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Research article

# Relationship between chlorophyll-a, rainfall, and climate phenomena in tropical archipelagic estuarine waters

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ABSTRACT

Similar to many estuaries worldwide with sources receiving nitrogen and phosphorus, i.e., nutrients, from point and diffuse sources, the waters in Jakarta Bay, Musi Estuary, and Rokan Estuary in Indonesia are facing negative impacts on water quality and ecosystems, i.e., eutrophication, because of rapid urbanization and human activities. The transport of nutrients through rivers and tributaries depends on rainfall and climate phenomena, ultimately dictating chlorophyll-a (Chl-a) concentrations and trophic levels in estuaries. The relationship between trophic level, Chl-a concentration, rainfall, and climate phenomena was explored in this study by examining monthly Chl-a concentrations from 2003 to 2021 in the three estuaries. Remote sensing Chl-a concentrations data from the NASA Aqua MODIS mission was subjected to Geographic Information System (GIS) and statistical analyses. The dynamic fluctuations of Chl-a concentrations in all estuaries showed eutrophic zones appearing at specific times, influenced by local rainfalls and their patterns. The first principal components of the Empirical Orthogonal Function (EOF) analysis of Chl-a concentration anomalies showed significant correlations with rainfall anomalies and the Indian Ocean Dipole (IOD) index. These relationships exhibited distinct patterns influenced by unique climate factors in each estuary. The study highlights the crucial role of wide-area continuous monitoring and early warning systems, facilitated by satellite remote sensing, in preserving the health of coastal ecosystems. The findings also offer valuable insights for designing future monitoring programs and targeted conservation efforts.

## 1. Introduction

Nutrients, specifically nitrogen and phosphorus, have become significant pollutants in global rivers, resulting in eutrophication in various watersheds worldwide [1]. Adding to the challenge, nutrient pollution from urban areas is exacerbated by anticipated global urbanization trends and is expected to rise in the coming decades [1,2]. Urban areas, especially in Southeast Asia, face heightened nutrient pollution levels because of the proliferation of densely populated areas, sewer connectivity rates, human waste production, and the effectiveness of wastewater treatment systems [1,3,4]. Furthermore, to accommodate the demands of a rapidly growing population, there has been a surge in agricultural activities, livestock farming, and fishing. The agricultural sector is a significant consumer of water. This sector accounts for 90 % of water consumption in Iran [5]. The increased application of pesticides and fertilizers in agriculture and the rapid expansion of aquaculture production may potentially endanger nearby water bodies [6,7]. In addition, livestock and poultry farms can also be sources of surface water contamination. In China, this sector accounted for 46.67 %, 11.51 %, 19.61 %, and 37.95 % of the total volumes of chemical oxygen demand (COD), ammonium nitrogen ($NH4^{+}$-N), total nitrogen (TN), and total phosphorus (TP), respectively, in 2017 ([8], as cited in Ref. [9]). Highlighting this issue [10], has demonstrated that the pollution level was present in one of Indonesia's major rivers. The rivers eventually transport nutrients to estuarine waters, exacerbating water pollution challenges.

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**Abbreviations**

| | |
|---|---|
| Chl-a | Chlorophyll-a |
| EOF | Empirical Orthogonal Function |
| ENSO | El Niño–Southern Oscillation |
| GIS | Geographic Information System |
| HAB | Harmful Algal Blooms |
| IOD | Indian Ocean Dipole |
| ITCZ | Intertropical Convergence Zone |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| NASA | National Aeronautics and Space Administration |
| USEPA | United States Environmental Protection Agency |

Renowned as the world's largest archipelagic nation, Indonesia covers a territory from 6°N to 10°S and from 95°E to 142°E, covering 18,110 islands. Notably, two major islands, Sumatra and Java, were reported as having high population densities [11]. These islands, particularly Java, home to the capital city of Jakarta, face significant environmental challenges. The rapid urbanization and human activities in these densely populated areas contribute to increased waste production, putting pressure on estuarine water quality and ecosystems. As a result, the Indonesian estuarine water quality, especially in the congested estuarine cities of Java, has been steadily declining [12]. This decline was primarily attributed to excessive nutrients and organic compounds from anthropogenic sources such as domestic wastewater, industry, mining, agriculture, aquaculture, and solid waste. These pollutants are the most significant contributors to Indonesian littoral water pollution [1,11,12].

Additionally, based on observation, human-caused stresses endanger Indonesia's aquatic ecosystems [13]. Despite being a tropical Southeast Asian country with a wet and humid climate, conducive hydrogeological conditions, and favorable conditions for terrestrial pollutant transport, systematic management of aquatic environments, particularly hypoxia and eutrophic conditions, is lacking. This highlights the need for extensive observations of hypoxia and eutrophication factors, including human activities, hydrology, and climate variability [13]. Rainfall variability, under the influence of climate phenomena such as El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), affects pollutant transport from watershed to estuary and hence the quality of riverine and estuarine waters [9–12]. Rainfall patterns can influence river water quality by altering pollutant-carrying discharges from rain-receiving tributaries to the river's main body, increasing pollution load as they flow downstream. Understanding the impact of climate phenomena on water quality is essential for effective management and conservation of estuarine ecosystems [14,15–17].

The concentration of chlorophyll-a (Chl-a), the primary photosynthetic pigment in algae and cyanobacteria (blue-green algae) [18], has been used as a surrogate measure of phytoplankton abundance in the water column. The concentration is directly related to the availability of nitrogen and phosphorus [19–21]. High concentrations of Chl-a indicate algae overproduction, leading to algal blooms. Because of this, the concentration of Chl-a has been used as a proxy for eutrophication and trophic status [22,23]. Several studies have also examined the relationship between climate and the phenological cycle variations of phytoplankton [16,24–32].

Extensive research conducted within the Indonesian waters has consistently highlighted the significant impacts of ENSO and IOD phenomena on phytoplankton blooms, leading to substantial fluctuations in Chl-a concentrations during El Niño/positive IOD and La Niña/negative IOD episodes [9,28–33]. Consequently, comprehending the intricate effects of ENSO and IOD on Chl-a concentration variability in Sumatera and Java has become a paramount research priority, essential for delineating the trophic dynamics of their estuarine ecosystems. In this case, leveraging advanced technologies has thus become essentially imperative. In this context, the Moderate Resolution Imaging Spectroradiometer sensor onboard NASA's Aqua satellite (Aqua MODIS) emerges as a vital tool. The Aqua MODIS provides an invaluable resource, providing unprecedented, extended temporal coverage of sea surface temperature and Chl-a concentration data from a single sensor [34–37].

