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Modeling Seasonal Variability of Trophic Index (TRIX) in Indonesian Waters Using PISCES Biogeochemical Data

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Abstract

Eutrophication poses a significant challenge in Indonesian waters, largely due to a lack of data for effective mitigation. This complex issue, characterized by a time lag and multi-phase progression, is triggered by an influx of nutrients like nitrate and phosphate, leading to harmful algal blooms (HABs) that degrade water quality. This study proposes a more comprehensive approach using the Trophic Index (TRIX), which integrates multiple parameters from the PISCES global biogeochemical model data. The PISCES model accurately captures seasonal TRIX trends, with high values in the southern islands during the southeast monsoon and in northern areas during the northwest monsoon. The model's reliability is confirmed by RMSE and Bias data to be quite low, respectively, for Chl-a (0.065, -0.005), Nitrate (0.144, -0.080), Phosphate (0.084, -0.059), and DO (3.109, 0.919), from the World Ocean Database. The highest TRIX values (8-10) were found in Jakarta Bay, while the Lombok Strait had values (5-7), a difference attributed to varying oceanographic conditions. However, it is crucial to consider physical oceanography and boundary conditions when using the TRIX model. So then, model TRIX data is more valuable for informing policy and mitigation plans for the various Indonesian waters, taking into account their unique characteristics. These findings underscore the importance of considering both monsoon cycles and local conditions when assessing eutrophication risk. The TRIX data is therefore a valuable tool for developing informed policies and mitigation plans for Indonesia's diverse coastal areas.

Keywords: *Eutrophication, Biogeochemistry, Trophic Index, Global Biogeochemical Model PISCES*

Introduction

Eutrophication has become a major issue in Indonesian waters. At least 59 prior studies have recorded eutrophication cases in Indonesian Waters. The primary challenges in mitigating and monitoring HABs were due to a lack of data (Samudra *et al.,* 2023). Eutrophication is complex to mitigate, due to its phase and time lag (Sidabutar *et al*., 2024). Start with an increase in nutrient levels, mainly nitrate and phosphate, which leads to rapid algal growth, shifts in ecological balance, and degradation of water quality. (Prayitno, 2017).· Rapid growth resulting in algal blooms or even Harmful Algal Blooms (HABs), which pose serious environmental risks (Ferreira *et al.,* 2011). But the source of light and dissolved oxygen play a crucial role as a limiting factor of algal blooms, causing a time lag or different effects (Krisna *et al.,* 2023).

Previous studies have achieved monitoring of eutrophication using ocean colour from remote sensing based on chlorophyll-a estimation (Terauchi *et al.,* 2014; Karki *et al.,* 2018; Kulshreshtha and Shanmugam, 2018; Raús Maúre *et al.,* 2021). However, to fully address eutrophication, more parameters are needed to increase confidence in predicting its occurrence in waters for mitigation purposes. This research proposes Trophic Index (TRIX) to measure eutrophication possibilities, due to its capability to integrate many eutrophication parameters (Rinaldi and Giovanardi, 2011). However, since the nutrient data were limited, this research proposes using the PISCES global biogeochemical model as the main data source for modelling the spatial and temporal distribution of TRIX. This model data has also been validated in southern Java in previous research (Triana and Wahyudi, 2021; Wahyudi *et al.,* 2023).

This research utilizes a 20-year TRIX model to map the potential for eutrophication in Indonesian waters. Through spatial and temporal analysis, the study evaluates the TRIX model's ability to track these changes across the monsoonal cycle. The resulting data will be crucial for developing mitigation plans and policy-making guidelines for coastal and marine spatial planning.

