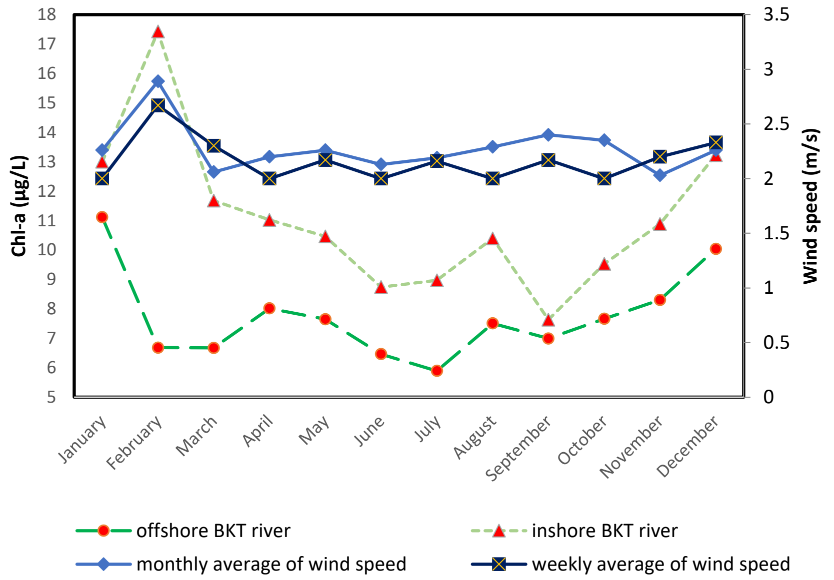

Figure 7. Same as Fig. 6 but for offshore Chl-a, inshore Chl-a and wind speed. The position of offshore and inshore areas is depicted in Fig. 2.

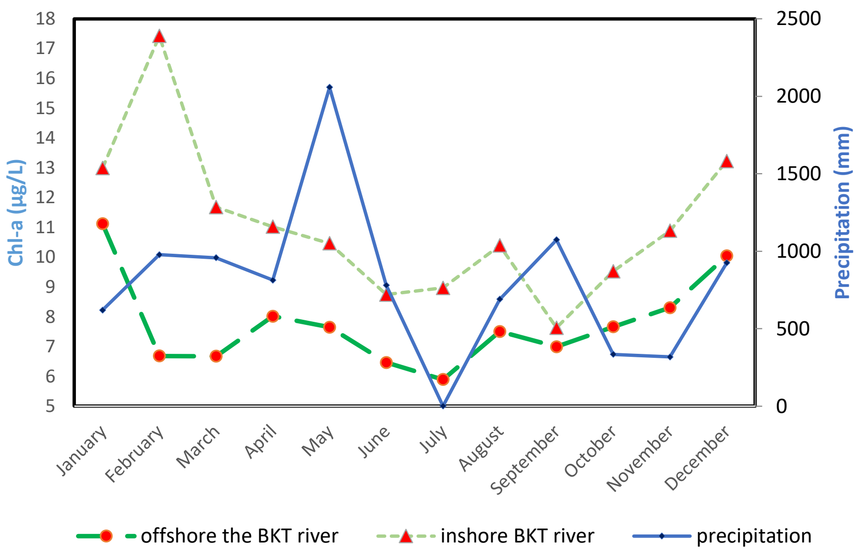

Figure 8. Same as Fig. 6 but for offshore Chl-a, inshore Chl-a and precipitation. The position of offshore and inshore areas is depicted in Fig. 2.

Figure 7 illustrates that, on the whole, the patterns exhibit similarity, except for February. The region adjacent to the estuary exhibits the highest amount in February, whereas the vicinity near the estuary demonstrates the lowest value. This variation is associated with the recorded monthly mean wind. The region adjacent to the estuary is characterized by a moderate degree of sediment input. The presence of sunlight reaching the depths of the water facilitates the flourishing of phytoplankton in these regions, as opposed to the adjacent coastal waters.

Seasonal dynamics of Chl-a

The island of Java is part of the maritime continent, so its climate is influenced by the Asian (Australian) monsoon which brings humid (dry) air, and causes the rainy season (Alifdini et al., 2021). The rainy season occurs from December to February, while the dry season is from June to August. From March to May and from September to November are known as the first and second transition seasons, respectively. Figure 8 depicts the temporal fluctuations of Chl-a levels in the BKT River. The images depicting the rainy season, first transition, dry season, and second transition are observed during the months of January and February, April and May, July and August, and October and November, respectively.

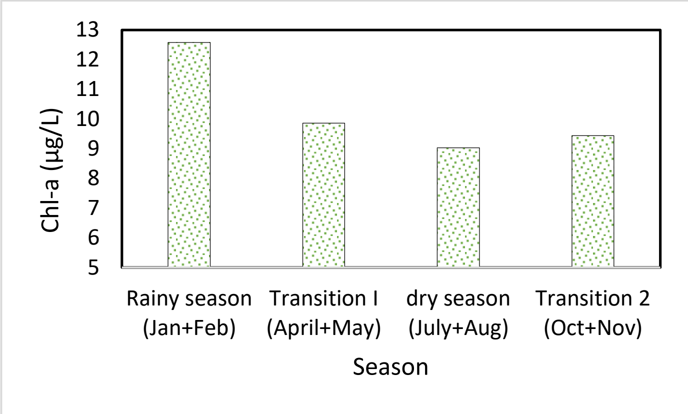

Figure 9. Seasonal variation of Chl-a in 2021 during the rainy season (January and February), first transition (April and May), dry season (July and August), and second transition (October and November).

According to the data presented in Figure 9, it is evident that the peak concentration of Chl-a is observed during the rainy season. During the rainy season, a notable elevation in the concentration of Chl-a, reaching up to 12 μg/L (approximately mg/m^3), was observed in the vicinity of the BKT river. However, this concentration then decreased in the subsequent season. In the second transition, the presence of Chl-a originating from the BKT Semarang River has resulted in a rise of 0.42 μg/L. According to the findings of Maslukah et al. (2021), the Chl-a concentrations in Semarang waters were observed to be higher during the rainy season (February) compared to the dry season (July), as indicated by the in situ (field measurement) data. Therefore, to examine potential factors contributing to the temporal fluctuations of Chl-a, we conducted a comparative analysis between Chl-a levels and various meteorological variables including precipitation, wind speed, average air temperature, and duration of solar irradiation. These data were obtained from a neighboring meteorological station located at Ahmad Yani airport in Semarang. The variation in Chl-a levels is influenced by terrestrial factors, particularly precipitation. Increased and prolonged precipitation can lead to higher runoff discharge in rivers, resulting in the transportation of additional nutrients from terrestrial areas. This influx of nutrients promotes the growth of phytoplankton (Maslukah et al., 2021). According to Hutasuhut et al. (2021), the velocity of wind can induce water currents that have the potential to initiate resuspension processes, leading to the liberation of nutrients from the sedimentary layer. Additional climatological factors, such as air temperature and duration of irradiation, play a role in influencing the variability of Chl-a in the BKT River. The findings pertaining to the relationships among climatological parameters are depicted in Figure 6 and summarized in Table 4.

The data presented in Table 2 demonstrates that air temperature and solar radiation have a negative correlation with Chl-a concentration. The findings of this study diverge from those presented by Aranha et al. (2021) in a tropical reservoir, wherein they observed a decline in Chl-a concentrations during periods of minimal solar radiation. According to a study conducted by Shabrina et al. (2018), the concentration of Chl-a in the northern waters of Central Java during the rainy season is influenced by the levels of sunlight and temperature. Nevertheless, the degree of correlation was not evaluated in this study.

It was observed that wind had a positive impact, although the correlation was not statistically significant ($p>0.05$). Wirasatriya et al. (2021) discovered a noteworthy pattern within the waters of South Sulawesi. In the northern region, it was observed that the wind exerted a significant impact on the rise of Chl-a concentrations. However, in the southern region, a distinct pattern emerged, wherein elevated levels of Chl-a were observed under conditions characterized by weakened wind speeds. This is related to sediment resuspension and influences the proliferation of phytoplankton. However, this analysis contains no field measurement data, which is a limitation. The responses of the optical properties captured by the imagery are substantially related to the water conditions, which may impact the analysis of the chlorophyll data captured by the imagery. In turbid regions, Maslukah et al. (2022) discovered that Chl-a concentrations in coastal waters derived from imagery data were underestimated.