The Aqua MODIS dataset offers almost two decades of daily global coverage, enabling comprehensive analyses of the relationships between Chl-a concentration and other variables sharing the same spatial and temporal characteristics, including rainfall and climate phenomena. The unique attributes of Aqua MODIS Chl-a concentration data make it the cornerstone of this study's objective. Notably, while satellite remote sensing data provides broader spatial and temporal coverage compared to field measurements of marine waters, it is essential to acknowledge potential limitations in accuracy inherent to satellite remote sensing Chl-a concentration data, especially when compared to precise field measurements [37,38].

The primary objective of this study is to investigate the spatio-temporal variations of Chl-a concentration within tropical archipelagic estuarine waters and their relationships with rainfall and climate phenomena. To achieve this, Geographic Information System (GIS) technology and the remote sensing dataset from the Aqua MODIS sensor are used in this study. The Aqua MODIS comprehensive dataset, including Chl-a concentration, will provide essential information on environmental conditions [12,22,34,35,39].

Indonesia's estuarine cities [25,40,34,35,39,41], specifically densely populated metropolitan areas such as Jakarta, confront formidable challenges of deteriorating estuarine water quality. Anthropogenic pollutants, including nutrients, stand as pivotal contributors to the issue of estuarine water pollution. Climate phenomena, such as ENSO and IOD, exacerbate this. The phenomena influence the intricate nutrient dynamics and productivity of estuarine ecosystems.

The findings of this research will have important implications for the management of estuarine waters in tropical archipelagos, specifically Java and Sumatra. By identifying areas of high productivity and understanding the effects of rainfall and climate phenomena on Chl-a concentration variability, decision-makers can develop targeted strategies for nutrient management and water quality improvement. Effective nutrient management will help alleviate estuarine water pollution by reducing excessive nutrient discharges from anthropogenic sources. Furthermore, the outcomes of this study can serve as a valuable baseline for future monitoring programs, allowing for better evaluation of the effectiveness of conservation efforts and the development of sustainable watershed management plans in Indonesia.

## 2. Methods

### *2.1. Study areas*

This study covered the areas of Jakarta Bay (5,92-6,15°S and 106,69–107,03°E), Musi Estuary (1,89-2,64°S and 104,60–105,35°E), and Rokan Estuary (1,10-2,75°S and 100,1–101,12°E), as shown in Fig. 1.

The Cikapadilan, Angke, Krukut, Ciliwung, Sunter, Cakung, Blencong, and Bekasi watersheds feed into Jakarta Bay, Java, covering an area of 3045.08 km2, which is a big part of the Jakarta megapolitan urban area. In 2021, they released an estimated 20,184 tons of N and 3884 tons of P from 41,461,312 people, 84,709 ha of harvested agricultural land, 67,981,241 chickens and other animals, and 127,238 tons of fish and seafood. The emissions of N and P have been increasing for the last two decades.

The Musi River, Sumatra, flows through two provinces, stretching over 750 km, and is divided into the upstream Musi River (Bengkulu Province), the middle Musi River, and the downstream Musi River (South Sumatra Province). The activities in the Musi River watershed, with an area of 59,942 $km^{2,}$ are diverse. In 2021, the Banyuasin Regency, a Musi Estuary area, had a population of 843,877 people. It was estimated that 72,460.52 tons of N and 2492.27 tons of P were emitted from the regency's 226,518 ha of agricultural land. In addition, the estimated potential increase in the regency's total emissions also came from the 110-ton fishery production sector and the 117,956,645 livestock population.

The Rokan Watershed, located in the western region of Sumatra Island, encompasses an estimated area of 22,454 $km^2$. Water from the river flows easterly and ultimately discharges into the Strait of Malacca, located on the eastern coastline of Sumatra (Rokan Estuary). In 2022, an estimated total of 17,848.82 tons of N and 2215.80 tons of P were emitted into the Rokan River from various human activities, specifically from the population of 646,791, agricultural and plantation areas of 2322.44 ha, 160,917 poultry and livestock, and the fishery industry, which produced 2928.96 tons of products. The natural resource potentials of the region also have the potential to influence environmental quality through nutrient pollution in the downstream Rokan River and its estuary.