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Materials and Methods

This research was conducted with the regional setting at 15°S to 10°N and 90°E to 145°E, which covers Indonesian Waters Regions. Jakarta Bay represented semi-closed coastal water and Lombok Strait represented straits and open ocean waters, applied as Area of Interest (AOI), shown in Figure 1. Nutrient data, i.e. chlorophyll-a (Chl-a), nitrate (N), phosphate (P), and dissolved oxygen (DO), were collected from Global Model Biogeochemical PISCES Hindcast produced at Mercator-Ocean (Toulouse, France) (http://marine.copernicus.eu/; https://doi.org/10.48670/moi-00019). Photosynthetically Active Radiation (PAR) data was collected from Ocean Colour (https://oceancolor.gsfc.nasa.gov/) and supporting physical oceanography data collected from reanalysis data produced by the NEMO platform (http://marine.copernicus.eu/; https://doi.org/10.48670/moi-00021).

Trophic Index (TRIX)

The potential eutrophication was described by classification with the calculated trophic index (TRIX) value (Table 1) with the following formula. (Vollenweider *et al.,* 1998).

$$TRIX = \frac{1}{1.2}[\log(M_{chl}M_{D\%O2}M_{DIN}M_{TP}) + 1.5]$$

TRIX calculations are carried out using data on dissolved inorganic nitrogen (DIN), total phosphorus (TP), and the value of % deviation of oxygen concentration from saturation conditions (D%O2); these values are obtained based on calculations $D\%O_2 = |100 - SatO_2|$ (Fiori *et al.,* 2016).

Seasonal variability analysis

The seasonal variability analysis conducted on the format compiles monthly climatology from 20 years of data (2000-2020) with the following formulation (Wirasatriya *et al.,* 2017).

$$\bar{X}\,(x, y) = \frac{1}{n}\sum_{i=1}^{n} xi\,(x, y, t)$$

Were, $(\bar{X}\,(x, y))$ compile data, (n) pairs data, $(xi\,(x, y, t))$ time-series data (t), (x, y) spatial dimension data $(longitude, latitude)$.

Pearson correlation

The Pearson correlation was conducted to show the highest linear correlation coefficient among all parameters by following the formula (Cohen, 1977). The Pearson correlation was conducted with monthly climatology from 20 years of data. There, (R_{xy}) correlation coefficient, (n) pairs data, (x_i, y_i) value.

$$R_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - (\sum x_i)^2}\sqrt{n\sum y_i^2 - (\sum y_i)^2}}$$

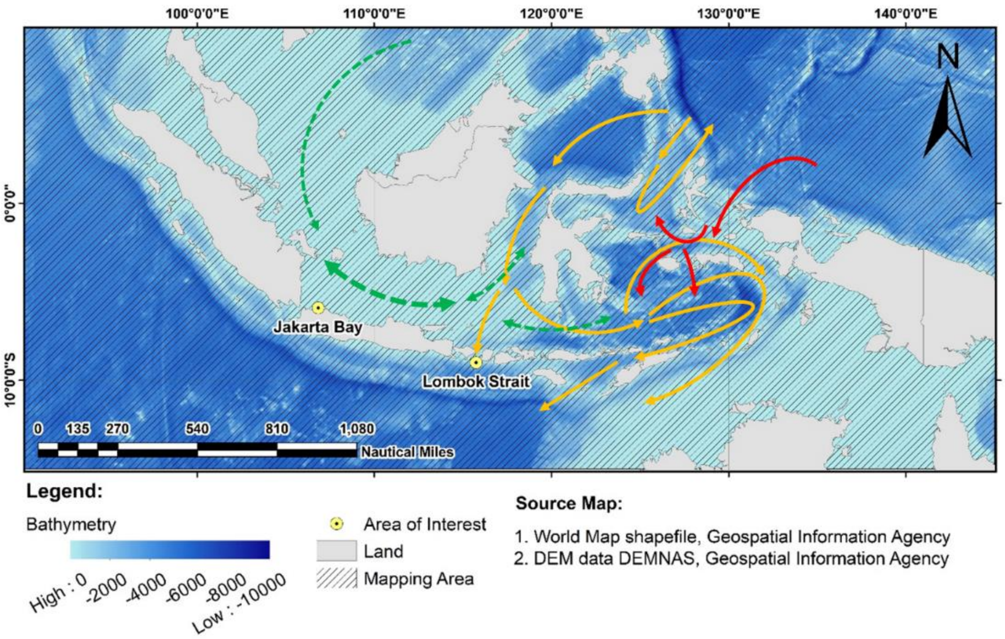

Figure 1. Area of Interest (AoI) and Indonesian throughflow pathways (green arrows represented surface water circulation, yellow arrows represented North Pacific ITF circulation, and red arrows represented South Pacific ITF circulation (Gordon, 2005).

