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# Spatial and Temporal Dynamics of Marine Trophic Status Using the Trophic Index in Bone Bay, Indonesia

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## ABSTRACT

Coastal waters are currently receiving anthropogenic impacts from the mainland that caused the natural conditions to change to higher nutrient content. This study was conducted to examine the spatial and temporal dynamics of trophic status and how zone location and rainfall category affect the distribution of trophic status. Water quality data were collected for 6 months with different rainfall intensities at 16 observation stations. Trophic status was determined using the TRIX index which combines biological, physical, and chemical water variables. Rainfall had no significant effect on the TRIX index with a p-value of 0.223 (> 0.05), but the distance from the land had a significant effect with a p-value of (< 2e-16). In coastal waters in the 1st zone, the average TRIX value was 5.93 ± 0.23 (high trophic status/eutrophy that tends to be very high/hypertrophy), in the 2nd zone was 5.49 ± 0.21 (high trophic status/moderate trophy), in the 3rd zone was 5.23 ± 0.25 (high trophic status/eutrophy that is slightly low) and in the 4th zone was 4.47 ± 0.47 (moderate trophic status/mesotrophy). Based on PCA analysis and correlation for water quality data, Index TRIX had a strong positive correlation with phosphate (0.92), TSS (0.91), chlorophyll-a (0.089), temperature (0.88), nitrate (0.83), and moderate positive correlation with turbidity (0.68). In addition, the TRIX index had a strong negative correlation with salinity (-0.85), a moderate negative correlation with TDS (-0.77) and DO (-0.62), and a weak correlation with pH (-0.09). There has been eutrophication in coastal areas, especially in the near shoreline zone and tends to decrease at more distant locations. It is necessary to manage anthropogenic waste based on quality standards to ensure that coastal waters are healthy and support sustainable ecosystems.

**Keywords:** status trophic, TRIX, eutrophication, water quality, coastal management.

## INTRODUCTION

Coastal ecosystems are unique areas that are directly adjacent to the sea and land, making them vulnerable to local disturbances such as human activities on land, also known as anthropogenic influences. Fertilizer and pesticide runoff from agriculture, along with livestock waste, aquaculture waste, harbor waste, and domestic sewage flow into rivers and eventually reach coastal waters (Burke et al., 2012). This terrestrial runoff alters water quality by enriching inorganic nutrients and particulate organic matter (Fabricius, 2005; Melati et al., 2021; Storlazzi et al., 2015). Terrestrial runoff from anthropogenic activities will sooner or later affect the growth rate of phytoplankton and algae (Prasetyo et al., 2022). Nutrients entering coastal waters from anthropogenic sources are referred to as eutrophication (Fabricius, 2011). Eutrophication refers to the presence of an abundance of nutrients in waters, which promotes the growth of algae and other aquatic plants, leading to increased productivity in those waters. Eutrophication is the result of nutrient enrichment, increased algal growth, and disturbance of the ecosystem, mainly due to nitrogen and/or phosphorus compounds. This leads to higher levels of primary productivity and algal biomass, shifts in the distribution of organisms and degradation of water quality (Ferreira et al., 2011). Rainfall patterns alter the discharge of pollutants from rainfall-receiving tributaries to the main body of the river, thereby increasing the pollution load as it flows into coastal waters (Strokal et al., 2021).

Waters can be classified according to their nutrient content and productivity, commonly known as trophic status, i.e., oligotrophy, mesotrophy, eutrophy and hypertrophy (Karydis, 2009). Excessive nutrient levels entering coastal waters can have a range of negative impacts, particularly on coastal ecosystems that are adapted to oligotrophic (low nutrient) conditions, such as mangroves, seagrasses, and coral reefs (Silbiger et al., 2018; Zhao et al., 2021). Eutrophication can damage coastal ecosystems by promoting harmful algal blooms, creating hypoxic zones and anoxic dead zones (D'Angelo and Wiedenmann, 2014), particularly in coral reef ecosystems (Donovan et al., 2020).

To assess the trophic status of coastal waters, the TRIX index can be used (Vollenweider et al., 1998). TRIX can cover a wide range of trophic statuses from oligotrophic to eutrophic and has been officially adopted in Italy to describe the trophic status of its coastal waters (Fiori et al., 2016; Tammi et al., 2015). The TRIX index uses a scale from 0 to 10 to distinguish the trophic state of water. The index is derived from a logarithmic calculation involving four factors related to water productivity: chlorophyll-a, dissolved oxygen, nitrogen, and total phosphorus. Due to the fact that the trophic state of waters is not independent in nature, comprehensive monitoring of water quality (physical, chemical, and biological) was an important strategy that enabled early detection of potential pollution sources, and water quality information is critical to support planning and management of coastal and marine areas under anthropogenic influence (Ngadi et al., 2023).

The purpose of this study is to examine the spatial and temporal dynamics of the trophic status of marginal waters, as well as how distance from land (different zones) and rainfall intensity affect the spatial distribution of aquatic tropical status. The results of this study are expected to provide valuable input for policymakers to facilitate making the right decisions to manage coastal waters that are healthy, natural, and support the life of the ecosystem in it.