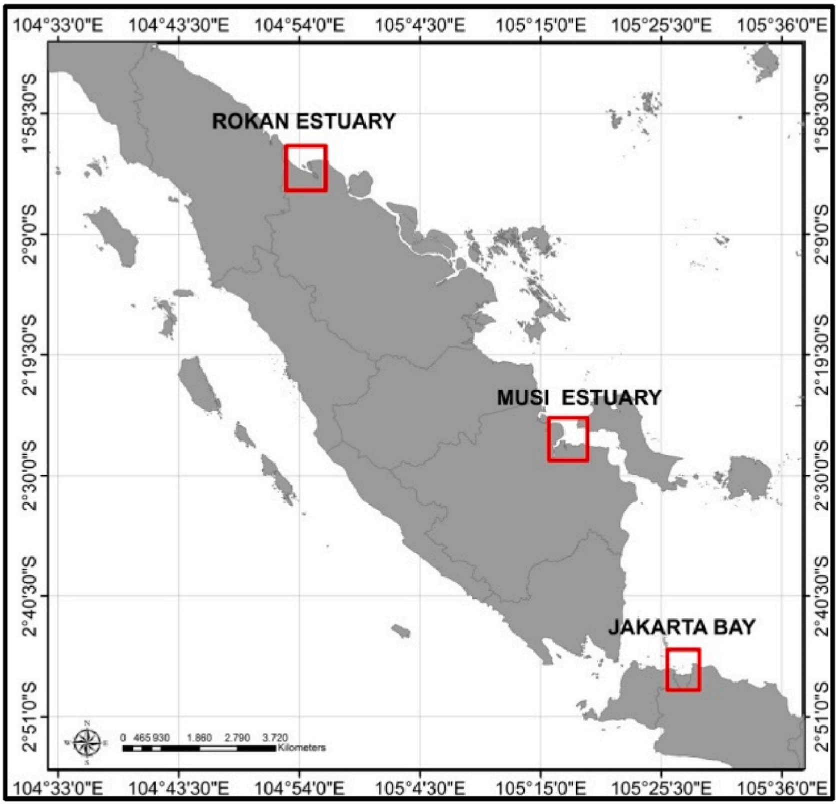


**Fig. 1.** Locations of jakarta bay, musi estuary, and rokan estuary.

### 2.2. Data collection

Monthly and climatology data from 2003 through 2021 were collected from the Aqua MODIS level 3 satellite imagery with a resolution of 4 km, which was directly obtained from https://oceancolor.gsfc.nasa.gov/l3/. Throughout its analysis, this study used monthly data, which was the mean of the daily data collected over the month. The monthly climatology data was a composite of all daily data collected during a single calendar month across all the years of the Aqua MODIS mission. Aqua MODIS data possesses a large band count of 36 and spectral values of 405–14385 and represents developments from previous satellites created by NASA [23,42]. The accuracy of the standard Aqua MODIS algorithm (OC3) was estimated to range between 60 and 85 percent for Indonesian seawater, depending on the accuracy of data collected in situ [42].

In addition, we attempted to visually compare Chl-a concentration data in Jakarta Bay from field measurements (in Fig. 9 of [43]) with satellite (Aqua MODIS) data (Fig. 2). The processing of satellite data was aligned with the Chl-a spatial distribution described in Ref. [43] and divided into two seasons in 2007: the dry season (comprising sample data for April and September) (Fig. 2a) and the rainy season (for January and November) (Fig. 2b). In line with [43], Fig. 2 shows that Chl-a concentration increased as they were closer to the coastal region of North Jakarta in the seasons. Satellite Chl-a concentrations tended to be underestimated in the dry season compared to previous observations of [43]. However, they were typically accurate during the rainy season, and the distribution pattern exhibited notable similarities between field data and satellite data.

Validating satellite data is challenging, requiring simultaneously collected field data. Furthermore, in addition to being costly, field sampling timing and points must be able to capture the actual conditions. Uncertainties in both measurements are associated with spatial, temporal, and spatial-temporal interactions and sampling and analysis methods [44]. Based on these, including the visual comparison, satellite data was resourceful for this study.

For this study, the required base map was obtained from https://tanahair.indonesia.go.id/with a scale of 1:25,000. Daily rainfall data was obtained from https://dataonline.bmkg.go.id/and the local meteorological, climatological, and geospatial agencies (BMKG).

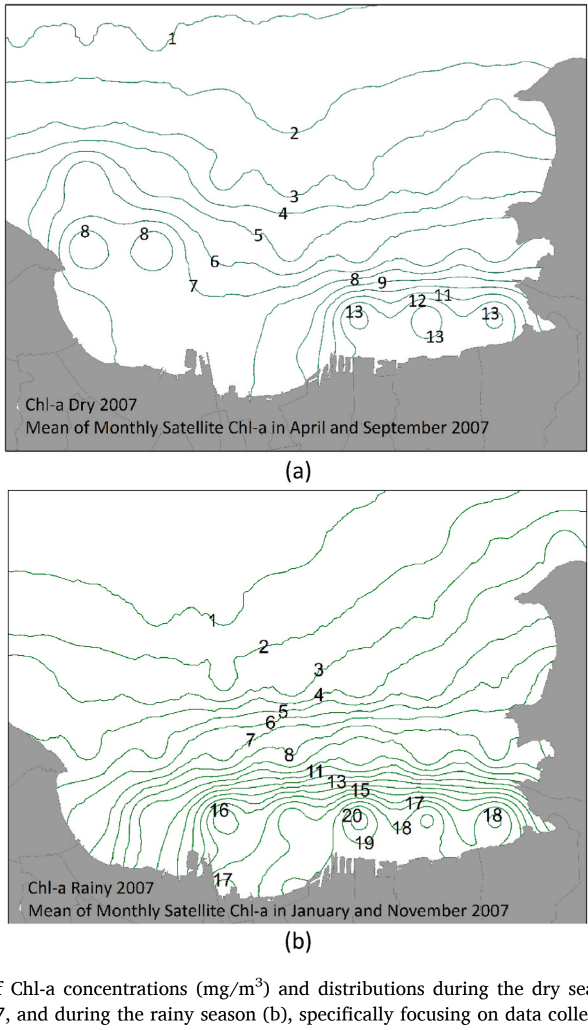


**Fig. 2.** Satellite Aqua MODIS data of Chl-a concentrations (mg/m$^3$) and distributions during the dry season (a), specifically focusing on data collected in April and September 2007, and during the rainy season (b), specifically focusing on data collected in January and November 2007.

The IOD index was obtained from http://www.bom.gov.au/climate/iod/and https://psl.noaa.gov/gcos_ wgsp/Timeseries/Data/dmi.had.long.data.

### 2.3. Data processing and analysis

The numerical data from satellite imagery was converted and interpolated into shapes of situational maps by using the inverse distance weighted method. Having a higher coefficient of determination and a lower RMSE value when compared to other methods [45,46,47], the inverse distance weighted method was the most effective method for mapping the spatial distribution of chlorophyll-a concentration. According to Ref. [45], some coastal regions exhibited significant data loss due to the optical complexity. This caused missing data at times. In modifications to Ref. [47], monthly climatology data were utilized for data filling. The value of Chl-a concentration was then converted to trophic status (see Table 1).

This study also used anomalies of monthly data, calculated by removing its seasonal value as follows [48]: where $\overline{X}(x,y)$ is the monthly value, $\overline{X}(x,y)_{clim}$ is the monthly climatology value, and $\Delta\overline{X}(x,y)$ is the anomaly value.

$$\Delta\overline{X}(x,y) = \overline{X}(x,y) - \overline{X}(x,y)_{clim} \tag{1}$$

The anomalies were then subjected to statistical analysis, including empirical orthogonal function (EOF) analysis. EOF analysis decomposes large datasets into different modes, with the information present in the observed data preserved. This technique not only aids in decomposing large datasets but also serves to extract meaningful information, ensuring a robust statistical analysis [49–51]. To make it correspond with the temporal scale of other datasets, daily rainfall data was transformed into monthly data, and accounting for monthly variations was also done, thus enabling comparison and analysis [48,52].