Discussion

Prior research has indicated that the waters adjacent to the Banjir Kanal Timut (BKT) exhibit elevated levels of Chl-a concentrations (Maslukah et al., 2019; Maslukah et al., 2021), indicating a state of eutrophication in terms of trophic status. Moreover, the escalation of industrial activities and population density has led to a consequential impact on the quality of estuarine waters. This is primarily due to the substantial influx of nutrients from land, resulting in an adverse influence on the growth and development of phytoplankton. The estimation of phytoplankton biomass can be derived by assessing the concentration of Chl-a, a predominant green pigment within phytoplankton, as indicated by Munandar et al. (2023). The presence of a significant amount of Chl-a serves as an indicator that can be utilized to assess alterations in water quality (Ciancia et al., 2020; Shaik et al., 2021; Saberioon et al., 2020). Hence, the assessment of environmental degradation can be conducted by observing alterations in the concentration of Chl-a. Long-term field measurements are characterized by high costs, significant time requirements, and substantial financial investments (Ogashawara et al., 2021; Aranha et al., 2022). The application of remote sensing presents a viable approach for addressing this issue.

The BKT river estuary exhibits a relatively constrained spatial extent in comparison to the expansive waters of the open ocean. Utilizing high-resolution satellites is a more advantageous approach for monitoring the variability of Chl-a. Hence, the focus of this research lies in the utilization of the Sentinel-2 MSI, renowned for its frequent revisits and possession of a red edge spectral band at a wavelength of 705 nm. According to Warren et al. (2019), this particular sensor demonstrates suitability to monitor water quality in both coastal and inland waters. The reflectance values utilized in this study were obtained from the BOA, which had undergone calibration using the Sen2Core. The algorithm used in this study, we developed the empirical method as in the previous study by combining four bands with a resolution of 10 metres (equation 5). Each of these bands is multiplied by the ratio of the Near-Infrared (NIR) band (Rrs 705). Warren et al. (2019) conducted a study in which they examined three separate spectral ratios: Rrs444/Rrs560, Rrs490/Rrs560, and Rrs704/Rrs665. However, their findings did not yield satisfactory results for both marine and inland areas.

The algorithm developed through the empirical model in this study (equation 5) was then validated to the observed Chl-a concentration, as illustrated in Figure 4. The bias was achieved in this study at -0.63 mg/m^3, indicating a slight underestimation of the Chl-a estimate compared to the observed Chl-a level. The study conducted by Moutzouris-Sidiris and Topouzelis (2021) investigated the application of different algorithms in case 1 and 2 waters within the Mediterranean Sea. The findings revealed the presence of diverse bias values, both positive and negative. In a study conducted by Maslukah et al. (2022), Sentinel-3 imagery was utilized to assess the Chl-a concentration in the western coastal waters of Semarang Bay. The researchers found that the Chl-a concentration derived from the imagery exhibited a significant disparity compared to the observation data. Specifically, the imagery displayed a bias value of 3.43, indicating a consistent overestimation of Chl-a levels. The observed range of Chl-a concentration in the imagery spanned from 0.70 to 9.07 mg/m^3. Nevertheless, the RMSE about the estimated Chl-a concentration is recorded as 2.47 mg/m^3, while the MAPE stands at 23.52%. This finding suggests that the algorithm used to estimate the Chl-a levels from the BKT River is still yielding relatively accurate results. The algorithm under consideration exhibits superior performance compared to the algorithm proposed by Aranha et al. (2021), as the latter demonstrated a relative mean error of 28%. In contrast to the findings of Maslukah et al. (2022), which reported a significantly lower percentage of relative error at 1.19%. The study conducted by Maslukah et al. (2022) exhibits several limitations. Firstly, the sample size is relatively small, consisting of only nine participants. Consequently, this limited sample may introduce potential biases in the findings. Additionally, the resulting bias in the study, measured at 3.5 mg/m^3, is relatively high.

Based on Figure 4, the MAPE value generated in this study has a high error. This can illustrate that the use of three of the visible and NIR bands (B8) at 10m resolution, cannot be used as an accurate estimation of Chl-a. Further development of algorithms related to the mixture of all bands both visible and NIR and the use of band ratio is recommended, as has been performed by Saberioon et al. (2020) with a combination of all bands, Shaik et al. (2021) with visible and NIR bands, Katlane et al. (2020) with single band (red), and Bramich et al. (2021) with a single band (NIR) and a combination of green and SWIR (Ouma et al., 2020).

The algorithm obtained is subsequently utilized to estimate the temporal and spatial variations. The present study demonstrates that temporal fluctuations exhibit a discernible seasonal pattern, wherein alterations in precipitation levels lead to subsequent modifications in river discharge. The westerly monsoon prevailing in Indonesia induces elevated wind velocities, thereby influencing the process of sediment resuspension. River discharge and resuspension are two mechanisms that have the potential to impact nutrient inputs into the water column, consequently influencing the growth of phytoplankton. The biomass of phytoplankton can be assessed by measuring Chl-a concentrations.

The determination of water's trophic status can be achieved by assessing the concentration of Chl-a. According to Hakanson and Bryann (2008), oligotrophy is characterized by Chl-a concentrations below 2 mg/m^3 in aquatic environments. Mesotrophic conditions are indicated by Chl-a concentrations ranging from 2 to 6 mg/m^3, while eutrophic conditions are associated with concentrations between 6 and 20 mg/m^3. Hypertrophic conditions, on the other hand, are defined by Chl-a concentrations exceeding 20 mg/m^3. According to the classification utilized, the coastal waters of BKT fall within the eutrophic classification. According to the findings of Maslukah et al. (2021), the trophic conditions of the Semarang coastal waters, which encompass the BKB and BKT estuaries, were determined based on field observations of Chl-a concentration data and chlorophyll analysis from images. Based on empirical data, coastal waters can be classified as eutrophic or mesotrophic based on the levels of Chl-a derived from satellite imagery. However, the findings of this study indicate that both samples exhibited eutrophic conditions. The issue at hand is closely tied to the limited spatial resolution of MODIS, which must not be conflated with observational data obtained from a localized region. According to the findings of Maslukah et al. (2019), the study elucidated that the concentration of Chl-a in the vicinity of the BKT estuary exhibits significant fluctuations within a range of approximately ± 500m, with variations in concentration ranging from 1 to 10 mg/m^3. The MODIS image data is acquired by sampling each pixel at a spatial resolution of 4 x 4 km.

Conclusion

In this study, the seasonal spatial and temporal distribution of near-surface chl-a concentrations in Semarang coastal waters in 2020 is described using visible and NIR band reflectance data from Sentinel-2 imagery. This study includes the use of a new empirical model based on Sentinel-2 observed in 2020 and taken from Semarang coastal waters specifically (BKT river front). In addition, the relationship between Chl-a concentration and climatological factors such as rainfall, length of sunshine wind and tidal conditions was studied. Therefore, we tuned the algorithm based on the blue, green, red, and Nir bands and derived the empirical method as follows: $\mathbf{Chl\text{-}a = 10^{(2.743 - 0.725(logB2*c) - 0.625(logB3*c) + 1.623(logB3) + 0.809(logB8*c))}}$ where c=0.036/B8. The accuracy of the empirical method can be reflected in the values of RMSE, MAPE, and bias of 2.44 µg/L, 23.52%, and -0.63 µg/L, respectively. The study revealed that there was a greater degree of spatial variation in Chl-a concentrations towards the mouth of the river compared to the offshore region. This study reveals that the temporal fluctuations in the area of the outer estuary are primarily driven by variations in wind speed rather than precipitation-related factors. The other climatological factors that exerted a significant influence were the air temperature and the duration of solar radiation (SS), exhibiting a negative correlation.