## MATERIAL AND METHOD

### Study area

Bone Bay is located in the southern part of Sulawesi Island, Republic of Indonesia, connecting 15 districts in South Sulawesi and Southeast Sulawesi provinces. One of the regencies in South Sulawesi province located on the western side of Bone Bay is Bone Regency. The regency has the third largest population in South Sulawesi with 819,590 people spread across 27 sub-districts and 372 villages. In addition, the district is crossed by 194 rivers (BPS Sulawesi Selatan, 2024). Observations were made around the coastline up to a distance of about 15 km from the coastline. The study area is located at 120° 28' 51.710" East and 4° 34' 11.239" N-S with an area of approximately 92,766.26 ha. To facilitate the categorization of the impact of human activities on land, the observation area was divided into four transect lines with four observation stations per transect, so that there was a total of 16 observation stations as presented in Figure 1. Each transect represents anthropogenic activity, with transect 1 signifying shrimp farming and residential activities, transect 2 representing residential areas along with fishing harbors and transport routes, transect 3 depicting a combination of aquaculture and agriculture, and transect 4 indicating a public shipping harbor alongside aquaculture. Data collection was conducted for 6 months in 2023, from April to September, which is expected to have different rainfall intensities (Meteorological Climatological and Geophysical Agency, 2022, 2022).

### Procedures

*Water quality parameters*

Data collection for TRIX index analysis included in-situ measurements of dissolved oxygen parameters using a HANNA water quality checker HI-9829 series with serial number 03360021. Surface seawater samples were collected for nitrate, phosphate, and chlorophyll-a parameters. Nitrate and phosphate samples were stored in 500 ml clear bottles, and the chlorophyll-a samples were placed

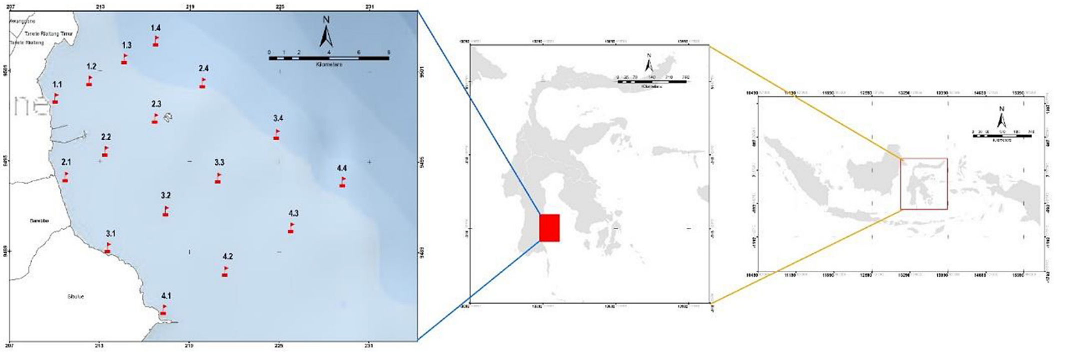


**Figure 1.** The research site was located in Bone Bay, particularly along the coast of Bone Regency. These waters are characterized by turbid water and have a diverse coral reef ecosystem around them. There were four transects held from around the coastline to the open sea. each transect had four observation stations.

in 500 ml bottles covered with black plastic to prevent light interference. The samples were packed in Styrofoam boxes filled with ice to maintain their condition during transport to the Water Quality Laboratory of the Faculty of Marine Science and Fisheries, Hasanuddin University in Makassar for further analysis. Nitrate concentration was measured using a spectrophotometer at 410 nm wavelength, phosphate at 650 nm, and chlorophyll-a at 750-664-647-630 wavelength range.

### *Rainfall*

Rainfall data estimation used global data from Climate Hazards InfraRed Precipitation with Station (CHIRPS) version 2 (Funk et al., 2015). CHIRPS is one of the global rainfall datasets developed by the U.S. Geological Survey (USGS) with a high resolution of 0.05° × 0.05° (about 5 km). CHIRPS rainfall data is a combination of station and satellite rainfall that covers almost all of the earth's land (50 °S–50 °N) and is available on daily, 5-day, and monthly time scales from 1981 to the present (Funk et al., 2015). For this purpose, to obtain high-resolution rainfall where the research was conducted, data from CHIRPS on the page https://chc.ucsb.edu/data/chirps was used. The data obtained in the form of raster data was then converted to points and then adjusted the projection using ArcGIS. The rainfall category is based on the BMKG category (Meteorological Climatological and Geophysical Agency, 2023) as shown in Table 1.

**Table 1.** Rainfall categories

| Rainfall (mm) | Categories |
|---|---|
| 0–100 | Low |
| 100–300 | Medium |
| 300–500 | High |
| >500 | Very high |

## Data analysis

### *Trophic status assessment with TRIX index*

The trophic index (TRIX) is a commonly used index for classifying coastal environments (Vollenweider et al., 1998) with four parameters such as total nitrogen (TN), total phosphorus (TP), chlorophyll-a (*chl-a*), and percentage dissolved oxygen (D%O2) are used in linear combination to assess the status of coastal waters (Vollenweider et al., 1998). To determine the trophic status, the TRIX index was used with the equation (Vollenweider et al., 1998):

$$TRIX = \frac{Log\ (chlA \times aD\%0 \times TN \times TP) + M}{K} \quad (1)$$

where: *ChlA* – chlorophyll-a (mg/m³); *aD*%0 – absolute value of deviation of oxygen concentration (%) to saturation concentration (*aD*%O = |100 – %O2|); *N* – nitrate; *P* – phosphate; *K* – 1.5 (Scale factor 0–10); *M* – 1.2 (constant).

To classify the condition of the trophic status of waters, the TRIX Index used a ranking system ranging from 0 to 10 (Fiori et al., 2016; Prayitno, 2019). TRIX values and water characteristics can be seen in Table 2.