## 3. Results and discussion

### 3.1. Monthly values and climatology of chl-a concentration and rainfall

The box-and-whisker plots of monthly Chl-a concentrations in the study areas are shown in Fig. 3. The average monthly Chl-a concentration in Jakarta Bay was 6.76 mg/m$^3$, with a minimum of 0.92 mg/m$^3$ in November 2005 and a maximum of 14.05 mg/m$^3$ in July 2010. Outliers in Jakarta Bay occurred in February 2005 and June 2016 with values of 15.82 and 14.35 mg/m$^3$, respectively, and extremes in April 2004, December 2007, February 2015, and October 2017, with values of 20.46, 29.53, 21.20, and 23.24 mg/m$^3$, respectively. The highest concentration of Chl-a in Musi Estuary occurred in May 2010 (7.33 mg/m$^3$), and the lowest concentration occurred in September 2012 (1.41 mg/m$^3$). An outlier in Musi Estuary occurred in June 2013 with a value of 7.91 mg/m$^3$, and extremes occurred in March 2004 and November and December 2010, with values of 9.70 mg/m$^3$, 9.50 mg/m$^3$, and 10.70 mg/m$^3$, respectively. In the past twenty years, Chl-a in Rokan Estuary has fluctuated from the average of 4.86 mg/m$^3$; in April 2018, the Chl-a concentration reached the minimum of 2.501 mg/m$^3$, while the highest concentration of Chl-a of 7.395 mg/m$^3$ was recorded in December 2006.

Fig. 4a shows the box-and-whisker plots of monthly rainfall in the three estuarine areas based on 20-year observational data. Jakarta Bay had a different monthly rainfall fluctuation from those of Musi Estuary and Rokan Estuary. The latter estuaries had two peaks of monthly rainfall during the year. The average monthly rainfall in the watersheds of Jakarta Bay was 173.96 mm; the maximum was 469.80 mm in February 2017, and the minimum was 0.15 mm in September 2006. Outliers in the watersheds occurred in December 2007 (531.89 mm), February 2008 (649.44 mm), January 2013 (581.26 mm), February 2014 (568.82 mm), 2015 (567.28 mm), 2020 (536.1 mm), and 2021 (504.56 mm), and the extremes were 738.88 and 816.80 mm in February 2007 and January 2014, respectively. In Musi Estuary, the average monthly rainfall was 204.80 mm; the maximum was 564.20 mm in March 2009, and the minimum was 0.20 mm in October 2015. Outliers in the Musi Estuary occurred in November 2008, November 2012, and March 2013, with values of 634.20, 650.00, and 617.00 mm, respectively. In Rokan Estuary, the average monthly rainfall was 291.40 mm; the maximum was 928.5 mm in November 2022, and the minimum was 17.70 mm in February 2014. Outliers in the Rokan Estuary occurred in January 2018 (722 mm) and August 2021 (671.50 mm).

Fig. 4b, c, and 4d depict three different types of rainfall climatology in Jakarta Bay (monsoonal), Musi Estuary (equatorial; the estuary is in the intermediate area between monsoonal and equatorial), and Rokan Estuary (equatorial), respectively. The wet northwest and dry southeast monsoon winds strongly influence the monsoonal type, and the movement of the Intertropical Convergence Zone (ITCZ) affects the equatorial type [53].

Fig. 5 shows the monthly distribution of trophic status (refer to Table 1) in Jakarta Bay (Fig. 5a), Musi Estuary (Fig. 5b), and Rokan Estuary (Fig. 5c) when the chlorophyll-a concentration was relatively high and eutrophic zones appeared. Several studies have

**Table 1**
USEPA National Coastal Assessment Program criteria for assessing trophic status based on chlorophyll-a concentration [30,40].

| TROPHIC STATUS | Chl-a Concentration (mg/m$^3$) |
|---|---|
| Oligotrophic (good) | <5 |
| Mesotrophic (fair) | 5–20 |
| Eutrophic (poor) | >20 |