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Conflict of Interest: The authors declare no conflict of interest

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The assessment of chlorophyll-a retrieval algorithm and its spatial-temporal distribution using sentinel-2 MSI off the Banjir Kanal Timur River, Semarang, Indonesia

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ABSTRACT

In aquatic ecology, Chlorophyll-a (Chl-a) plays a pivotal role in biogeochemical cycles, as well as a key indicator for the trophic state in the environment. Coastal area of Semarang is known as eutrophic waters. Thus continuous monitoring of Chl-a will be beneficial for the management of the impact of the trophic dynamic in the coastal waters of Semarang. Taking the benefit of the continuous monitoring of satellite measurement, the present study provides the assessment of Chl-a off the Banjir Kanal Timur (BKT) River, Semarang, using the proper remote sensing approach. In this study, algorithms were generated according to bands sensitive to Chl-a scattering properties, using multiple regression between in-situ Chl-a and Bottom of Atmospheric (BoA) reflectance from Sentinel-2 with 10 m resolution. A total of 43 water samples were collected to build the algorithm and 43 of the water samples were used for validation during the passing time of Sentinel-2 at the equator i.e., on 21 August 2021 at 9.00–11.00 local time. The results show that the performance of the algorithm generated in this study has high accuracy as denoted by the low RMSE, and MAPE, respectively. For the seasonal variation, the highest (lowest) concentration of Chl-a is observed in December (September), with values reaching 11.92 μg/L (7.06 μg/L). The seasonal fluctuation of Chl-a depends on air temperature and sunshine duration. High (low) air temperature and long (short) duration of solar exposure result in increased (decreased) Chl-a off the BKT River. Conversely, the elevated wind velocity only impacts the rise of Chl-a in the region far from the river estuary, which is associated with the mixing process. BKT waters are categorized as eutrophic conditions, with a concentration exceeding 6 μg/L. These algorithms can provide valuable insights into the health and productivity of coastal ecosystems, aiding in their monitoring and management.

1. Introduction

Phytoplankton holds significant ecological importance within the marine ecosystem owing to its capacity for photosynthesis, a metabolic process that facilitates the synthesis of organic compounds utilizing light energy and carbon dioxide (Rost et al., 2008; Abbas et al., 2019; Aranha et al., 2022). Phytoplankton possesses chlorophyll-a (Chl-a) within its cellular structure and plays a crucial role in ecological systems, serving as a fundamental component of the aquatic life cycle and serving as the primary source of energy within oceanic food webs. Chl-a is a crucial factor in assessing water quality due to its regulatory role in biological processes occurring within coastal waters (Ogashawara et al., 2021; Tran et al., 2023).

The determination of Chl-a distribution within a given area is typically achieved through the implementation of field sampling techniques, which are subsequently complemented by laboratory-based analyses (Abbas et al., 2019; Maslukah et al., 2019). Nevertheless, this approach proves to be ineffective and inefficient due to its prolonged duration, elevated expenses, and restricted geographical reach (Duan et al., 2010; Ogashawara et al., 2021; Aranha et al., 2022). To address these concerns, several remote sensing techniques have been devised to monitor Chl-a (Ouma et al., 2020;). Remote sensing methods show promise for monitoring Chl-a levels in a given area due to their extensive coverage and ability to provide periodic observations (Maslukah et al., 2019; Ouma et al., 2020). The utilization of ocean color data within the visible and near-infrared (VNIR) wavelength bands facilitates the

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estimation of Chl-a levels (Ouma et al. 2020). The acquisition of Chl-a data from these satellites necessitates the utilization of an algorithm that is heavily reliant on the band and spectral resolution capabilities offered by the satellite (Ogashawara et al., 2021).

The quantification of Chl-a in reservoirs and lakes has been extensively studied, and multiple algorithms have been devised for this purpose. These algorithms encompass different approaches, such as utilizing two bands (red and near-infrared) as demonstrated by O'Reilly et al. (1998) and Tran et al. (2023), as well as employing a single band, as explored by Bramich et al. (2020). The phenomenon above is similarly observed in marine regions, where algorithms are employed to calculate the ratio between blue and green color bands (Tilstone et al., 2021; Tran et al., 2023). In the expanse of open ocean waters, the presence of colored dissolved organic matter (CDOM) and suspended particulate matter is limited to relatively small quantities (Nelson and Siegel, 2002). Additionally, the concentration of Chl-a in these waters is comparatively lower than that observed in coastal regions. Estuarine regions, characterized by terrestrial influence, exhibit heightened optical complexity as a result of the absorption caused by CDOM and non-algal particles (Ouma et al., 2020; Tran et al., 2023). The optical properties of water are significantly influenced by the presence of turbid coastal waters characterized by high concentrations of CDOM and suspended non-phytoplanktonic particles (Lewis & Arrigo, 2020). Those mentioned above intricate aquatic conditions diminish the efficacy of the band ratio algorithm in estimating Chl-a concentration. This is because the signal of the blue band declines below the detection threshold as a result of substantial absorption by phytoplankton (Soja-Wozniak et al., 2020).

The utilization of ocean color remote sensing in turbid regions (case 2) presents significant challenges due to the unique characteristics exhibited by each coastal area. Hence, an algorithm formulated for a specific domain may lack generalizability to other domains. The Sentinel-2 satellite has a superior spatial resolution of 10 m for the visible NIR band (Ouma et al., 2020), making it particularly useful for monitoring and evaluating Chl-a levels in complex coastal waters (Gohin et al., 2020).

The Banjir Kanal Timur (BKT) River is one of Semarang's flood control systems located in the eastern part of the city (Fig. 1). This river has a length of ± 14.50 km. The BKT River is the unification of several rivers and canals such as the Penggaron River through the Pucang Gading outlet, Kedung Mundu River drainage outlet, Candi River, Bajak River, Kartini pump drainage and large rice field / Sambirejo pump drainage and empties into the Java Sea. The upstream flow have a major influence on the input of organic and non-organic materials from soil erosion and solid and liquid waste, which can affect water quality. During the rainy season, sediment from land enters the marine waters at a higher rate and causes the estuary to become more turbid. The results of research by Utama et al. (2021) explained that the suspended solids in front of the BKT estuary reached 290 mg/L in the rainy season and 60 mg/L in the dry season (Hutasuhut et al., 2022). Apart from high turbidity, the front of the river mouth is also a eutrophic area with an average range of chlorophyll-a of 12.67 μg/L in the dry season (Maslukah et al., 2019) and 18.06 μg/L in the wet season (Maslukah et al., 2020). Based on the classification of Hakanson & Bryan (2008), BKT waters are in eutrophic conditions. Thus, temporal and continuous monitoring of Chl-a is required to manage the impact of the trophic dynamic in the coastal waters of Semarang.

The previous monitoring of Chl-a using Sentinel-2 in front of the BKT Semarang estuary was conducted by Subiyanto et al. (2018) following the algorithm used by Nuriya et al. (2016) in the Madura Strait. In the algorithm, the development band is the ratio of the red and NIR (Near Infra Red) bands to the green band. However, this research is still questionable because it is without validation of field data. The use of the NIR band for coastal waters reduces the absorption of colored dissolved organic matter (Gilerson et al., 2010). It was further explained by Yoon et al. (2019) that the empirical algorithm of blue and green bands is more suitable for oligotrophic and mesotrophic coastal waters. Given the absence of a Chl-a estimation algorithm for Sentinel-2, which