## Statistic analysis

Data were processed using R studio software. The effect of zone and rainfall category on the distribution of the TRIX index was analyzed using a one-way analysis of variance (ANOVA) followed by the Tukey test. ANOVA data with P <

**Table 2.** Characteristics of coastal waters based on the TRIX index

| TRIX value | Status trophic | Eutrophication levels | Water conditions |
|---|---|---|---|
| 0 < TRIX < 4 | Oligotrophy | Low | • Low water productivity<br>• High water brightness<br>• Absence of watercolor anomalies<br>• Oxygen concentration at the bottom of saturated waters |
| 4 < TRIX < 5 | Mesotrophy | Medium | • Medium water productivity<br>• Water is sometimes cloudy<br>• Sometimes watercolor anomalies appear<br>• Sometimes there are hypoxic events at the bottom of the water |
| 5 < TRIX < 6 | Eutrophy | High | • High water productivity<br>• Low water brightness<br>• Watercolor anomalies often appear<br>• Hypoxic waters<br>• Sometimes there are anoxic events at the bottom of the water<br>• Benthic organisms under stress |
| 6 < TRIX < 10 | Hypertrophy | Very high | • Very high-water productivity<br>• Very high-water turbidity<br>• Watercolor anomalies are widespread and persistent<br>• The incidence of hypoxia and anoxia is widespread and sustained<br>• High mortality rate of benthic organisms<br>• There was a change in the benthic community and a high decline in biodiversity |

Source: (Fiori et al., 2016; Prayitno, 2019; Vollenweider et al., 1998)

0.05 were classified as statistically significant. To investigate the relationship between water quality variables and the TRIX index, principal component analysis (PCA) was used and Pearson correlation was used to see the correlation.

## RESULT AND DISCUSSION

### Trophic status assessment using TRIX index application

Assessing trophic status is essential for determining the health of coastal aquatic ecosystems. Through analyzing nutrient levels and trophic dynamics, researchers, and decision-makers can gain an understanding of the ecological state of coastal marine ecosystems (Bricker et al., 2003) such as Bone Bay. The results of the calculation of the four parameters of trophic status assessment using the TRIX index application can be seen in the distribution of each month at the observation location as shown in Figure 2.

For convenience, station grouping is carried out based on distance from the coastline (zone) where the 1$^{st}$ zone as the closest zone includes stations 1.1, 2.1, 3.1 and 4.1. In the 2$^{nd}$ zone there are stations 1.2, 2.2, 3.2, and 4.2. In the 3$^{rd}$ zone is a combination of stations 1.3, 2.3, 3.3, and 4.3 while the 4$^{th}$ zone as the zone with the most distance is station 1.4, 2.4, 3.4, and 4.4. Figure 2 shows the variation of TRIX index value in different months at each observation station. The TRIX index value seems to constantly decrease with the distance of the station from the coastline (Figure 2a). This was quite different when viewed from the temporal pattern shown by the TRIX value per month which did not show a constant pattern between months of observation (Figure 2b).

Based on the TRIX value at each station (Figure 2a), it can be seen that the 1$^{st}$ station has a higher value compared to stations further away from the coastline. The average TRIX value in the 1st zone was 5.93 ± 0.22 which can be categorized as waters with high trophic status (eutrophy) and even tend to be very high (hypertrophy). The highest TRIX value in the 1st zone was 6.23 (hypertrophy) at station 2.1 in April and the lowest value was 5.46 (eutrophy) at station 1.1 in June (Figure 2a). The high value of the TRIX Index throughout the month of observation in the 1$^{st}$ zone is thought to be due to the influx of nutrients from land and changing the trophic status of coastal waters to be more fertile. The average TRIX index value in the 2$^{nd}$ zone was 5.49 ± 0.20 (eutrophy), the highest value found was 5.86 in July and the lowest found was 5.04 in September, both of which were at observation station 4.4

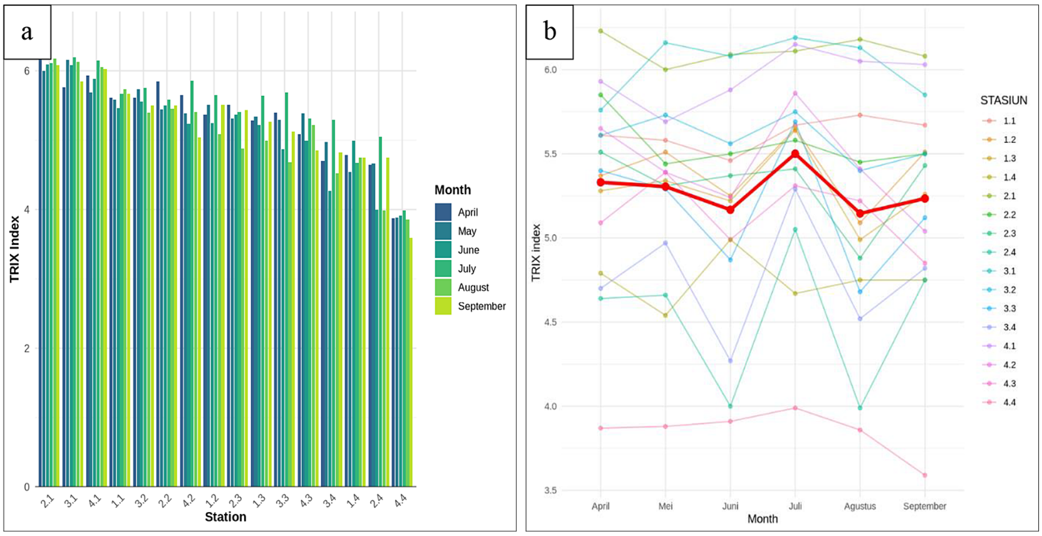


**Figure 2.** Distribution of TRIX index values every month at each observation station (a) and the trend of TRIX index values per month of observation with thick red lines showing the average TRIX index (b)

(Figure 2a). The average trophic status of the waters was in eutrophic conditions throughout the observation month, presumably because the influence of water conditions in the 1st zone still had a strong enough influence on the 2nd zone. The mixing of seawater masses due to various forces that occur in the ocean such as current patterns, wind, tides, and the topographic, has encouraged the mixing of water masses between very high trophic status categories from the coastline with water masses from more distant waters so that in general the condition of trophic status at the 2nd station was eutrophic (high).