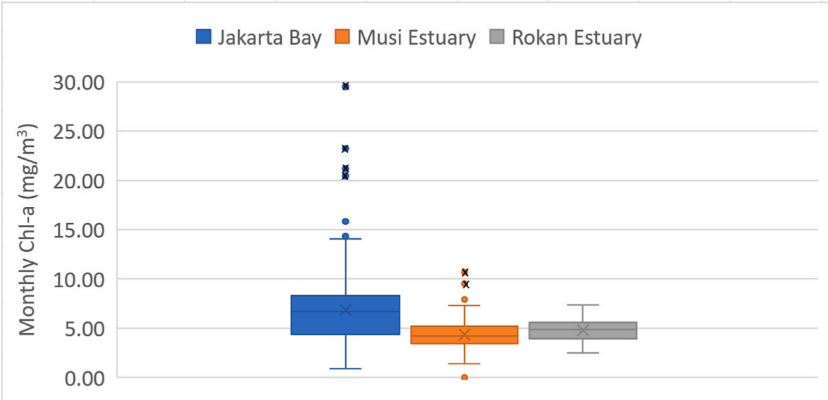


**Fig. 3.** Monthly Chl-a concentration during 2003–2021.

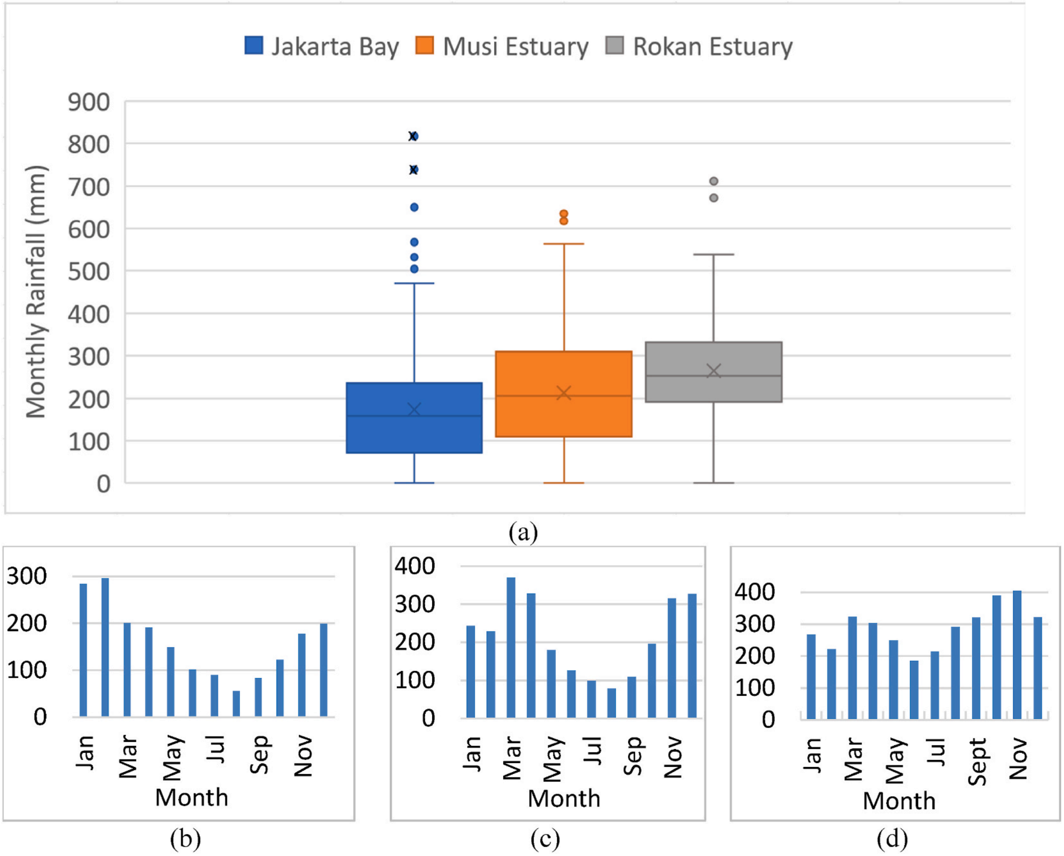


**Fig. 4.** Monthly rainfall in study areas (a) and rainfall climatology in Jakarta Bay (b), Musi Estuary (c), and Rokan Estuary (d) during 2003–2021.

reported the presence of algal blooms that coincided with eutrophic status in Jakarta Bay, suggesting that Chl-a concentration grouping to trophic levels is an appropriate indicator for evaluating water quality [54–56]. Harmful algal blooms (HABs) can be attributed to several contributing variables, including the decrease in water level and the increase in water temperature. Fig. 5 also shows that the closer to the coast, the greater the concentration of Chl-a; the Friedman test suggested that the outer area of Jakarta Bay had a lower Chl-a concentration than its inner area, indicating a significant role of terrestrial nutrient sources [54–56].

Monthly climatological maps show that eutrophic zones (refer to Table 1) appeared only in February (FEB), May (MAY), July (JUL), and August (AUG) in Jakarta Bay (Fig. 6). Receiving nutrient-laden water from their rivers that flew through densely populated areas, eutrophic zones appeared near N Island (a reclamation island) and downstream of Sunter Watershed in February (FEB), downstream of Cakung Drain and Marunda Beach in July (JUL), and Cikarang River Estuary and Tawar Estuary (near a green shell cultivation site) in

