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Water Quality Analysis for Ecosystem Health in Tropical Estuary Bali, Indonesia

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ABSTRACT

Anthropogenic activities and land-use change have exhibited significant impacts on estuarine ecosystems. Like many tropical estuarine systems, the Perancak estuary in Bali, Indonesia, experiences substantial seasonal water quality variations. In the current study, seasonal variation in water quality across three zones: the upper (U.E.), middle (M.E.), and lower (L.E.) of the estuary, representing residential areas, mangrove, and aquaculture ecosystems from January to December 2018, were observed. Principal component analysis was used to determaine the variable relationship at each station. The results showed that water quality generally declined during the dry and transition (dry to wet) seasons. This decline occurred mainly during hypoxia in the U.E. zone, indicating a combination of natural and anthropogenic factors. The main natural factor that influences water quality is rainfall. Anthropogenic and vegetation cover factors play equally important roles in the health of estuary ecosystems. The importance of tropical estuary health will become increasingly evident, requiring a thorough understanding of healthy ecosystem functions and management. Effective management and regulation of activities around estuary ecosystems are crucial to protect water quality and the health of these ecosystems.

INTRODUCTION

As human populations grow and urbanization intensifies in coastal regions, oceans, waterways, and aquatic ecosystems often have negative impacts. Estuaries, serving as the natural transition zones between rivers and the ocean, are particularly affected. These areas are especially vulnerable due to their large watersheds, often exceeding the estuaries' size. Urbanization impacts estuaries by increasing sediment, nutrient, and fecal microbial loads, leading to changes in water quality and potentially causing harmful algal blooms.

Additionally, urbanization alters streamflow and salinity, affecting plankton, marshes, seagrasses, shellfish, and fish within these ecosystems **(Freeman *et al.*, 2019)**. Water is a resource that humans require to survive in nature **(WHO, 2014)**. The estuary ecosystem is a transition zone between river basins and coastal water **(Elliott *et al.,* 2019)**. Estuaries are impacted by maritime amplitude, causing changes in the salinity and nutrients. The most severe pollution in the estuaries is the decline in water quality **(Karydis *et al.*, 2013)**. The significant sources of water quality degradation in estuarine aquatic ecosystems are changing the physical, chemical, and biological characteristics of water **(Breitburg *et al.*, 2009)**, as well as reductions in water volume and the discharge of agricultural, household, urban area, and industrial pollutants **(Dunn *et al.*, 2019; Zhou *et al.*, 2021)**. In marine and coastal waters, dissolved oxygen directly impacts environmental health **(Breitburg *et al.*, 2009)**. A hypoxia situation occurs when there is a low concentration of dissolved oxygen in the water **(Zhang *et al.*, 2010)** due to the frequency of effluent and organic matter flows into coastal waters **(Roselli *et al.*, 2013)**. Decreasing oxygen levels in waters has an impact on the ecology of various populations of organisms (growth, distribution, recruitment, reproduction, and survival) and the state of local pollutants **(Breitburg *et al.*, 2009)**. Reduced dissolved oxygen in water is the primary signal of poor water quality and should be monitored and rectified.

Water quality evaluations ensure optimal conditions across whole basins, including estuaries and surrounding coastal waters **(Karydis *et al.*, 2013)**. Recent information on water quality and its changing patterns is essential for the responsible management and sustainable use of natural resources **(Dunn *et al.*, 2019; Mohd-Shazali *et al.*, 2022; WHO, 2014)**. To effectively adapt both episodic and permanent management plans, a comprehensive understanding of factors influencing water quality and the availability of natural resources over different periods is necessary. The estuarine environment is highly dynamic, with water quality potentially changing significantly over short periods. Water quality is affected by seasonal variations, rainfall, and storms **(Wang *et al.*, 2021)**. Therefore, assessing water quality over extended periods is essential rather than relying solely on individual sampling events. In the Jembrana district of Bali, Indonesia, the Perancak estuary spans approximately 7.5km^2 **(Gusmawati *et al.,* 2016)**. This estuary is influenced by the inflow of saline water from the Bali Strait and fresh water from the various rivers that flow through it. The main activities along the Perancak Estuary include aquaculture, port operations, agriculture, recreation, mangrove ecosystem, and household waste disposal. Pollution in the estuary has detrimental effects on the entire basin, impacting water use for public consumption and agriculture **(Costa *et al.*, 2017; Dunn *et al.*, 2019; Elliott *et al.*, 2019)**. Such conditions can degrade the quality of estuarine habitats, leading to potentially hazardous forms of water pollution **(Purba *et al.,* 2020)**. Aquaculture effluent, rich in organic matter, nitrogen, and phosphorus, contributes nutrients that flow into the adjacent mangroves and coastal waters **(Hastuti *et al.*, 2018; Rintaka *et al.*, 2019)**. This study aimed to analyze the seasonal variation in water quality based on indicators monitored in the Perancak Estuary, Bali, Indonesia, from January to December 2018 and to identify the main drivers of these changes.