Table 1. Trophic water classification based on TRIX value (Fiori *et al.,* 2016)

TRIX	Trophic water classification	Potential Eutrophication
0 < TRIX < 4	Ultra oligotrophic	Very low
4 < TRIX < 5	Oligotrophic	Low
5 < TRIX < 6	Mesotrophic	Moderate
6 < TRIX < 8	Eutrophic	High
8 < TRIX	Hypertrophic	Very High

Result and Discussion

Model nutrient data capability

The availability of macronutrients is essential for primary production in aquatic ecosystems, as part of the biogeochemical cycle (Prismayanti *et al.,* 2019). Macronutrients, particularly nitrogen (N), phosphorus (P), oxygen (O), and light, become limiting factors for primary growth, with their balance described by the Redfield ratio (Redfield, 1958). Ideally, nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations are available in a 16:1 ratio (N) for optimal primary production (Liu *et al.,* 2011). The nutrient balance influences chlorophyll-a levels, which serve as a proxy for primary productivity (O'Reilly and Werdell, 2019). This is the main concept of data modelling of Global Model Biogeochemical PISCES Hindcast. The Global Model Biogeochemical PISCES Hindcast data provide us with good spatial and temporal availability for time series or climatological analysis, as shown in Figure 2. The data give Root Mean Square Error (RMSE), linear regression (R^2), and Mean Absolute Percentage Error (MAPE) respectively at parameter Chl-a (0.032, 0.971, 9.9%), Nitrate (0.554, 0.994, 12.6%), Phosphate (0.039, 0.973, 12.1%), and DO (14.942, 0.99, 11.1%) with Widya Nusantara Expedition 2015 on the upwelling area of southwestern Sumatra waters (Wahyudi *et al.,* 2023). Moreover, verification conducted using the World Ocean Database shows the RMSE and Bias data to be quite low, respectively, for Chl-a (0.065, -0.005), Nitrate (0.144, -0.080), Phosphate (0.084, -0.059), and DO (3.109, 0.919), with up to 500 pairs of data. This result shows the model data capability for the mitigation and monitoring of algal blooms in Indonesia's marine ecosystems.

Seasonal variability of potential eutrophication

The Trophic Index (TRIX) reveals that monsoon seasons drive eutrophication in Indonesian waters, as shown in Figure 3, as a result of fluctuation of its components in Figure 2. With optimal Photosynthetically Active Radiation (PAR) levels (Harmel and Chami, 2016), the potential for eutrophication increases (Ferreira *et al.,* 2011; Prayitno, 2017; Krisna *et al.,* 2023). Two main peaks occur: one during the first transition monsoon in the South and West Kalimantan coastal areas (TRIX 5-6), and another during the southeast monsoon in Southern Java and the surrounding straits. However, while intense currents often prevent full algal blooms (Susanto and Ray, 2022). Eutrophication can reach advanced stages in enclosed bays with limited water circulation (Darmawan *et al.*, 2021; Sudradjat *et al.*, 2024). Upwelling in southern Indonesian waters also sustains nutrient availability (Purba and Khan, 2019; Tjasyono *et al.,* 2008). This study proposed two areas of interest, with their TRIX values shown in Table 2. The TRIX index, supported by long-term data, offers a robust framework for enhancing fisheries and coastal management. Ultimately, it contributes to the health and productivity of Indonesia's marine ecosystems.