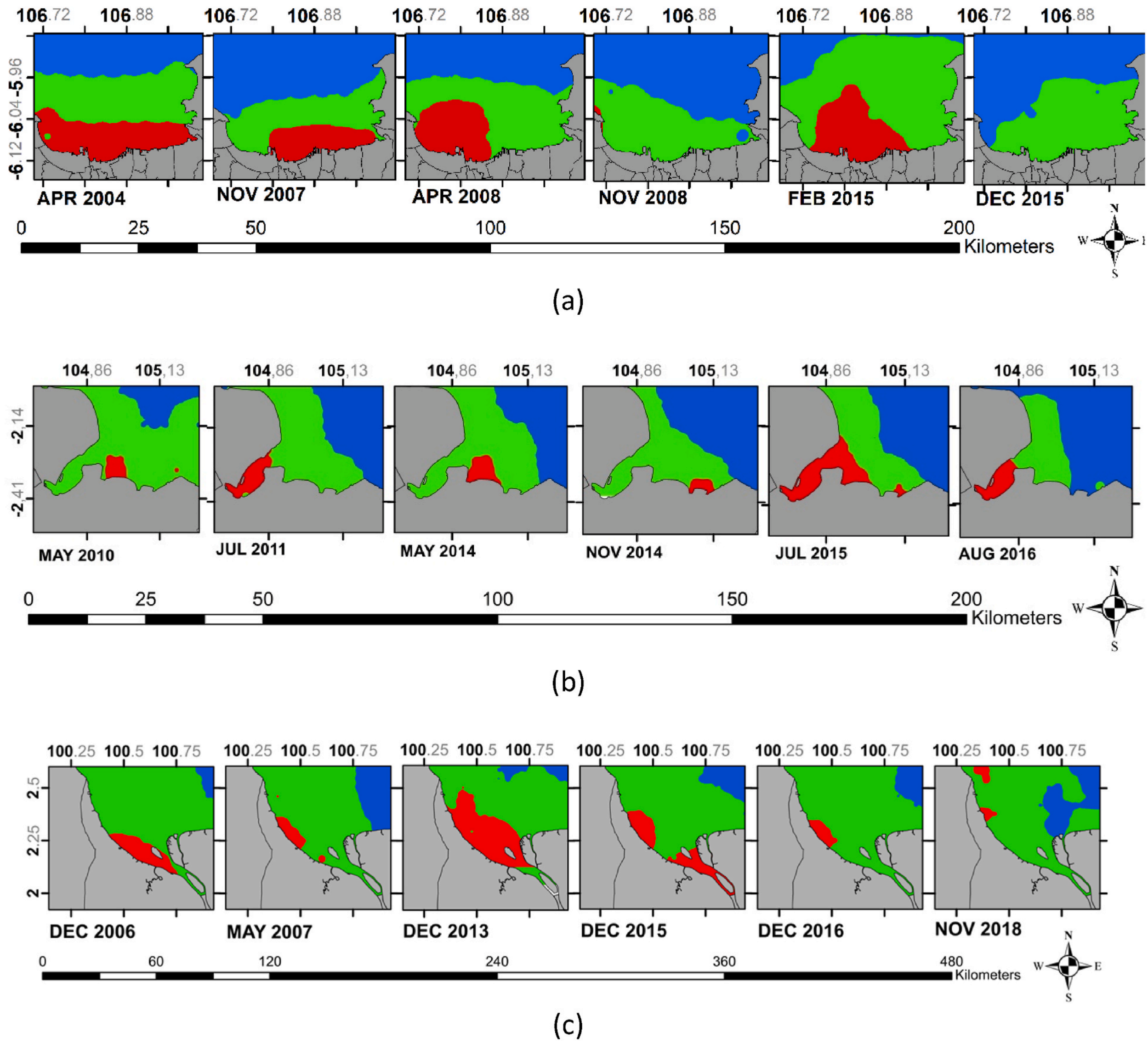


**Fig. 5.** Spatial distribution of trophic status in Jakarta Bay (a), Musi Estuary (b), and Rokan Estuary (c) in months characterized by significantly elevated Chl-a concentrations and the presence of eutrophic zones in these areas. (Blue: oligotrophic zone; green: mesotrophic zone; red: eutrophic zone). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

May (MAY) and August (AUG). When the current velocity was moderate, reclamation increased sedimentation near the island and river mouth by changing the current speed and direction, supporting eutrophication [44].

Eutrophic zones occurred in the summer months, July (JUL) and August (AUG), in Musi Estuary (Fig. 7), when high concentrations of Chl-a were observed. Such phenomena were not exclusive to Musi Estuary and have occurred elsewhere. Eutrophic conditions were observed in the summer months of August and September in the Caspian Sea when high concentrations of Chl-a were detected [57]. High concentrations of Chl-a in Musi Estuary might be attributed to its large watershed, the heavy use of fertilizers in agriculture, and nutrient-laden wastes from industrial activities. Also, strong light penetration was observed to raise the concentration of Chl-a in the South Caspian Sea [58].

Eutrophic zones occurred in December (DEC) in Rokan Estuary (Fig. 8); this is in line with previous studies that noted the moderate growth of Chl-a in Rokan Estuary (mesotrophic in general) [59,60,61]. Tidal mixing and inundation might cause high concentrations of Chl-a in estuaries, resulting in the release of interstitial nutrient-containing anoxic water (i.e., dissolved inorganic nutrients) [62].

Typically, a mid-to-high concentration of Chl-a indicates the presence of abundant nutrient sources. Increasing nutrient concentrations in estuarine areas cause algae and phytoplankton to grow faster than offshore. Thus, the part of the estuary closest to the coast is more vulnerable [19]. This is because the river's runoff is laden with nutrients [63], and driving forces such as rainfall and surface runoff rate affect sediment wash-off. The source-limited wash-off model implies a constant decline in available wash-off sediment. The

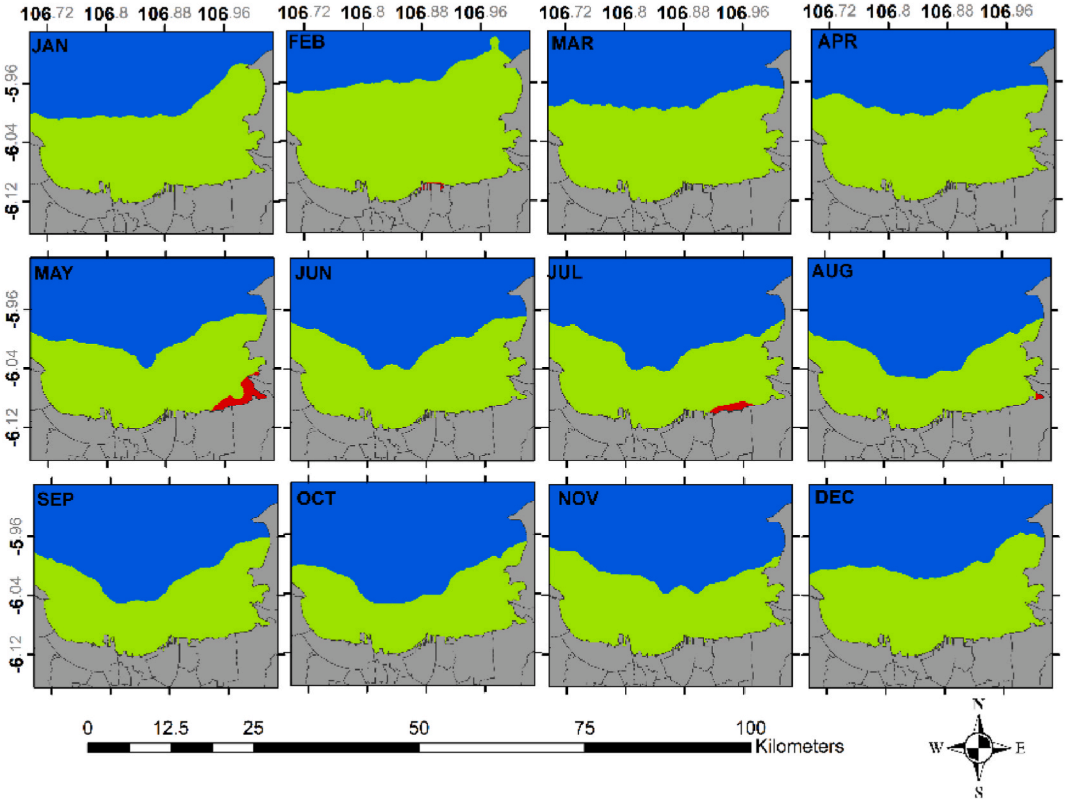


**Fig. 6.** Monthly climatology of trophic status in Jakarta Bay: January (JAN), February (FEB), March (MAR), April (APR), May (MAY), June (JUN), July (JUL), August (AUG), September (SEP), October (OCT), November (NOV), December (DEC). Blue: oligotrophic zone; green: mesotrophic zone; red: eutrophic zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

wash-off driving forces and sediment sources might influence the wash-off at different times in the rainy season [64]. This result is consistent with the findings of previous studies, which found that several factors, including precipitation, which caused river runoff, and the time lag of nutrients, influence the variability of Chl-a [15,19,29,40,65].