MATERIALS AND METHODS

Study area

Perancak estuary is located between 08°22'0"S - 08°24'0"S and 114°29'20"E 114°35'20", directly facing the Bali Strait, Indonesia. This estuary is filled by four main tributaries: Tukad Gading, Sablong, Daya Barat, and Daya Timur, which flow from the north (mountainous region) to the south (Bali strait). The area is particularly interesting for research due to the diversity of farming techniques and the dynamic nature of its mangrove ecosystems, combining natural and human-influenced landscapes **(Gusmawati *et al*., 2016)**. The estuary contains a variety of land uses, including active shrimp ponds with semi-intensive or intensive culture systems, abandoned shrimp ponds, fish ponds, polyculture ponds (algae/fish and shrimp), natural mangroves, mangrove plantations, and various forms of abandoned aquaculture **(Rahmania *et al*., 2015; Gusmawati *et al*., 2016)**.

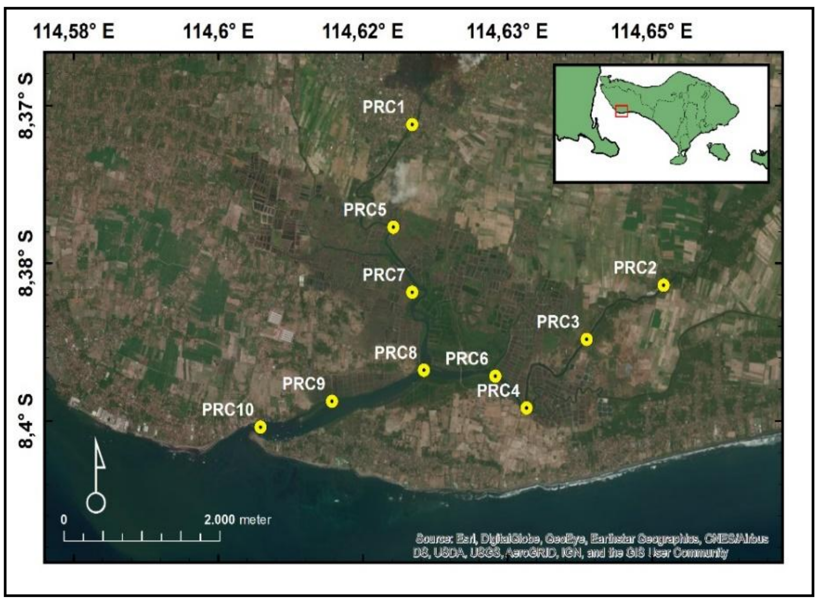

Fig. 1. Location of surface water sample in Perancak Estuary, Bali, Indonesia (Source: Google Maps, adapted)

Data acquisition

Water sampling and analyses

Surface water samples were collected monthly from multiple locations during high tide, from January to December 2018, at ten fixed stations across three zones in the estuary: upper estuary (U.E.), middle estuary (M.E.), and lower estuary (L.E.) (Fig. 1). U.E. is residential (PRC1 and PRC2), M.E. is dominated by aquaculture ponds and mangrove-forested (PRC3 to PRC7). The L.E. zone, including stations PRC8 to PRC10, represented a transitional marine ecosystem zone with multiple river estuaries coverage and intense interactions between tidal movement and river currents. Each month, 50 sample measurements were taken, totaling 600 sample measurements for the year. These measurements included physical parameters such as hydrological temperature (°C) and salinity (ppt), pH, turbidity, T.S.S. (total suspended solids), and dissolved oxygen (D.O.; mgL^{-1}), all measured using a handheld Multi-Parameter Water Quality Checker (*DKK-TOA WQC-24*). Chemical parameters measured included phosphate (PO_4-P), nitrate (NO_3-N), ammonia (NH_3-N), and silica (SiO_2). The study focused on months at the end of each season, as these periods show more distinct environmental reactions. Temperature and salinity were reliable indicators of hydrologic conditions (e.g., marine intrusion, riverine discharges, seasonal changes), while turbidity was a key parameter for understanding hydrodynamics. DO content provided a direct indication of water quality. Water samples for analysis of phosphate (PO_4-P), nitrate (NO_3-N), ammonia (NH_3-N), silica (SiO_2), and biological parameters, including plankton were further analyzed at the water quality laboratory of the Institute for Marine Research and Observation, Ministry of Marine Affairs and Fisheries, Jembarana, Bali, Indonesia.

Meteorolgical data

A monthly rainfall time series from 2015 to 2018 was analyzed to provide a detailed understanding of the climate environment. The data were recorded at the Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG) weather station in Negara, Bali, Indonesia, located 10km north of the Perancak estuary (08°20′40″S - 114°36′98″E).