In the 3rd zone, the average TRIX value is 5.23 ± 0.25 which is still in the eutrophy category. The highest TRIX value of 5.69 was found in July and the lowest value of 4.68 in August and both were found at station 3. In this 3rd zone, spatial and temporal dynamics fluctuate where there is an average trophic status in the high category (eutrophy) but there are also several moderate trophic statuses (mesotrophy). Mesotrophy conditions can be seen in June (stations 3.3 and 4.3), August (stations 1.3, 2.3, and 3.3), and September (station 4.3). Fluctuations in the value of the TRIX Index in the 3rd zone are not only influenced by the water conditions from the mainland, but also by current patterns in open sea.

In the 4th zone which is the farthest observation station from the mainland, the average TRIX index was 4.47 ± 0.46 which is a trophic status with the mesotrophy category. The highest value was 5.29 found at station 3.4 in July and the lowest value of 3.59 was found at station 4.4 in September. In the average TRIX value based on the month of observation, there is an observation station that has an oligotrophic trophic status, namely station 4.4 which is the farthest observation station from the mainland. In this zone, the influence of land on water conditions decreases and is more influenced by various oceanographic factors, especially current patterns which are considered as one of the factors that affect the mixing of water masses (Dewi et al., 2019).

The spatial distribution of aquatic trophic status can be visualized in a map using kriging interpolation as shown in Figure 3. The interpolation was done on an area of 92,766.26 ha and showed 4 categories of trophic status with different spatial and temporal distributions. The very high trophic status category (hypertrophy) was found around the mainland and more concentrated around the estuary with varying areas. In most of the water areas directly adjacent to the mainland, the trophic status of the waters was in the high category (eutrophy), except in July when most of the waters adjacent to the mainland were in the very high category. In areas farther from land and more open waters, the condition of the waters slowly changed to medium trophic status and some areas experienced low trophic status conditions (oligotrophic). These oligotrophic conditions are around the fringing coral clusters surrounded by deep waters. The high distribution of trophic status along the observation area should be a warning to all of us that the potential for ecological disasters in the coastal waters of Bone Bay could be worse, both for the biota utilized by fishermen and for the coastal ecosystem.

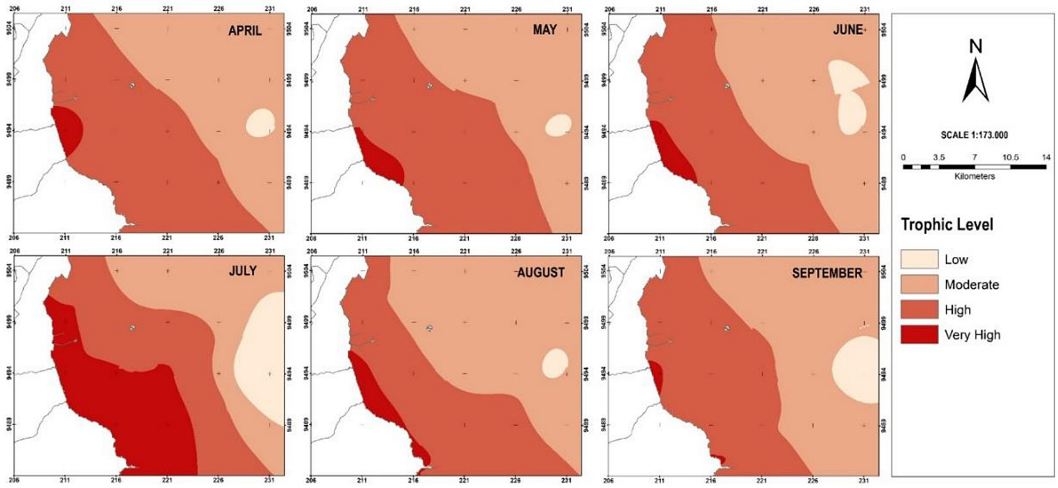


**Figure 3.** Spatial and temporal distribution of trophic status using the TRIX index during observations in April–September

## Trophic status dynamics based on local rainfall

Rainfall is a significant variable that contributes to the dispersion of nutrients from urban areas through rivers to reach coastal waters. Although rainfall is a short-term variation and dynamic change, it can determine important changes in nutrient concentrations and trophic status of coastal waters (Fonseca et al., 2021). Based on the 2023 season forecast issued by the Meteorological, Climatological, and Geophysical Agency of Indonesia (BMKG) (Meteorological Climatological and Geophysical Agency, 2022), the rainy season on the eastern side of Bone district lasts from March to July and the dry season starts in August (Meteorological Climatological and Geophysical Agency, 2022).

Average rainfall in April–September based on data published by CHIRPS at the research location as shown in Table 3. The results of processing rainfall data obtained from CHIRPS showed that rainfall in April–May was categorized as moderate intensity (range 100–300 mm/month), June–July was at high intensity (range 300–500 mm/month) and in August–September had low rainfall intensity (range 0–100 mm/month). The intensity of rainfall that occurs on the eastern side of Bone Regency will be one of the variables that will be used to see changes in the trophic level.