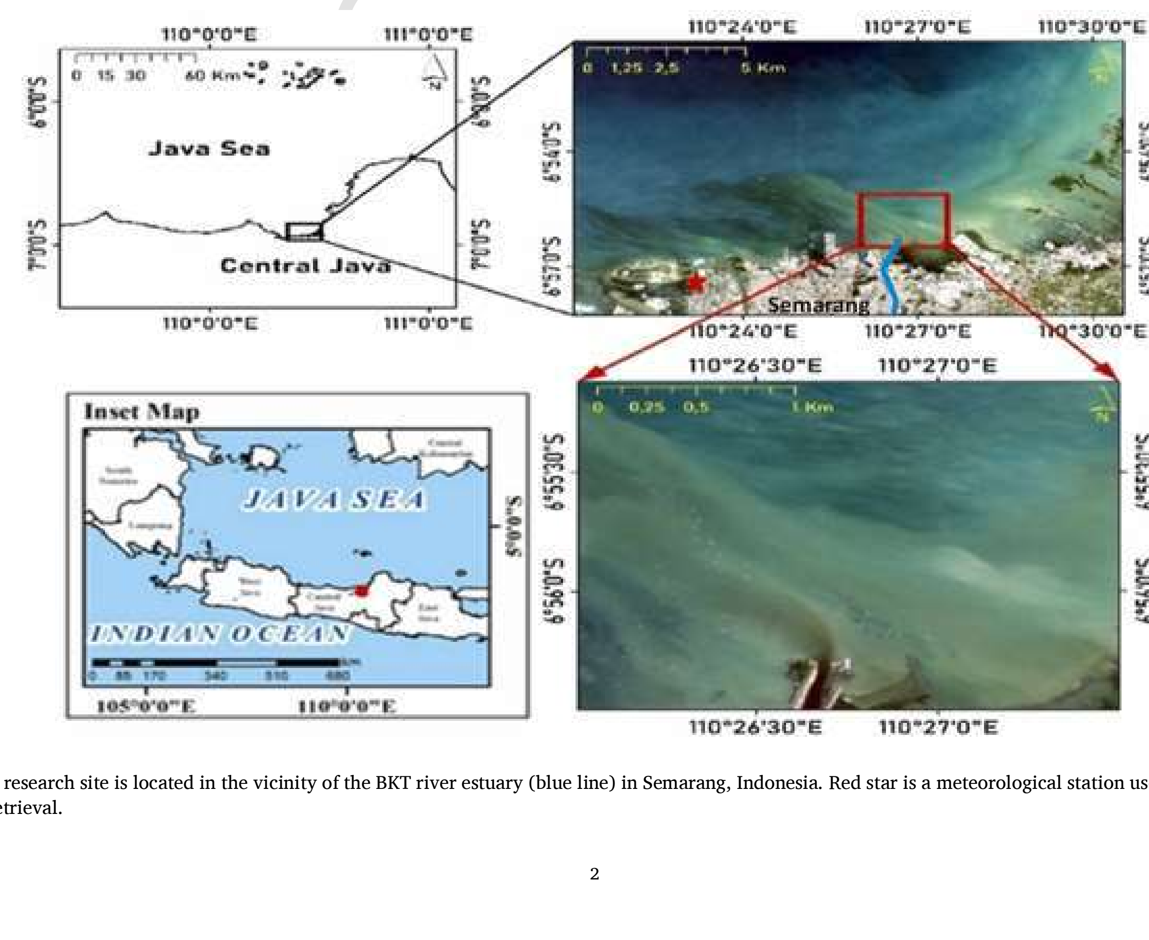

Fig. 1. The research site is located in the vicinity of the BKT river estuary (blue line) in Semarang, Indonesia. Red star is a meteorological station used for precipitation data retrieval.

characterizes the foreshore waters of the BKT river and accommodates the existence of previous studies regarding the bands, this study aims to develop an algorithm for estimating Chl-a levels in Sentinel-2 imagery.

This study examined the response of each spectral band with 10 m spatial resolution to field Chl-a concentrations. In addition, statistical analyses and validation techniques were performed to determine the reliability of the algorithm in estimating chlorophyll-a concentrations, which have never been previously investigated. The resulting algorithm was further utilized on other images to capture the spatial-temporal fluctuations of Chl-a around the BKT River. This study is the first investigation into the seasonal fluctuations of Chl-a levels in the BKT River, using the self-built Sentinel-2 algorithm. It is expected that this algorithm can estimate Chl-a concentrations in other eutrophic and shallow waters.

2. Data and methods

2.1. Satellite data

The satellite data employed in this study consisted of the Sentinel-2 image, which encompassed the coastal region of Semarang City. The Sentinel-2 image has undergone geometric and radiometric corrections, resulting in reflectance values derived from the Bottom of the Atmosphere (BOA). This image is equipped with twelve multi-spectral bands, spanning a range of wavelengths from 443 nm to 22,202 nm (Gatti & Bertolini, 2015). In the present investigation, a novel approach was devised to assess Chl-a concentration. This approach integrates elements from the methodology proposed by Moutzouris-Sidiris and Topouzelis (2021), which employs the blue to green band ratio, as well as the green and red band ratio introduced by Ha et al. (2017). Additionally, insights from Chen et al. (2017) regarding the NIR band and Aranha et al. (2021) concerning the visible band were incorporated into the combined method. This research investigates the application of visible (blue, green, red)-NIR bands, with a spatial resolution of 10 m, for the analysis of Chl-a levels in the BKT River. An analysis was conducted to establish a Chl-a algorithm for the region adjacent to the BKT River by comparing the visible and NIR bands with in-situ Chl-a measurements. Therefore, in order to derive the seasonal fluctuations of Chl-a, our algorithm was implemented on Sentinel-2 images that accurately represent each month of the year 2020.

2.2. Meteorological data

The meteorological data regarding daily rainfall and wind speed were collected from the Achmad Yani International Airport's Meteorological Station (red star at Fig. 1). The data collected on a daily basis were subsequently aggregated to form monthly averages. The data can be accessed through the official website of the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) at https://dataonline.bmkg.go.id/home.

2.3. Sample collection and analysis

A total of 100 field samples were collected. The sampling procedure took place on August 21, 2021, between the hours of 08:00 and 11:00 a.m., aligning with the specific date and time of the Sentinel-2 data acquisition over Semarang City (refer to Fig. 3). It is worth mentioning that the sampling area under consideration exhibited characteristics of eastern monsoon conditions. Analysis of meteorological data revealed that the recorded wind speed ranged from 2.19 to 2.40 m per second.

Water samples of 500 mL were collected from the near surface, with a depth range of ±30 cm. The spectrometric method was employed to conduct the chlorophyll analysis, utilizing three wavelengths (trichromatic). The suspension was extracted using a solvent consisting of 90 % acetone. The filtration process employed filter paper made from cellulose nitrate with a pore size of 0.45 μm, specifically sourced from Millipore Merck. The Chl-a concentration in water samples was determined using the calculation formula prescribed by the American Public Health Association (APHA) method, as described in the studies conducted by Maslukah et al. (2019) and Maslukah et al. (2021).

In order to refine the Chl-a algorithm, a dataset was generated comprising of match-up data. This dataset included in-situ Chl-a measurements as the ground truth, along with corresponding satellite observations obtained from collocated locations. In order to ensure the representation of the sampling distribution, the match-up positions for algorithm tuning and validation were evenly distributed across the study area. Out of the total 100 match-ups, we allocated 50 for the purpose of tuning and the remaining 50 for validation. In both subsets, the exclusion of outlier data was implemented. The figure provided, Fig. 2, displays the positions of the stations used for tuning and validation purposes. The initial analysis involved evaluating the correlation (r) between the overall concentration data and the visible-NIR band's Rrs. Subsequently, a total of 43 match-ups were employed to develop the Chl-a algorithm for Sentinel-2A, while an additional 43 match-ups were utilized for the purpose of validation. Table 1 displays the statistical data pertaining to in-situ Chl-a for the purposes of algorithm tuning and validation.

2.4. The algorithm assessment

The accuracy test of the algorithms developed in this research is based on three statistical techniques, namely the coefficient of determination (R^2) as reported by Shaik et al. (2021) and Moutzouris-Sidiris and Topouzelis et al. (2021), the root mean square error (RMSE), the mean absolute percentage error (MAPE), and the bias, as discussed by Watanabe et al. (2018) and Ciancia et al. (2020). The mathematical equations employed for the evaluation of algorithms are derived from formulas 1, 2, 3, and 4, correspondingly.

$$R^2 = \left| \frac{N \quad x \quad \sum_{i=1}^{N} (Chl\, a_i, meas) \quad x\, Chl\, a_{i,retr}) - \sum_{i=1}^{N}}{\sqrt{\left[N \quad x \sum_{i=1}^{N} (Chl\, a_i, meas)^2 - (\sum_{i=1}^{N} \left(Chl\, a_{i,} meas\right)^2 \quad \right] \quad [N}} \right.$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} \left(Chla_i, meas - Chla_{i,retr}\right)^2}{N}} \tag{2}$$

$$\text{MAPE} = \frac{100\%}{N} \quad x \quad \sum_{i=1}^{N} \frac{\left| \left(Chla_i, meas - Chla_{i,retr}\right) \right|}{Chla_{i,meas}} \tag{3}$$

$$\text{BIAS} = \frac{1}{N} \quad x \quad \sum_{i=1}^{N} \left(Chla_{i,retr} - Chla_{i,meas}\right) \tag{4}$$

where $Chla_i,meas$ and $Chla_i,retr$ refer to the measured (in-situ) and retrieved (estimated) Chl-a respectively; and N is the total number of samples.