### *3.2. Interannual variability of chl-a concentration and its relation with rainfall and climate phenomena*

The monthly Chl-a concentration anomalies (Chl-a anomalies) were further investigated through EOF analysis. The first modes of EOF, accounting for 35 %, 46 %, and 25 % of total variances in Jakarta Bay, Musi Estuary, and Rokan Estuary, respectively, are shown in Fig. 9a, b, and 9c. In Jakarta Bay and Musi Estuary, the first principal components of Chl-a anomalies have significant ($n = 226$, at 95 % confidence level) positive correlations with monthly rainfall anomalies and significant ($n = 226$, at 95 % confidence level) negative correlations with the IOD index. However, the first principal component of Chl-a anomalies in Rokan Estuary has significant ($n = 226$, at 95 % confidence level) positive correlations with monthly rainfall anomalies and the IOD index. These results are consistent with previous research [66], indicating that rainfall in southern Sumatra and Java was positively correlated with negative IOD. On the other hand, rainfall in northwestern Sumatra was positively correlated with positive IOD.

According to Australia's Bureau of Meteorology, a negative IOD was observed in 2010, resulting in high wind intensity from the west to the east and, thus, increased rainfall. The conditions caused the highest recorded rainfall since 1974 and harmed many aspects of Australia and other countries, including Indonesia. This rainfall also carried nutrients, washing them off from catchment areas, thus increasing coastal water's Chl-a concentrations [19,54,55]. This was relevant to Jakarta Bay, the Musi Estuary, and other regions. Based on a previous study on Kuwait's coastline [67], Chl-a concentrations were doubled after high rainfalls, highlighting the effects of higher discharge from Shatt Al-Arab River during the 2018–2019 season. During warm SST anomalies and negative rainfall anomalies, the surface-layer dissolved-inorganic nitrogen concentrations in the Bohai and North Yellow Seas were also decreased, leading to negative Chl-a concentration anomalies and vice versa [68].

In Rokan Estuary, however, cloud cover tends to be closer and, hence, diminishes the intensity of sun radiation during negative IOD events [14,69,17,66]. A lack of the primary energy source and high-intensity precipitation may inhibit phytoplankton growth. Thus, negative IOD events tend to have reducing impacts on the concentration of Chl-a, and vice versa. Previous studies also show that the watershed appears significantly more susceptible to declines in N imports during the western season, with discrete peaks and subsequent decreases in N concentration [15–17,69,24,40].

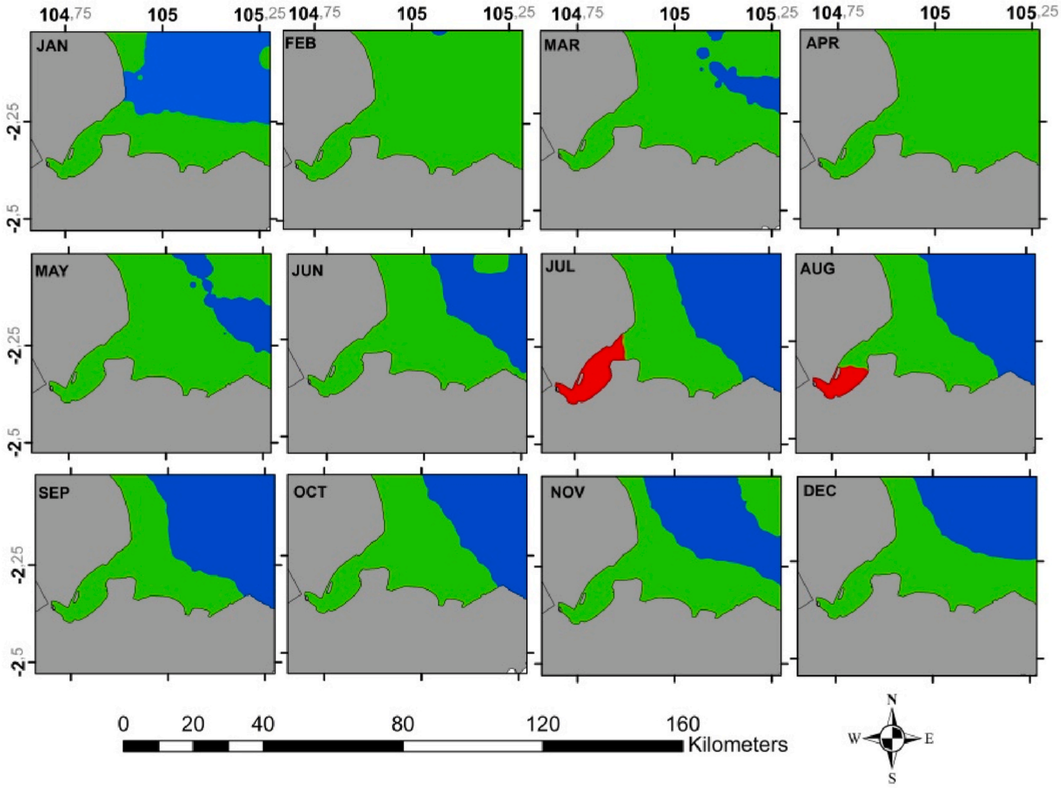


**Fig. 7.** Monthly climatology of trophic status in Musi Estuary: January (JAN), February (FEB), March (MAR), April (APR), May (MAY), June (JUN), July (JUL), August (AUG), September (SEP), October (OCT), November (NOV), December (DEC). Blue: oligotrophic zone; green: mesotrophic zone; red: eutrophic zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

## 4. Conclusion

In this study, we investigated the Chl-a concentrations and their relation to rainfall and climate phenomena in three estuarine areas in Indonesia: Jakarta Bay, Musi Estuary, and Rokan Estuary. The monthly Chl-a concentration time series revealed dynamic fluctuations in the past two decades, with each estuary displaying unique patterns influenced by its local rainfall and pattern. The three estuaries, however, show similar patterns of Chl-a concentrations: the closer to the coast, the greater the concentrations of Chl-a, indicating a significant role of terrestrial nutrient sources.