In Figure 4 it can be seen that the high rainfall category has the highest average TRIX index of 5.40 ± 0.60, followed by medium rainfall with an average TRIX index of 5.31 ± 0.43 and low rainfall of 5.13 ± 0.76. The low rainfall category has a wide range of TRIX index values which can be seen in Figure 4 if the box and whisker size look longer than the others. Visually, the difference in TRIX index values consistently decreases based on low rainfall but statistically needs to be tested further. The results of statistical analysis using ANOVA to see the significance of differences between rainfall categories are displayed in Table 4.

The P-value (Pr (> F)) for this variable was 0.223 which was greater than the 0.05 level of significance which indicated that there was no statistically significant difference in the TRIX index between the various rainfall categories (Table 4). It can also be explained that there is no effect of rainfall category in determining the trophic status value of waters using the TRIX index. The low F value (1.526) indicates that the variability between rainfall categories is not much greater than the variability within categories. In future research, more rainfall data and longer observation time may be required given that in the tropics, rainfall intensity does not fluctuate to extremes.

**Table 3.** Average monthly rainfall around the study site based on CHIRPS data

| Month | Rainfall average (mm) | Category |
|---|---|---|
| April | 190.55 ± 5.07 | Medium |
| May | 232.15 ± 43.33 | Medium |
| June | 321.55 ± 70.22 | High |
| July | 321.85 ± 99.74 | High |
| August | 65.9 ± 20.81 | Low |
| September | 44.85 ± 9.59 | Low |

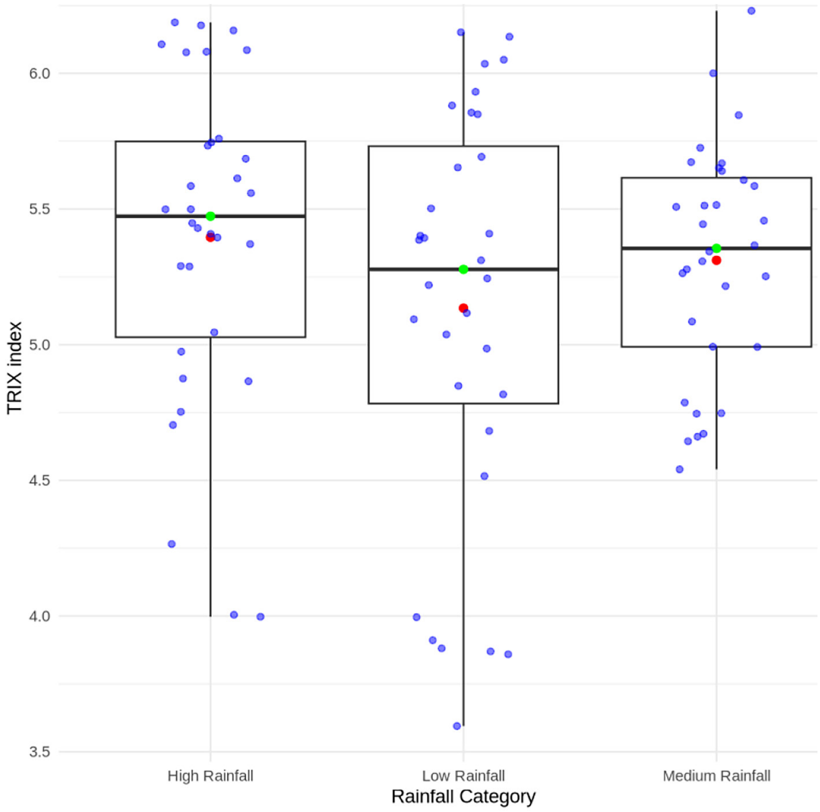


**Figure 4.** Boxplot distribution of aquatic trophic status with TRIX index based on rainfall category

**Table 4.** Results of analysis of variance (ANOVA) rainfall category on TRIX index values

| Specyfication | Df | Sum Sq | Mean Sq | F value | Pr (> F) |
|---|---|---|---|---|---|
| Rainfall category | 2 | 01.14 | 0.5677 | 1.526 | 0.223 |
| Residuals | 93 | 34.61 | 0.3721 | – | – |

## Trophic status dynamics based on distance from shoreline (zone)

Eutrophication in coastal waters caused by anthropogenic activities that are not properly treated has been considered one of the most important effects of global changes in water conditions, especially in tropical countries because round-the-clock sunlight increases the metabolic response of phytoplankton and algae (Fonseca et al., 2021). Visualization of trophic status based on the TRIX index in different zones based on distance from the coastline can be seen in Figure 5.

Based on Figure 5, it can be seen that there was a decreasing trend in the average TRIX from the 1$^{st}$ zone to the 4$^{th}$ zone. In the 1$^{st}$ zone, the average TRIX value is 5.93 ± 0.23, in the 2$^{nd}$ zone is 5.49 ± 0.21, in the 3$^{rd}$ is 5.23 ± 0.25 and in the 4$^{th}$ zone is 4.47 ± 0.47. Although there is a decreased TRIX value based on the distance of the zone from the mainland, the standard deviation shows an increasing trend from the 1st zone to the 4th zone, indicating that the farther away from the mainland the data variation becomes more diverse. In zones closer to land, TRIX index data tends to be more stable throughout the study period. This can be influenced by the intensity of anthropogenic and oceanographic influences which are more stable when compared to the zone furthest from land. To determine the effect of a zone on the TRIX index value, a one-way ANOVA was conducted with the results shown in Table 5. The very small p-value (< 2e-16) indicates that there was a very significant difference in the TRIX index between

**Table 5.** Results of analysis of variance (ANOVA) station distance from shoreline (zone) with TRIX index value

| Specyfication | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
|---|---|---|---|---|---|
| Rainfall category | 2 | 27.042 | 9.014 | 95.29 | -2e-16*** |
| Residuals | 93 | 8.703 | 0.095 | | |