Jakarta Bay

Jakarta Bay is a semi-enclosed body of water in northern Jakarta, which has experienced numerous algal blooms shown in Figure 5a (Damar *et al.,* 2020; Sidabutar *et al.,* 2021; 2023; 2024). According to Figure 5b, the bay's trophic level ranges from eutrophic to hypertrophic, with TRIX values between 7.0 and 10.5. TRIX values are highest during the northwest monsoon and lowest during the southeast monsoon, inversely correlating with dissolved oxygen. Jakarta Bay's classification as a hypertrophic zone indicates significant ecological problems, including poor light penetration, oxygen deficiency, nutrient enrichment, and intense human pressure (Damar *et al.*, 2020). These issues impact the bay's productivity, biodiversity, and overall health. This is closely tied to the monsoon cycle, as monsoons influence Indonesia's rainfall and oceanographic conditions (Giarno *et al.,* 2020). Rainfall contributes to land runoff, which brings nutrients to the bay, a key factor in eutrophication, particularly in estuarine areas (Koropitan *et al.,* 2009). Since Jakarta Bay has a semi-enclosed boundary in the Java Sea, it gives Jakarta Bay low ocean circulation, as represented by ocean currents, compared to the Lombok Strait, as shown in Figure 5a. Figure 5c shows TRIX and its components tend to give high positive correlation, but no correlation with the ocean current. High trophic

Table 2. Overview of TRIX in area of interest with possible causes

Area of Interest (AOI)	Highest TRIX class	Period of Highest TRIX	Boundary condition	Possible cause
Jakarta Bay	Hypertrophic	Northwest monsoon period	A semi-enclosed coastal water near highly populated area	The northwest monsoon brings increased precipitation, which leads to higher river discharge. This influx of freshwater carries nutrients from the land into the coastal waters.
Lombok Strait	Hypertrophic	Southeast monsoon period	A strait water area part of the Indonesian Through Flow canal	Nutrient flux from ITF plus coastal upwelling period in south Java extend.

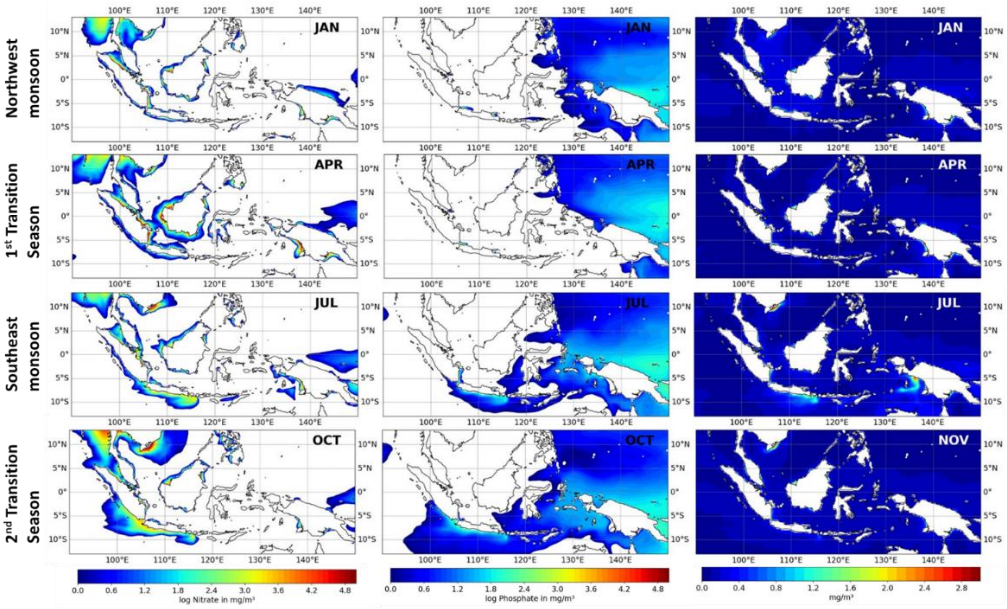

Figure 2. Modeled seasonal variability of Nitrate, Phosphate, and Chlorophyll-a concentration in Indonesian Waters.