The interannual variability of Chl-a concentration was investigated by applying EOF analysis, and its association with rainfall and climate phenomena was analyzed. In all three estuaries, significant correlations between the first principal component of Chl-a concentration anomalies and rainfall anomalies and the Indian Ocean Dipole (IOD) index were found. Significant positive correlations with rainfall anomalies and significant negative correlations with the IOD index were found in Jakarta Bay and the Musi Estuary. In the Rokan Estuary, however, significant positive correlations with rainfall anomalies and the IOD index were found. The different effects of IOD events on Chl-a concentrations in the three estuaries because of differences in rainfall and cloud cover, affecting the sun's radiation as the primary energy source for phytoplankton growth, were suggested.

In conclusion, this paper provides valuable insights into Chl-a concentration variability and its relationship with rainfall and climate phenomena in Jakarta Bay, Musi Estuary, and Rokan Estuary. Future research on important determining factors is needed to develop conceptual models relating Chl-a concentrations, rainfall, and climate phenomena in these three areas. This study highlights the crucial role of wide-area continuous monitoring and early warning systems through satellite remote sensing for managing water quality in estuaries. This requires an integrated approach involving structural and non-structural efforts, including regulatory measures, sustainable domestic wastewater management, sustainable agriculture, livestock, and fishery practices, to manage the nutrient flow from land to estuaries.

## Data availability statement

The authors do not have permission to share data.

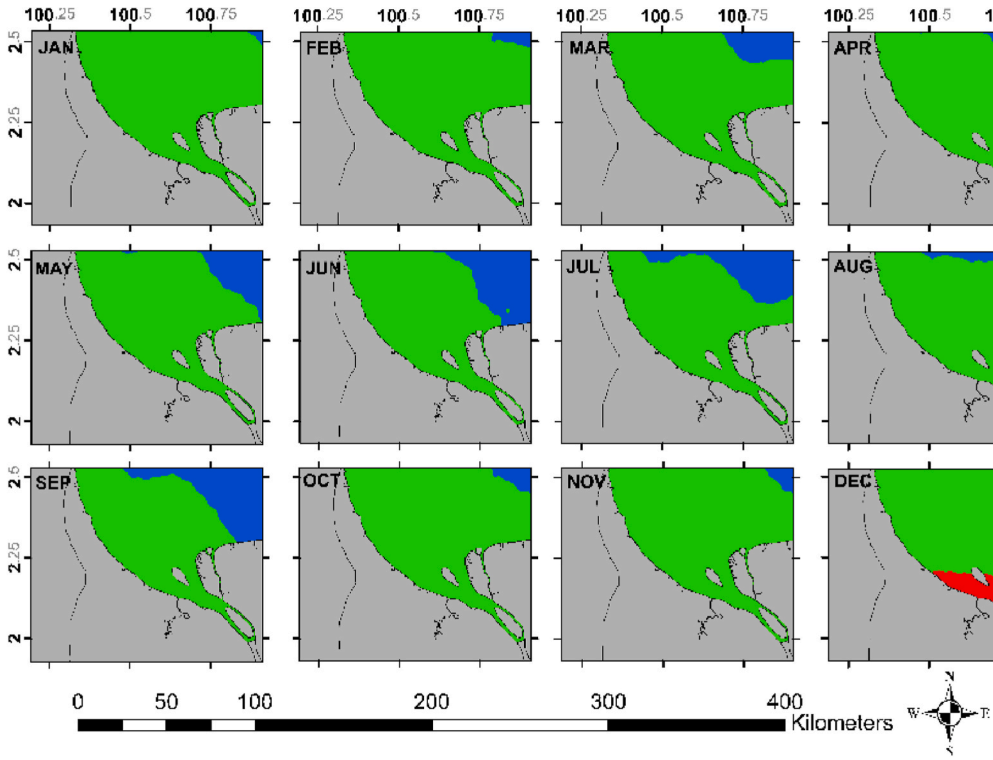


**Fig. 8.** Monthly climatology of trophic status in Rokan Estuary: January (JAN), February (FEB), March (MAR), April (APR), May (MAY), June (JUN), July (JUL), August (AUG), September (SEP), October (OCT), November (NOV), December (DEC). Blue: oligotrophic zone; green: mesotrophic zone; red: eutrophic zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

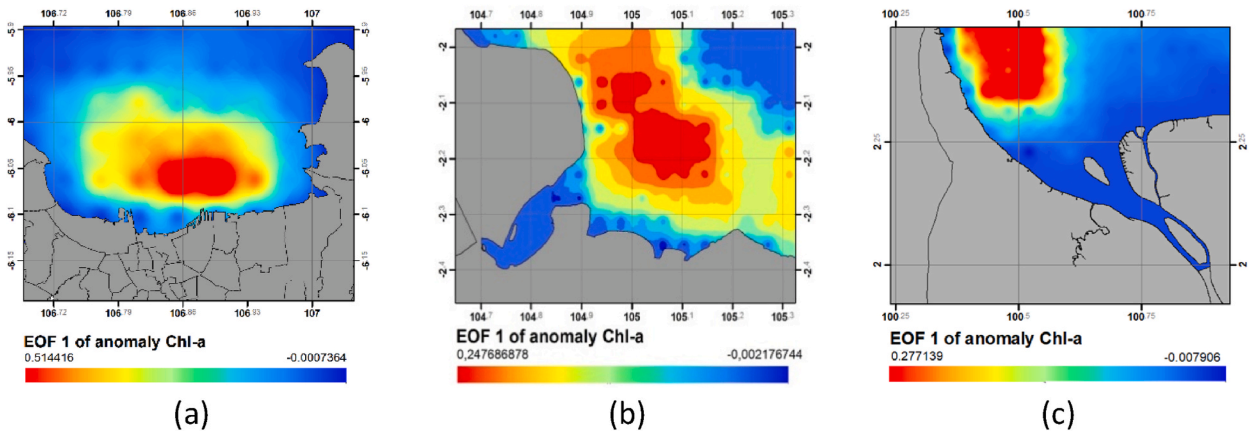


**Fig. 9.** The first EOFs of Chl-a anomalies in Jakarta Bay (a), Musi Estuary (b), and Rokan Estuary (c).

## CRediT authorship contribution statement

**Arief Sudradjat:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Barti Setiani Muntalif:** Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Nabila Marasabessy:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Investigation, Formal analysis, Data curation. **Fadli Mulyadi:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Investigation, Formal analysis, Data curation. **Muhamad Iqbal Firdaus:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Investigation, Formal analysis, Data curation.

## Declaration of competing interest

The 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.

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