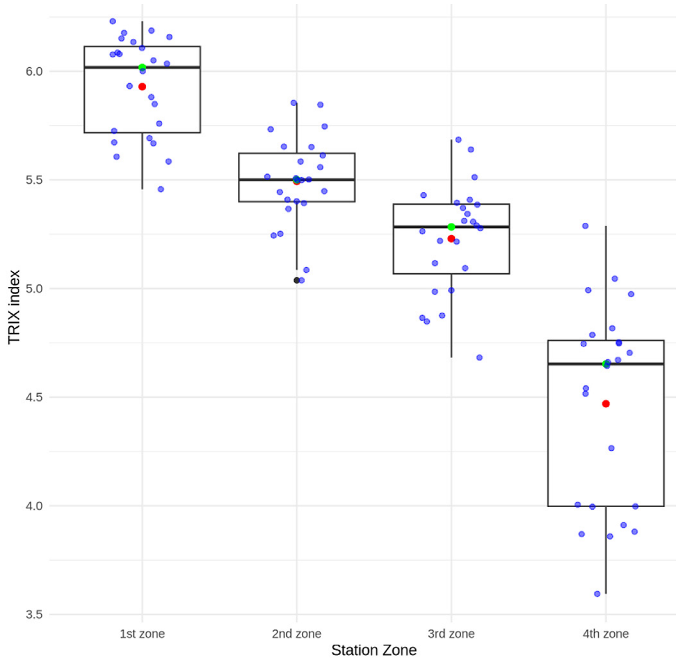


**Figure 5.** Boxplot of the distribution of trophic status with the TRIX index based on the distance category of the observation zone from the mainland.

the various zones and the zone variable had a significant influence on the TRIX index. The high F-value (95.29) (Table 5) indicates that the variability between zones was much greater than the variability within zones. This supports the conclusion that the zone has a significant influence on the TRIX index. The significant difference could be influenced by the higher nutrient load received by the water zone close to the shoreline compared to the zone far from the shoreline.

## Water quality variables

The average temperature observed was 29.59 ± 0.85 °C with the highest average temperature being 32.73 °C and the lowest 27.97 °C (Figure 6a). The highest temperature variation was found an area close to land (station 3.1) while the lowest temperature was found far from land (station 4.4). The highest temperature occurred in May and the lowest in September. The average salinity measured was 33.59 ± 0.93 ppm with the highest mean salinity being 35.67 ppm and the lowest 30.51 ppm (Figure 6b). Rainfall with moderate and high intensity in May-June caused salinity to decrease to 30 ppm at observation stations close to the river in that month. The average water acidity (pH) was 7.77 ± 0.09 and there was no significant difference between the observation stations (Figure 6c). The average dissolved oxygen (DO) concentration is 6.82 ± 0.09 ppm (Figure 6d). The lowest DO value was 5.43 ppm measured at station 1.1 which is the station the closest to land and the highest value was 8.91 ppm measured at station 4.4 which is the farthest station from land. The lowest DO concentration was found in September and the highest concentration was found in June which has high rainfall intensity. Lower DO concentrations near the mainland indicate the potential for organic matter decomposition, where bacteria require dissolved oxygen for the decomposition process. Therefore, higher organic matter content in the water will lead to greater oxygen demand.

The average turbidity value was 3.85 ± 8.26 FNU with a minimum value of 0.00 FNU and a maximum value of 51.20 FNU (Figure 6e). The highest turbidity occurred at all observation stations close to land with shallow waters than at stations further away with deep water conditions. The average turbidity value of distant and deep stations was 0.03 FNU. Likewise, the total suspended sediment (TSS) parameter where the average concentration was 173.36 ± 52.01 ppm (Figure 6f) with the highest value of 282 ppm found at the nearshore and the lowest value of 93 ppm at the distant station. The average value of TSS in shallow water was 209.92 ppm and in areas further from land with deeper water conditions, the average concentration was 136.81