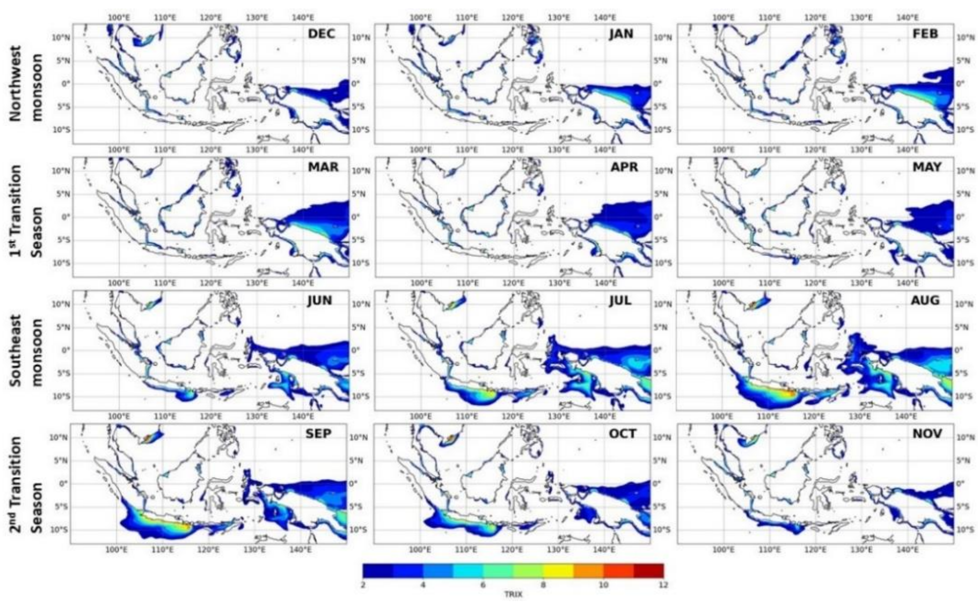

Figure 3. Seasonal Variability of Trophic Index (TRIX) in Indonesian Waters.

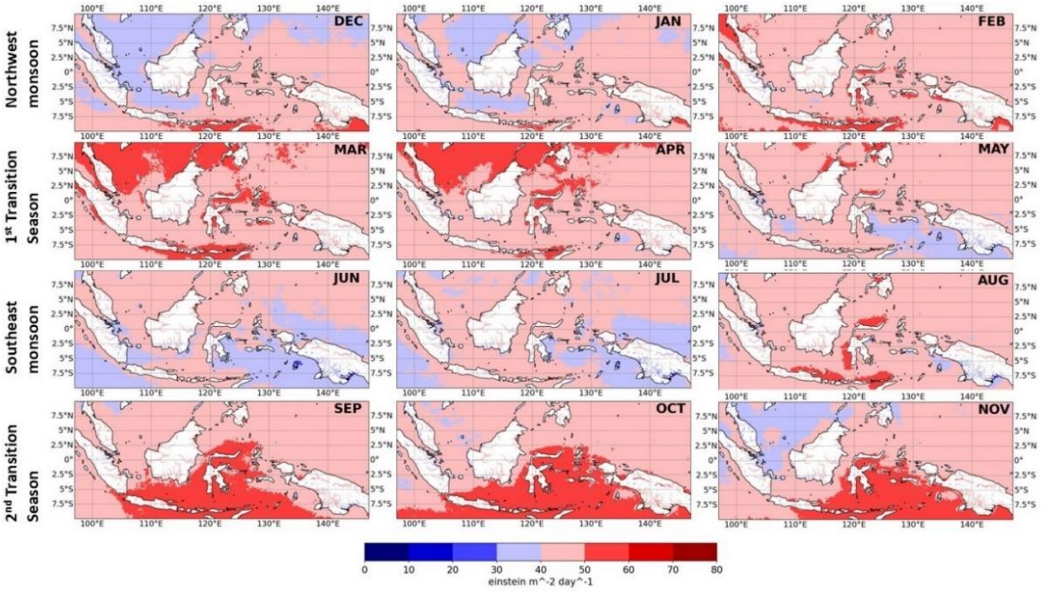

Figure 4. Seasonal Variability of Photosynthetically Active Radiation (PAR) in Indonesian Waters.