3. Results

3.1. Generating Chl-a algorithm

In order to generate the Chl-a algorithm, the initial step involves assessing the correlation between the visible-NIR (blue/B2, green/B3, red/B4, and NIR/B8) spectral bands and Chl-a observations. The resulting coefficients obtained are 0.69, 0.69, 0.65, and 0.65, respectively (as shown in Fig. 3). Fig. 3 demonstrates that all Rrs exhibit significant correlations with the observed Chl-a levels. To develop the new algorithm, we utilized Rrs NIR, red, green, and blue wavelengths to estimate the concentration of Chl-a in the BKT offshore region. According to Aranha et al. (2022), bodies of water characterized by a prevalence of phyto-

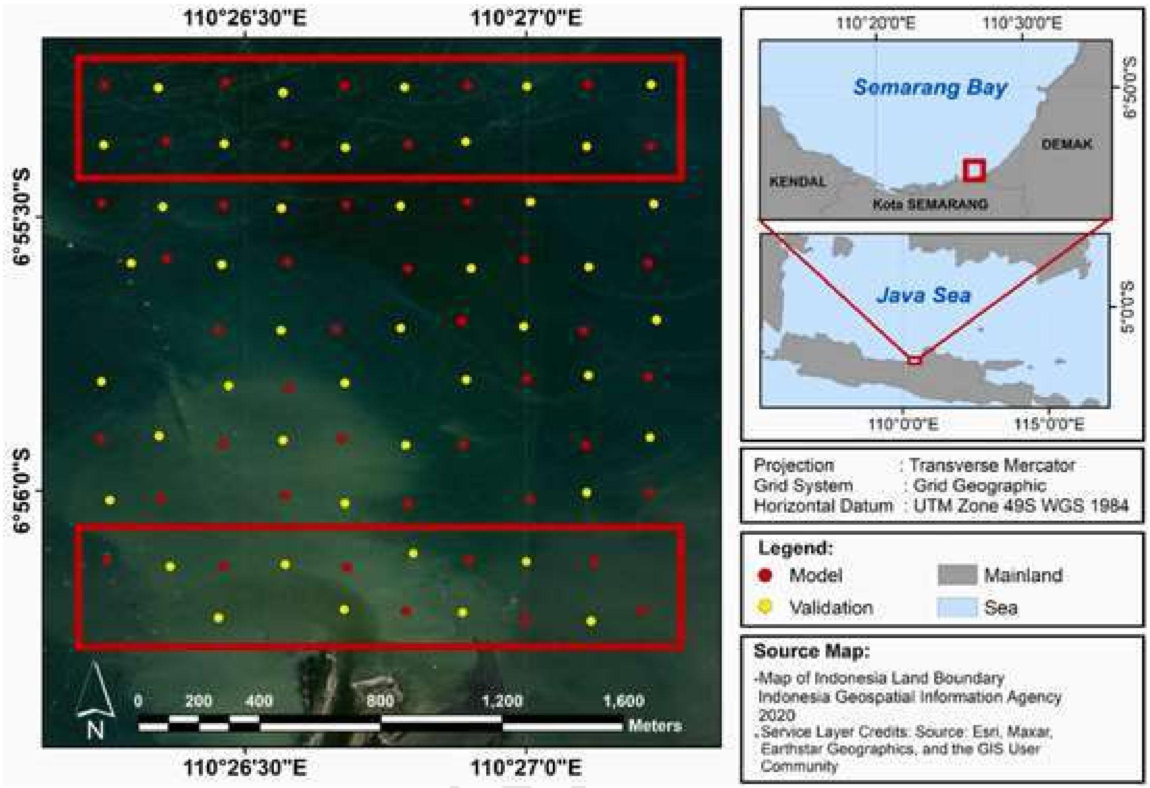

Fig. 2. Location of sampling for match-up model (●) dan validation (●). The red rectangle (□) denotes (inshore and offshore) the regions in closest proximity to and furthest distance from the river's mouth.

Table 1
Statistics on in situ Chl-a used for algorithm tuning and validation.

Data	n	average (μg/L)	Min (μg/L)	Max (μg/L)	St. Dev (μg/L)
Tunning	43	9.49	2.15	17.27	3.47
Validation	43	8.75	3.5	14.52	2.90

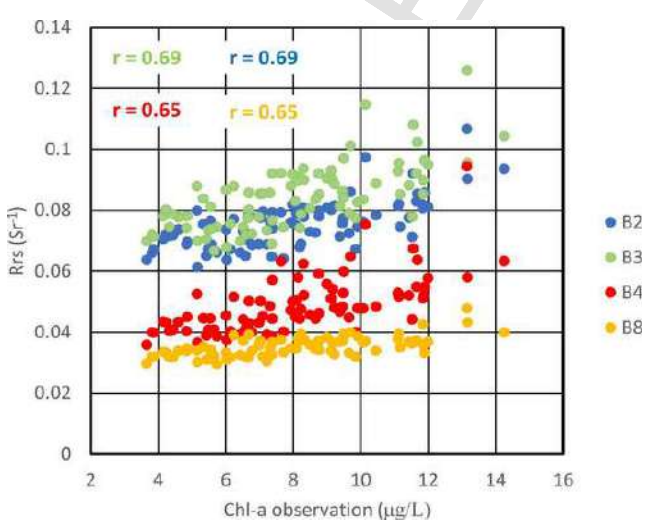

Fig. 3. Scatter plot of observed Chl-a versus remote sensing reflectance of the visible-NIR.

plankton exhibit two distinct peaks of absorption in the electromagnetic spectrum. Specifically, one peak is observed in the blue region at approximately 440 nm, while the other peak is located in the red region at around 670 nm. The green band, characterized by a wavelength range of 560 nm, exhibits a high reflectance of Chl-a owing to its low absorption coefficient. Furthermore, the existence of phytoplankton is distinguished by its maximum reflection at 700 nm, specifically within the near-infrared spectrum (Matthews et al., 2012). Given the intricate nature of the region under investigation, the study incorporated an examination of the utilization of four bands on Sentinel-2 satellites, each possessing an equivalent spatial resolution of 10 m.

A model was constructed employing multiple regression analysis to derive estimations of Chl-a levels in the BKT River. The calculated coefficient of determination (R^2) is 0.45, The statistical significance of this relationship is supported by a p-value of less than 0.05. The empirical model produced between the observation and reflectance data is as follows Eq. 5.(Fig. 4)

$$Chl - a = 10^{(2.743-0.725*(log(B2*c))-0.625*(log(B3*c))+1.623*(log(B4*c))+0.809*(log(B8*}$$

Where c: 0.036/B8; B2; B3; B4; B8 (reflectant blue, green, red and NIR).

The performance of the algorithm model in Eq. 5 was then tested statistically, which resulted in RMSE, Bias and MAPE values of 2.47 μg/L, −0.63, and 23.52, respectively (Fig. 5). The negative bias indicates that estimated Chl-a underestimates the observed Chl-a. Since the RMSE and MAPE are quite small, the Chl-a off the BKT River estimated from the obtained algorithm has a good accuracy. Thus, Eq. (5) can be used to estimate TSS off the BKT River.

Hence, the Eq. (5) can be employed for the estimation of Chl-a levels off BKT River. Figs. 5 and 6 depict the spatial and temporal distribution, respectively.