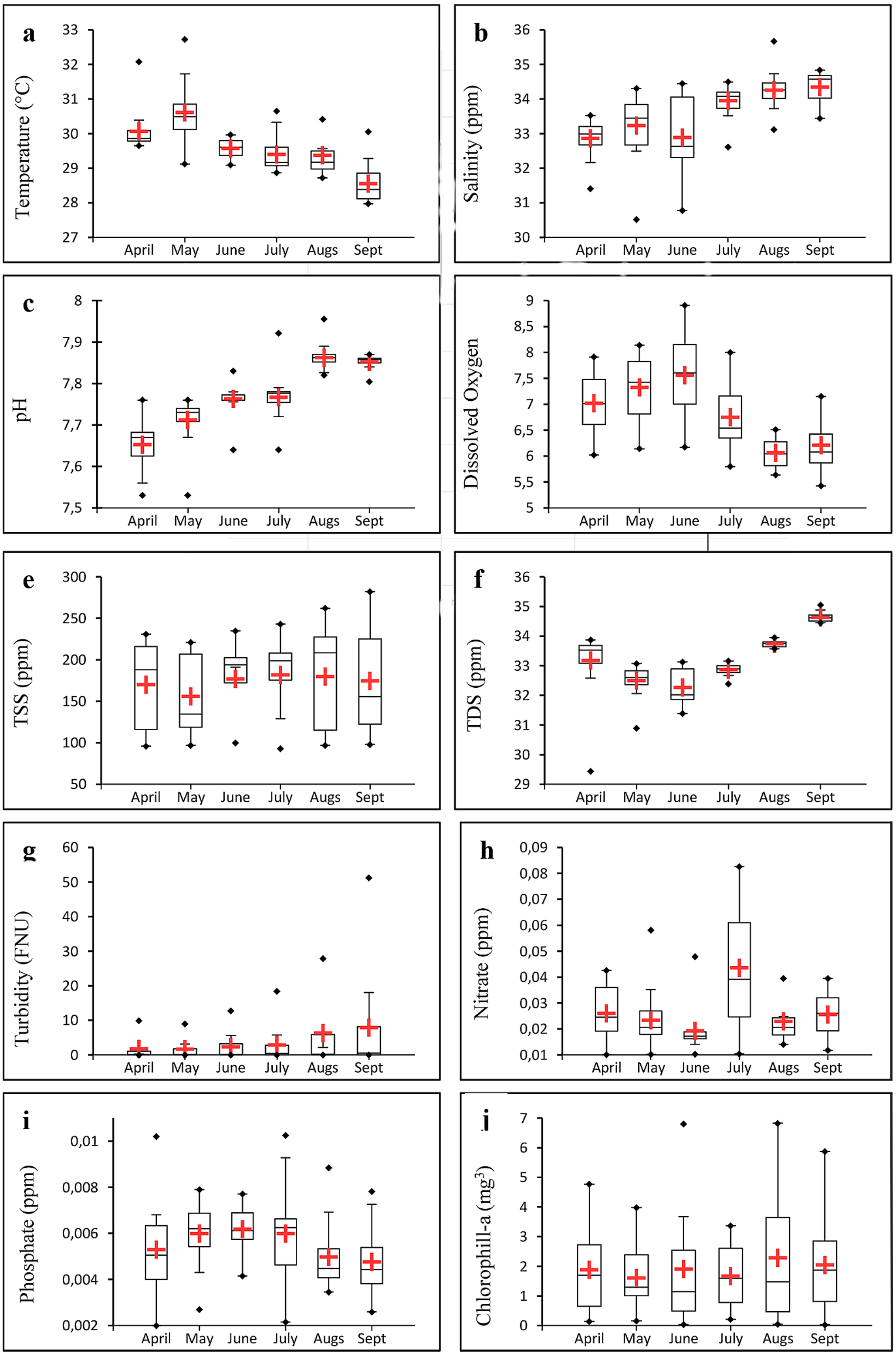


**Figure 6.** Characteristics of surface water quality in Bone Bay. Temperature (a) salinity (b) pH (c) dissolved oxygen (d) TSS (e) TDS (f) turbidity (g) nitrate (h) phosphate (i) and chlorophyll-a (j)

ppm. Similarly, the total dissolve solid (TDS) parameter was higher in the nearshore waters where the average TDS was 33.20 ± 0.96 ppm with a minimum value of 29.44 ppm and the highest of 35.20 ppm (Figure 6g).

Based on the results of observations, the average concentration of nitrate was 0.0269 ± 0.0147 (Figure 6h) and this result exceeded the quality standards set by the Government of the Republic of Indonesia which set a value of 0.008 mg/l for good marine biota life (Keputusan Menteri Lingkungan Hidup No. 51 Tahun 2004 Tentang Baku Mutu Air Laut, 2004). The lowest nitrate concentration was measured at station 4.4 in April at 0.0101 mg/l and the highest concentration was measured at station 4.1 in July at 0.0826 mg/l. In April, there was high rainfall which increased the nitrate concentration especially in the waters bordering the land as observed at station 4.1.

Phosphate is an essential element for the growth and maturation of marine life forms, especially phytoplankton. However, excessively high levels in the water can cause potentially harmful phytoplankton blooms that can result in the loss of various marine organisms. Based on the results of observations, the average concentration of phosphate is 0.0055 ± 0.0016 (Figure 6i) and this result exceeded the quality standards set by the Government of the Republic of Indonesia which set a value of 0.015 mg/l for good marine biota life (Keputusan Menteri Lingkungan Hidup No. 51 Tahun 2004 Tentang Baku Mutu Air Laut, 2004). The lowest phosphate concentration value 0.0020 mg/l was found at station 2.1 and the highest concentration value was 0.0102 which was found at observation station 4.4. This may reveal that anthropogenic activities from land are likely to influence the increase in phosphate concentration in coastal waters directly adjacent to land.

Chlorophyll-a is an important pigment in algae and plants, playing a critical role as a molecule that plays an important role in the photosynthetic process (Soares et al., 2021) and is often used as a surrogate to assess the amount of algal biomass in an ecosystem (Fabricius, 2005; Zhao et al., 2021). Chlorophyll-a levels in aquatic environments can be an indicator of primary productivity and overall ecosystem health (Thompson et al., 2014).

High chlorophyll-a concentrations in coral reef environments may indicate increased algal blooms caused by nutrient pollution. This excess of nutrients can lead to eutrophication, which adversely affects coral reef health and function. The average concentration of chlorophyll-a during the field observation was 1.9005 ± 1.62 $mg^3$ (Figure 6j) with the lowest concentration of 0.03 $mg^3$ in September at station 4.4 which is the farthest station from land and the highest concentration of 6.83 $mg^3$ was found at station 3.1. The low chlorophyll-a concentration in September was similar to that found by (Safruddin et al., 2018) in Bone Bay. To determine the water quality components that affect the trophic status of waters based on the calculation of the TRIX index, a PCA analysis was carried out, the results of which are shown in Figure 7.