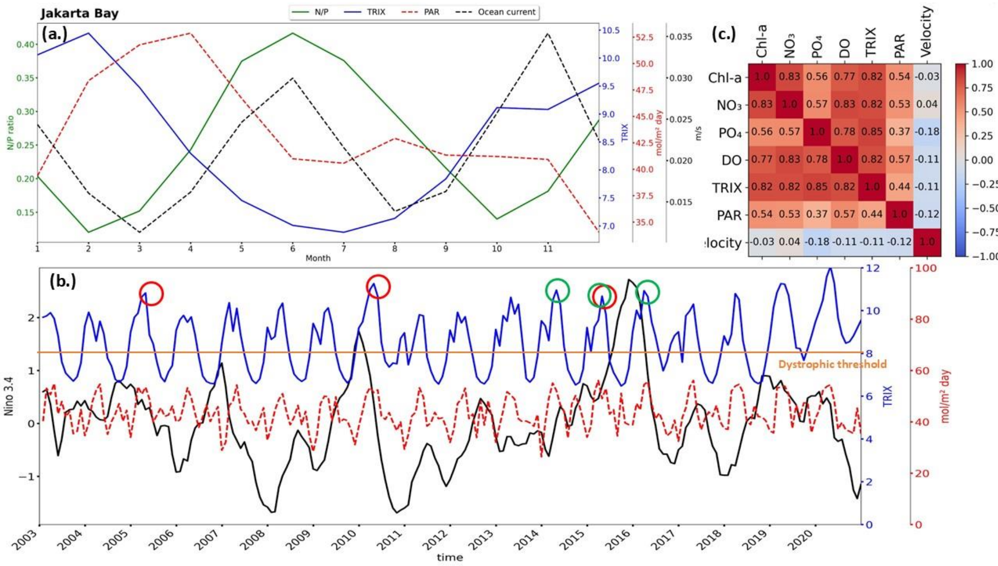

Figure 5. Area of interest: Jakarta Bay: (a.) Seasonal Variability parameters, (b.) Timeseries TRIX, PAR, and Nino 3.4, (c.) Pearson correlation of parameters. Red circle: reported mass fish mortality in (Sidabutar *et al.,* 2021) and green circle reported large area alga-blooms in (Damar *et al.,* 2020).

and low ocean circulation conditions cause frequent algal blooms and hypoxia, negatively impacting fish populations and leading to fish kills (Ladwig *et al.,* 2016). These conditions threaten local fisheries and food security, while also contributing to the degradation of coral reefs and the exploitation of other marine resources (Baum *et al*., 2016). To address these issues, effective management strategies are needed to reduce nutrient inputs from urban and river runoff. These strategies include better wastewater treatment, stricter regulations on industrial discharges, and promoting sustainable agricultural practices to minimize nutrient runoff.