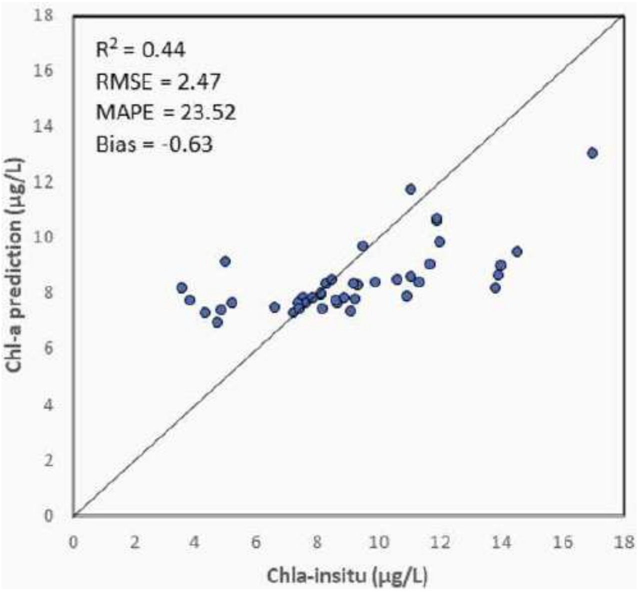

Fig. 4. Validation of Chl-a from Eq. (5) with observed Chl-a (observation).

The highest concentration was observed in December, reaching a value of 11.92 µg/L, while the lowest concentration was recorded in September, with Chl-a concentration of 7.06 µg/L. The observed pattern in this study diverges from the findings of Wirasatriya et al. (2019), who utilized MODIS imagery to examine the area adjacent to the northern coast of Java. Wirasatriya et al. (2019) reported that the pattern reached its maximum in June and January. It is important to note that the previous study analyzed data over a longer time span of 10 years, encompassed a significantly larger regional area, and employed a lower image resolution of 4 km. Shabrina et al. (2018) also demonstrated distinct variations in seasonal dynamics during the summer period (March-August 2015 and 2016), with the highest concentration of Chl-a observed in June. The finding suggests that the temporal patterns of each region exhibit distinct variations.

High Total Suspended Solids (TSS) concentrations in estuaries cause disturbances in the photosynthesis process, which results in low phytoplankton biomass. The results of Wirasatriya et al. (2023) explained that the river is the main contributor of TSS and wind affects its distribution pattern, which will influence the temporal dynamics of Chl-a. To investigate this, in this study, we divided two areas, near and off the river, which are given a red box in Fig. 1, and the time series are shown in Fig. 7 & Fig. 8 and the correlation results are shown in Table 2.

Fig. 7 illustrates that, on the whole, the patterns exhibit similarity, except for February. The region adjacent to the estuary exhibits the highest amount in February, whereas the vicinity near the estuary demonstrates the lowest value. This variation is associated with the recorded monthly mean wind. The region adjacent to the estuary is characterized by a moderate degree of sediment input. The presence of sunlight reaching the depths of the water facilitates the flourishing of phytoplankton in these regions, as opposed to the adjacent coastal waters.

3.2. Seasonal dynamics of Chl-a

The island of Java is part of the maritime continent, so its climate is influenced by the Asian (Australian) monsoon which brings humid (dry) air, and causes the rainy season (Alifdini et al., 2021). The rainy season occurs from December to February, while the dry season is from June to August. From March to May and from September to November are known as the first and second transition seasons, respectively. Fig. 8 depicts the temporal fluctuations of Chl-a levels in the BKT River. The images depicting the rainy season, first transition, dry season, and second transition are observed during the months of January and February, April and May, July and August, and October and November, respectively.

According to the data presented in Fig. 9, it is evident that the peak concentration of Chl-a is observed during the rainy season. During the rainy season, a notable elevation in the concentration of Chl-a, reaching up to 12 µg/L (approximately mg/m^3), was observed in the vicinity of the BKT river. However, this concentration then decreased in the subsequent season. In the second transition, the presence of Chl-a originating from the BKT Semarang River has resulted in a rise of 0.42 µg/L. According to the findings of Maslukah et al. (2021), the Chl-a concentrations in Semarang waters were observed to be higher during the rainy season (February) compared to the dry season (July), as indicated by the in situ (field measurement) data. Therefore, to examine potential factors contributing to the temporal fluctuations of Chl-a, we conducted a comparative analysis between Chl-a levels and various meteorological variables including precipitation, wind speed, average air temperature, and duration of solar irradiation. These data were obtained from a neighboring meteorological station located at Ahmad Yani airport in Semarang. The variation in Chl-a levels is influenced by terrestrial factors, particularly precipitation. Increased and prolonged precipitation can lead to higher runoff discharge in rivers, resulting in the transportation of additional nutrients from terrestrial areas. This influx of nutrients promotes the growth of phytoplankton (Maslukah et al., 2021). According to Hutasuhut et al. (2021), the velocity of wind can induce water currents that have the potential to initiate resuspension processes, leading to the liberation of nutrients from the sedimentary layer. Additional climatological factors, such as air temperature and duration of irradiation, play a role in influencing the variability of Chl-a in the BKT River. The findings pertaining to the relationships among climatological parameters are depicted in Fig. 6 and summarized in Table 2.

The data presented in Table 2 demonstrates that air temperature and solar radiation have a negative correlation with Chl-a concentration. The findings of this study diverge from those presented by Aranha et al. (2021) in a tropical reservoir, wherein they observed a decline in Chl-a concentrations during periods of minimal solar radiation. According to a study conducted by Shabrina et al. (2018), the concentration of Chl-a in the northern waters of Central Java during the rainy season is influenced by the levels of sunlight and temperature. Nevertheless, the degree of correlation was not evaluated in this study.

It was observed that wind had a positive impact, although the correlation was not statistically significant ($p > 0.05$). Wirasatriya et al. (2021) discovered a noteworthy pattern within the waters of South Sulawesi. In the northern region, it was observed that the wind exerted a significant impact on the rise of Chl-a concentrations. However, in the southern region, a distinct pattern emerged, wherein elevated levels of Chl-a were observed under conditions characterized by weakened wind speeds. This is related to sediment resuspension and influences the proliferation of phytoplankton. However, this analysis contains no field measurement data, which is a limitation. The responses of the optical properties captured by the imagery are substantially related to the water conditions, which may impact the analysis of the chlorophyll data captured by the imagery. In turbid regions, Maslukah et al. (2022) discovered that Chl-a concentrations in coastal waters derived from imagery data were underestimated.

4. Discussion

Prior research has indicated that the waters adjacent to the Banjir Kanal Timut (BKT) exhibit elevated levels of Chl-a concentrations (Maslukah et al., 2019; Maslukah et al., 2021), indicating a state of eutrophication in terms of trophic status. Moreover, the escalation of industrial activities and population density has led to a consequential im-