Based on Figure 7a, it is known that based on the direction of the same or adjacent arrows, the TRIX Index is positively correlated with TSS, phosphate, temperature, and chlorophyll-a. Meanwhile, water quality variables in the opposite direction of the arrow show a negative correlation where salinity, TDS, and DO are in the opposite direction of the TRIX index. The variables of temperature, phosphate, and chlorophyll-a are seen to have more arrow lengths than the other variables which can explain that

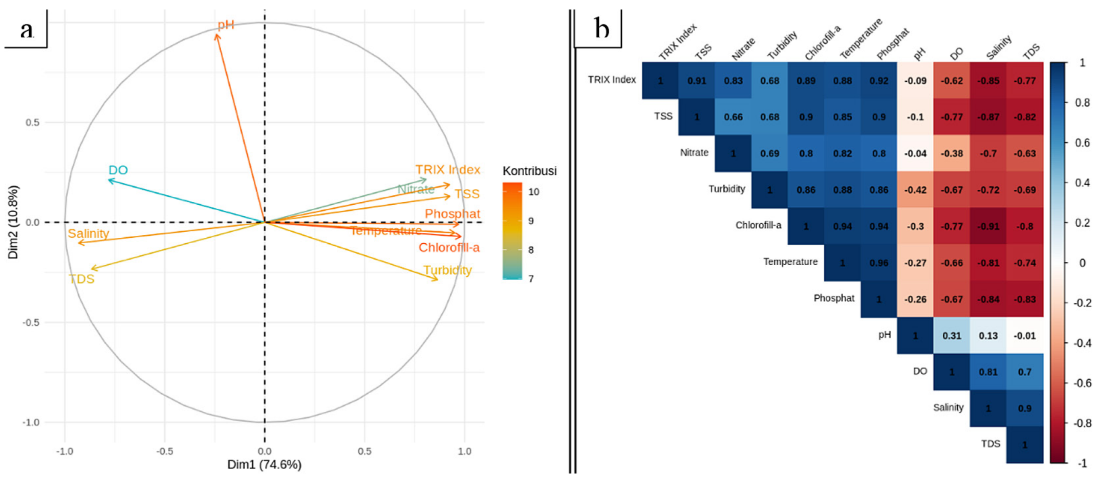


**Figure 7.** Variable factor map showing the contribution of variables to the main dimensions. Each arrow represents one variable and its direction shows how the variable contributes to the main components (dimensions 1 and 2), the length indicates the strength of the contribution and the color of the arrow indicates the level of contribution. Variables with the same or similar arrows show a positive correlation and if opposite show a negative correlation (a) and correlation matrix between TRIX index and water quality variables (b)

the influence of these parameters is greater on the variability of the data. Based on Figure 6 (b) it can be explained that the TRIX index value has a strong positive correlation with phosphate (0.92), TSS (0.91), `chlorophyll-a (0.089), and temperature (0.88) while the TRIX index with the nitrate variable has a moderate to strong positive influence (0.83) and the turbidity variable has a moderate positive correlation (0.68). The TRIX index has a strong negative influence on salinity (-0.85), and a moderate negative correlation with TDS (-0.77) and DO (-0.62). On the pH variable, the TRIX index had a weak relationship (-0.09).

Based on the PCA visualization (Figure 7a) and correlation matrix (Figure 7b), a consistent picture of the relationship between variables in the results of this study can be obtained. Variables with the same or adjacent arrows in the PCA do show a strong positive correlation, while those in the opposite direction show a negative correlation. The TRIX Index value as an indicator of aquatic trophic status, seems to be strongly influenced by temperature, phosphate, TSS, and chlorophyll-a positively and negatively influenced by the Salinity variable.

## CONCLUSIONS

Our results showed that the waters of Bone Bay have been eutrophied based on the TRIX index. The interpolation map of TRIX values shown that the spatial and temporal dynamics of trophic status in Bone Bay have almost the same distribution pattern, except for July which has a wider distribution of trophic status in the very high category compared to other months. During the observation, there were differences in rainfall intensity that supported the temporal dynamics of trophic status, but statistically rainfall did not show a strong relationship with the TRIX index. A different thing happens with the zone system that has been constructed in this study to show spatial dynamics. Statistically, the zones have shown a very strong relationship with the TRIX index values. The closer a zone to the coastline, the higher its trophic status value and the farther a zone from the coastline, the lower its trophic status value. Our results showed that the spatial decline in trophic status by zone was in the range of mean TRIX values of 5.93–4.47. In this study we divided 4 zones and the analysis showed that 3 zones had a TRIX value > 5 (high trophic status or eutrophy) and 1 zone (the farthest zone) had a TRIX value > 4 < 5 which is categorized as medium trophic status or mesotrophy. The distance between the coastline and the farther zone is about 15 kilometres.

The distance of 15 kilometres from the shoreline in this study area can be one of the considerations to provide a scientific reference in determining the spatial distribution of trophic status in marginal bay waters in tropical countries. The distance of about 15 kilometres, ¾ of the area covered by the waters with high trophic status and under the waters there are ecosystems and marine life as a source of food and other functions in the ecology. One of the important ecosystems in the coastal area contained in this research area is coral reefs. More in-depth research on the adaptation of coral reefs in marginal coastal waters with high trophic status is needed, which is very important to understand in supporting the sustainability of the ecosystem, especially the strategic location of Bone Bay which is in the middle of the world's coral triangle. The results of this study are expected to provide preliminary information to encourage further research into the adaptation and role of coral reefs and other ecosystems in highly eutrophied waters.

In the context of bay management by stakeholders, the results of this paper should provide additional information on field conditions. The management of anthropogenic waste on land is very important so that the wastewater is ensured to enter coastal waters according to the quality standards set by the government. The sustainability of coastal resources and ecosystems needs to be a common concern, including strengthening research in coastal waters.

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