Lombok Strait

Lombok Strait is a strait ecosystem connected with the Indonesian Throughflow (ITF), and located Southern Java upwelling area (Wahyudi *et al.,* 2023) as shown in Figure 1. Trophic status of the Lombok Strait is classified as hypertrophic, with its highest TRIX value of 9.0 occurring during the southeast monsoon (Figure 6a). Blooming of chlorophyll-a in the strait happens later and lasts longer shown in Figure 2, because of constant high nutrient flux from ITF (Purba and Khan, 2019; Taufiqurrahman *et al.,* 2020). This nutrient influx is greater and more consistent during

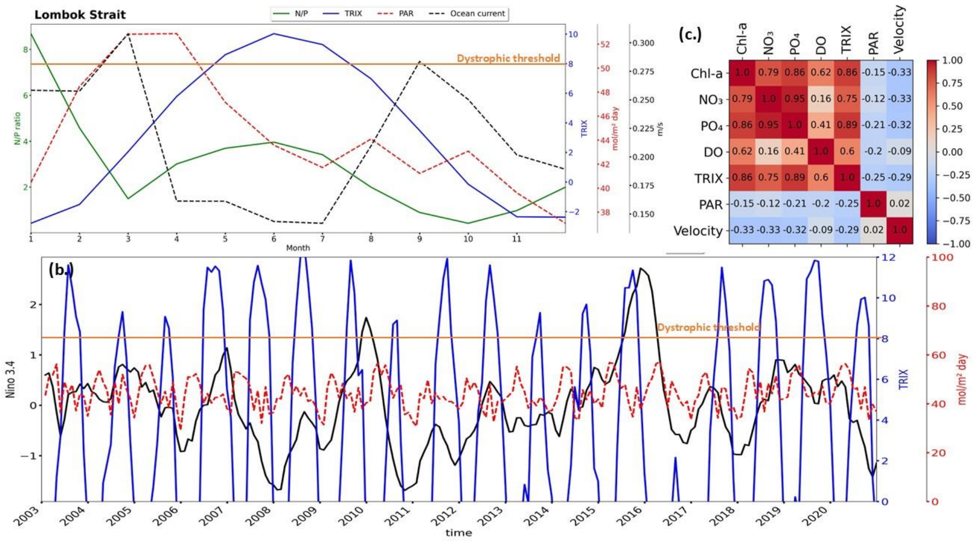

Figure 6. Area of interest: Lombok Strait: (a.) Seasonal Variability parameters, (b.) Timeseries TRIX, PAR, and Nino 3.4, (c.) Pearson correlation of parameters

the northwest monsoon, supported by its lower current velocities, as shown in Figure 6a (Ayers *et al.,* 2014). Inversely, during the northwest monsoon shown in Figure 6a, TRIX tends to be low since the end of the upwelling session and the strengthening ocean current. It shows a moderate negative correlation between TRIX and ocean current velocity, as shown in Figure 6c. Additionally, tidal mixing in this area enhances nutrient distribution and primary production (Susanto and Ray, 2022). Since Lombok Strait is open ocean, high trophic levels don't imply a high risk of eutrophication disaster. Instead, these conditions support the growth of high-trophic biota, making it an ideal area for fisheries (Xu *et al.,* 2021). Therefore, applying just TRIX as a potential eutrophication disaster is not enough. Physical oceanography and boundary conditions should be considered.

Conclusion

The Global Model Biogeochemical PISCES Hindcast data effectively maps the spatial and seasonal patterns of eutrophication in Indonesian waters. TRIX model is higher in the southern islands during the southeast monsoon and in the northern islands during the northwest monsoon. This seasonal variation is primarily driven by monsoons, which affect Photosynthetically Active Radiation (PAR) and ocean currents. However, using TRIX model alone is insufficient for predicting eutrophication disasters; physical oceanography and boundary conditions must also be considered. This leads to different implications depending on the area. In this research, high trophic levels in low-circulation, semi-enclosed areas like Jakarta Bay tend to lead to algal blooms. In contrast, in high-circulation waters like Lombok Strait, algal blooms are less likely, and these conditions can be a positive indicator for suitable fisheries areas. This TRIX data is valuable for informing policy and mitigation plans for Indonesian waters. Future studies should improve the accuracy of models for coastal areas by incorporating more specific parameters such as anthropogenic activity and population growth. This will enhance the effectiveness of monitoring and mitigating algal blooms and assist in assessing water quality for marine spatial planning.

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