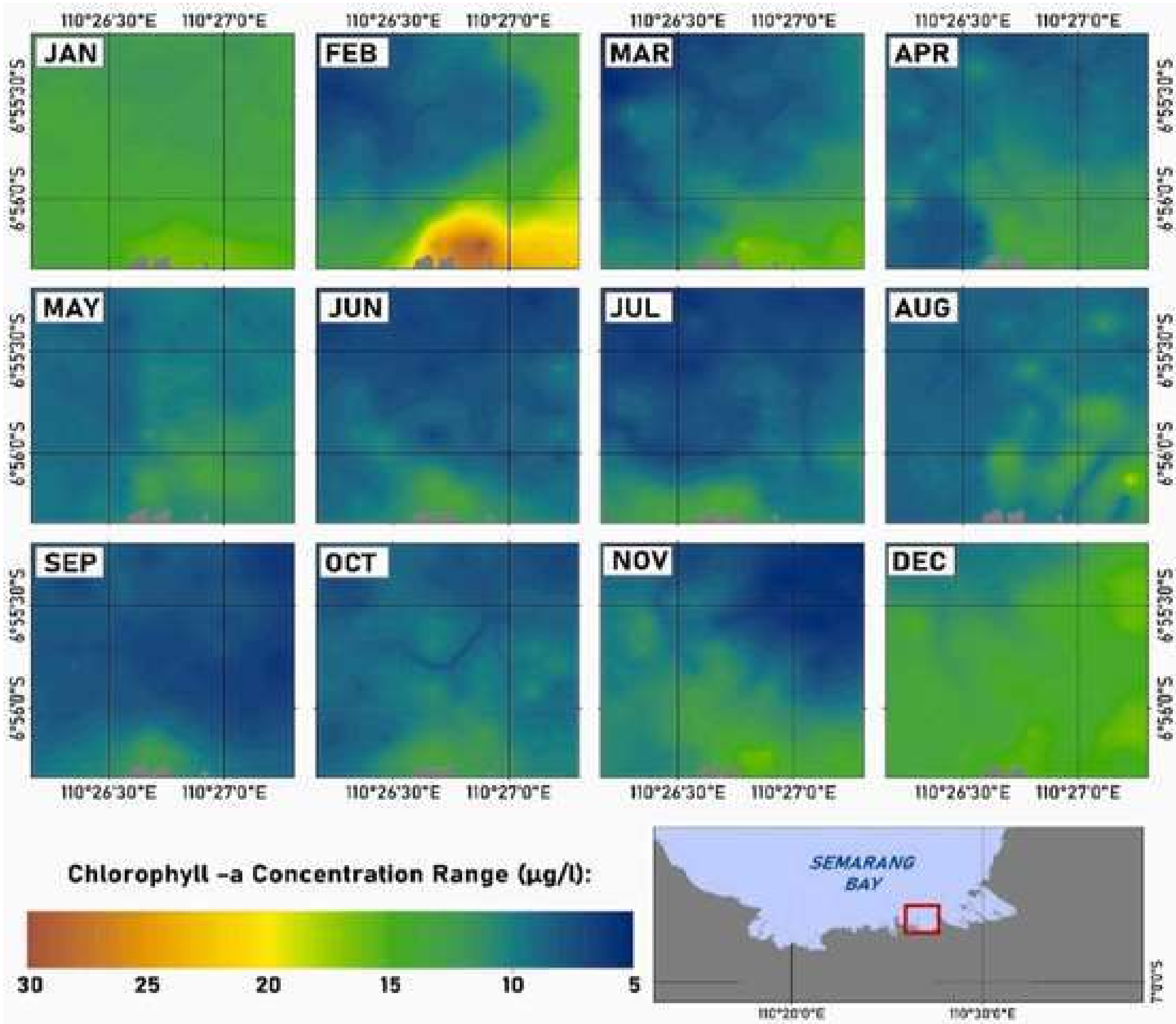

Fig. 5. Distribution of Chl-a (a) 3 January 2021 (b) 27 February 2021 (c) 14 March (d) 23 April 2021 (e) 13 May 2021 (f). June 22, 2021 (g). 27 July 2021 (h) 21 August 2021 (I) 10 September 2021 (j) 10 October 2021 (k). November 4, 2021 (l). December 14, 2021 estimated from Sentinel-2 imagery using Eq. (5). The BKT Semarang estuary, depicted with a red box.

pact on the quality of estuarine waters. This is primarily due to the substantial influx of nutrients from land, resulting in an adverse influence on the growth and development of phytoplankton. The estimation of phytoplankton biomass can be derived by assessing the concentration of Chl-a, a predominant green pigment within phytoplankton, as indicated by Munandar et al. (2023). The presence of a significant amount of Chl-a serves as an indicator that can be utilized to assess alterations in water quality (Ciancia et al., 2020; Shaik et al., 2021; Saberioon et al., 2020). Hence, the assessment of environmental degradation can be conducted by observing alterations in the concentration of Chl-a. Long-term field measurements are characterized by high costs, significant time requirements, and substantial financial investments (Ogashawara et al., 2021; Aranha et al., 2022). The application of remote sensing presents a viable approach for addressing this issue.

The BKT river estuary exhibits a relatively constrained spatial extent in comparison to the expansive waters of the open ocean. Utilizing high-resolution satellites is a more advantageous approach for monitoring the variability of Chl-a. Hence, the focus of this research lies in the utilization of the Sentinel-2 MSI, renowned for its frequent revisits and possession of a red edge spectral band at a wavelength of 705 nm. According to Warren et al. (2019), this particular sensor demonstrates suitability to monitor water quality in both coastal and inland waters. The reflectance values utilized in this study were obtained from the BOA, which had undergone calibration using the Sen2Core. The algorithm used in this study, we developed the empirical method as in the previous study by combining four bands with a resolution of 10 m (Eq. 5). Each of these bands is multiplied by the ratio of the Near-Infrared (NIR) band (Rrs 705). Warren et al. (2019) conducted a study in which they examined three separate spectral ratios: Rrs444/Rrs560, Rrs490/Rrs560, and Rrs704/Rrs665. However, their findings did not yield satisfactory results for both marine and inland areas.

The algorithm developed through the empirical model in this study (Eq. 5) was then validated to the observed Chl-a concentration, as illustrated in Fig. 4. The bias was achieved in this study at -0.63 mg/m^3, indicating a slight underestimation of the Chl-a estimate compared to the observed Chl-a level. The study conducted by Moutzouris-Sidiris and Topouzelis (2021) investigated the application of different algorithms in case 1 and 2 waters within the Mediterranean Sea. The findings re-

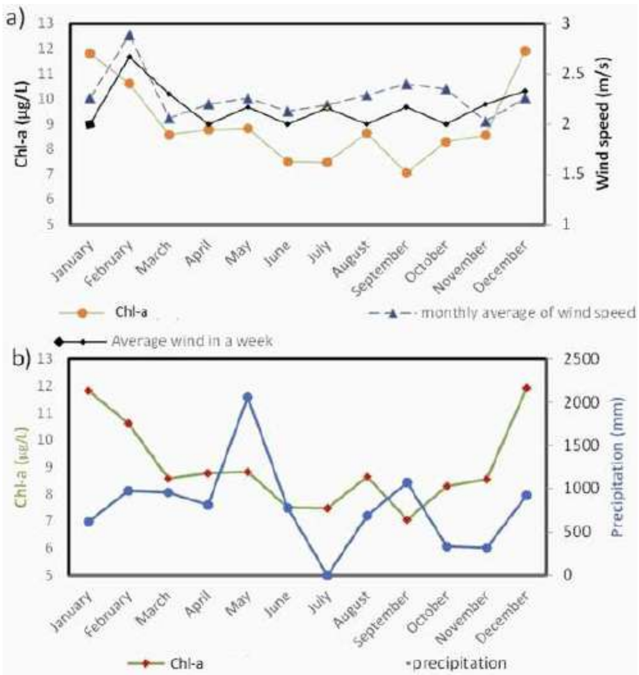

Fig. 6. Temporal variation of Chl-a with wind speed (a) and precipitation (b) based on Sentinel imagery on 3 January 2021, 27 February 2021, 14 March 2021, 23 April 2021, 13 May 2021, 22 June 2021, 27 July 2021, 21 August 202, 10 September 2021, 10 October 2021, 4 November 2021, 14 December 2021 for whole study area (Fig. 2).

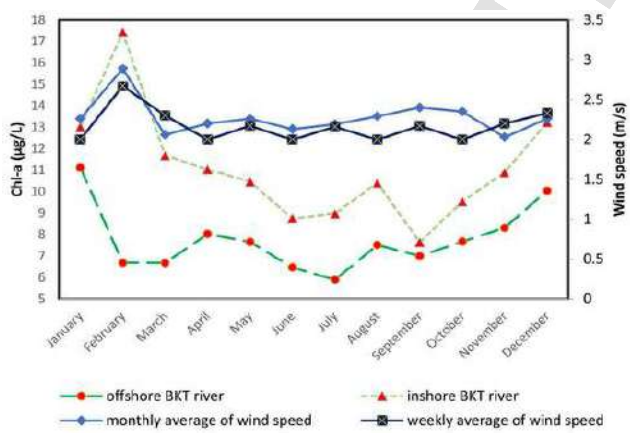

Fig. 7. Same as Fig. 6 but for offshore Chl-a, inshore Chl-a and wind speed. The position of offshore and inshore areas is depicted in Fig. 2.

vealed the presence of diverse bias values, both positive and negative. In a study conducted by Maslukah et al. (2022), Sentinel-3 imagery was utilized to assess the Chl-a concentration in the western coastal waters of Semarang Bay. The researchers found that the Chl-a concentration

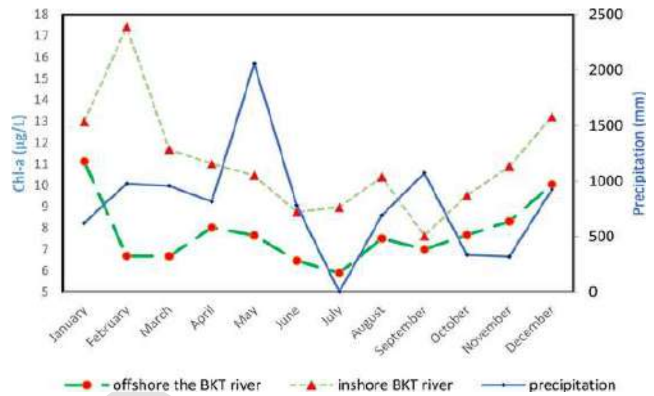

Fig. 8. Same as Fig. 6 but for offshore Chl-a, inshore Chl-a and precipitation. The position of offshore and inshore areas is depicted in Fig. 2.

derived from the imagery exhibited a significant disparity compared to the observation data. Specifically, the imagery displayed a bias value of 3.43, indicating a consistent overestimation of Chl-a levels. The observed range of Chl-a concentration in the imagery spanned from 0.70 to 9.07 mg/m^3. Nevertheless, the RMSE about the estimated Chl-a concentration is recorded as 2.47 mg/m^3, while the MAPE stands at 23.52 %. This finding suggests that the algorithm used to estimate the Chl-a levels from the BKT River is still yielding relatively accurate results. The algorithm under consideration exhibits superior performance compared to the algorithm proposed by Aranha et al. (2021), as the latter demonstrated a relative mean error of 28 %. In contrast to the findings of Maslukah et al. (2022), which reported a significantly lower percentage of relative error at 1.19 %. The study conducted by Maslukah et al. (2022) exhibits several limitations. Firstly, the sample size is relatively small, consisting of only nine participants. Consequently, this limited sample may introduce potential biases in the findings. Additionally, the resulting bias in the study, measured at 3.5 mg/m^3, is relatively high.

Based on Fig. 4, the MAPE value generated in this study has a high error. This can illustrate that the use of three of the visible and NIR bands (B8) at 10 m resolution, cannot be used as an accurate estimation of Chl-a. Further development of algorithms related to the mixture of all bands both visible and NIR and the use of band ratio is recommended, as has been performed by Saberioon et al. (2020) with a combination of all bands, Shaik et al. (2021) with visible and NIR bands, Katlane et al. (2020) with single band (red), and Bramich et al. (2021) with a single band (NIR) and a combination of green and SWIR (Ouma et al., 2020).

The algorithm obtained is subsequently utilized to estimate the temporal and spatial variations. The present study demonstrates that temporal fluctuations exhibit a discernible seasonal pattern, wherein alterations in precipitation levels lead to subsequent modifications in river discharge. The westerly monsoon prevailing in Indonesia induces elevated wind velocities, thereby influencing the process of sediment resuspension. River discharge and resuspension are two mechanisms that have the potential to impact nutrient inputs into the water column, consequently influencing the growth of phytoplankton. The biomass of phytoplankton can be assessed by measuring Chl-a concentrations.

The determination of water's trophic status can be achieved by assessing the concentration of Chl-a. According to Hakanson and Bryann

Table 2
The Pearson correlations of Chl-a with climatological data.

	Chl-a near	Chl-a far	the monthly of wind	the weekly of wind	the weekly of rain	the monthly of rain	Temperature of_ air	sunshine duration (hour)
Chl-a	.786**	.797**	.298	.344	.022	.128	-.682*	-.803**
Chl-a inshore	1	.319	-.113	-.191	-.016	.031	-.325	-.646*
Chl-a offshore	.319	1	.590*	.715**	-.128	.141	-.833**	-.753**

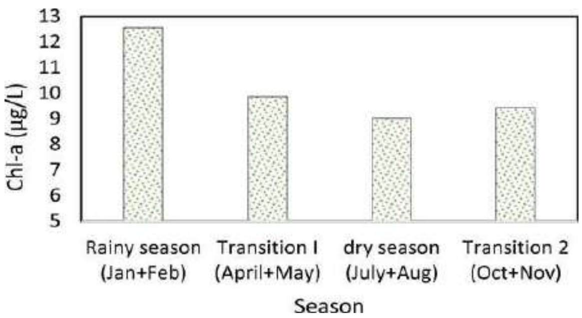

Fig. 9. Seasonal variation of Chl-a in 2021 during the rainy season (January and February), first transition (April and May), dry season (July and August), and second transition (October and November).

(2008), oligotrophy is characterized by Chl-a concentrations below 2 mg/m^3 in aquatic environments. Mesotrophic conditions are indicated by Chl-a concentrations ranging from 2 to 6 mg/m^3, while eutrophic conditions are associated with concentrations between 6 and 20 mg/m^3. Hypertrophic conditions, on the other hand, are defined by Chl-a concentrations exceeding 20 mg/m^3. According to the classification utilized, the coastal waters of BKT fall within the eutrophic classification. According to the findings of Maslukah et al. (2021), the trophic conditions of the Semarang coastal waters, which encompass the BKB and BKT estuaries, were determined based on field observations of Chl-a concentration data and chlorophyll analysis from images. Based on empirical data, coastal waters can be classified as eutrophic or mesotrophic based on the levels of Chl-a derived from satellite imagery. However, the findings of this study indicate that both samples exhibited eutrophic conditions. The issue at hand is closely tied to the limited spatial resolution of MODIS, which must not be conflated with observational data obtained from a localized region. According to the findings of Maslukah et al. (2019), the study elucidated that the concentration of Chl-a in the vicinity of the BKT estuary exhibits significant fluctuations within a range of approximately ± 500 m, with variations in concentration ranging from 1 to 10 mg/m^3. The MODIS image data is acquired by sampling each pixel at a spatial resolution of 4 × 4 km.

5. Conclusion

In this study, the seasonal spatial and temporal distribution of near-surface chl-a concentrations in Semarang coastal waters in 2020 is described using visible and NIR band reflectance data from Sentinel-2 imagery. This study includes the use of a new empirical model based on Sentinel-2 observed in 2020 and taken from Semarang coastal waters specifically (BKT river front). In addition, the relationship between Chl-a concentration and climatological factors such as rainfall, length of sunshine wind and tidal conditions was studied. Therefore, we tuned the algorithm based on the blue, green, red, and Nir bands and derived the empirical method as follows: **Chl-a** = $10^{(2.743-0.725(\log B2^{*}c)-0.625(\log B3^{*}c)+1.623(\log B3)+0.809(\log B8^{*}c))}$ where c = 0.036/B8. The accuracy of the empirical method can be reflected in the values of RMSE, MAPE, and bias of 2.44 µg/L, 23.52 %, and −0.63 µg/L, respectively. The study revealed that there was a greater degree of spatial variation in Chl-a concentrations towards the mouth of the river compared to the offshore region. This study reveals that the temporal fluctuations in the area of the outer estuary are primarily driven by variations in wind speed rather than precipitation-related factors. The other climatological factors that exerted a significant influence were the air temperature and the duration of solar radiation (SS), exhibiting a negative correlation.

CRediT authorship contribution statement

Rikha Widiaratih: Visualization, Methodology. **Heru Nur Krisna:** Visualization, Formal analysis. **Lilik Maslukah:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Anindya Wirasatriya:** Supervision, Conceptualization. **Yusuf Jati Wijaya:** Writing – review & editing. **Dwi Haryo Ismunarti:** Software, Formal analysis.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lilik Maslukah reports financial support was provided by Diponegoro University. Other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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