Data analysis

Data collected were processed into an orthogonal matrix for analysis (n = 600). Coahran's test was used to check the homogeneity of variance, and the original data were Box-Cox transformed to ensure they conformed to a normal distribution. A factorial ANOVA was conducted with a 5% level significance to determine whether there were significant differences existed between categorical predictors, specifically zone (U.E., M, E, and L.E.) and season (dry and wet). The variables (water temperature, salinity, pH, turbidity, and D.O.) were first analyzed separately to study their behavior and detect any differences between repeated sample measurements 1, 2, and 3. The ANOVA results indicated no significant differences between these repeated measurements. Using a complete linkage approach with Euclidean distance, clusters were identified based on similarity matrices. A principal component analysis (P.C.A.) was conducted for each variable under study with a 95% confidence interval. The multivariate analysis demonstrated that physicochemical characteristics of water were interdependent. Given the large number of samples (n = 600), the data were homogenized into averages to enhance the accuracy of observation and interpretations. These averages were calculated by combining samples with the same spatio-temporal condition (season and zone). P.C.A. was used to analyze variables at each station, revealing a relationship between variables and providing a graphical representation **(Ariyanto *et al.*, 2019)**. P.C.A. is widely used for reducing the dimensionality of multivariate problems. The analysis used equation (1) : i and j are row indices, and k represents the colum index (varying from 1 to p). The smaller the Euclidean distance between the substations, the more similar the environmental characteristics are, and vice versa.

$$d^2(i,i') = \sum_{i=1}^{p} \left(x_{ij} - x_{i',j}\right)^2 \quad \text{Eq. (1)}$$

RESULTS

Seasonal variation of rainfall

Perancak estuary in Bali island experiences two primary seasons – the wet season (typically from November to March) and the dry season (from April to October). Seasonal pattern in Indonesia is influenced by monsoon winds in the form of the East and South Asian (SAM) monsoon and the Australian monsoon (AM). Monsoon winds impact the rainfall variability. SAM (October-March) blows, Indonesia will experience the wet season, meanwhile AM (April-September) blows Indonesia will experience the dry season **(Aldrian *et al*., 2003; Chang *et al*., 2004)**.

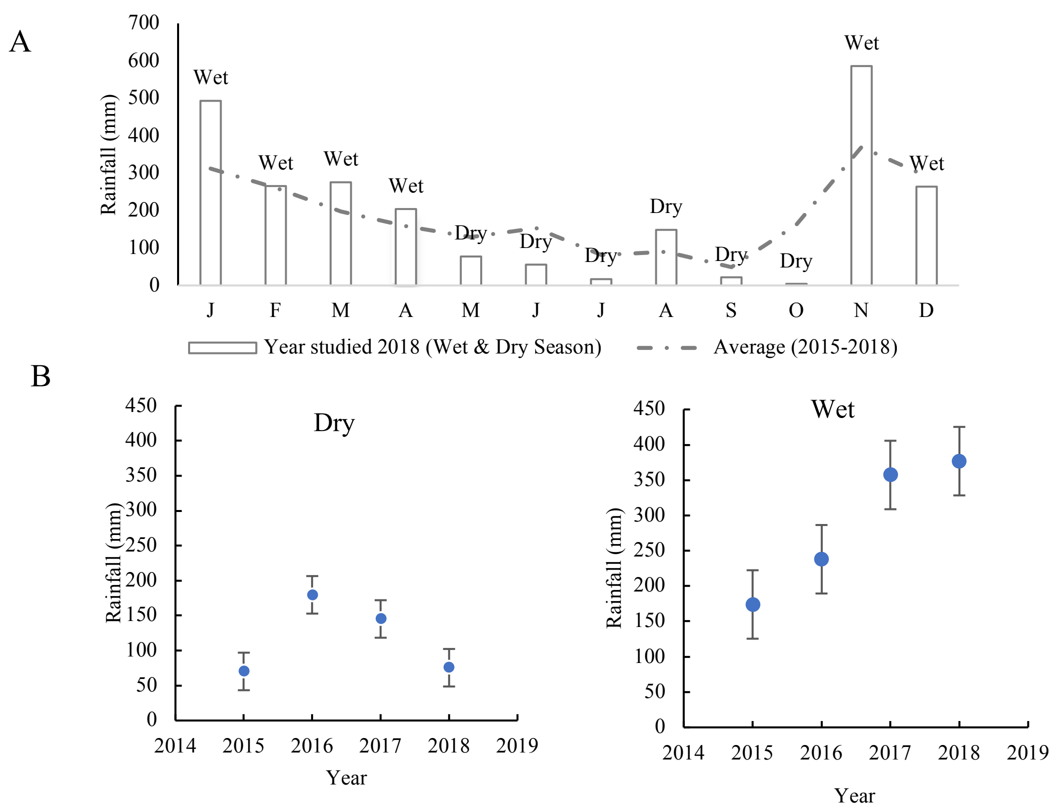

Fig. 2. (A) Most recent climatic rainfall 2015 – 2018 (dotted line) at Perancak estuary in period 2018 of wet and dry season **(B)** Average rainfall of years 2015 – 2018

These seasons significantly impact water quality. The total monthly rainfall varied between 48.9 - 369.4mm during the study period. Averages ranged from 75.5 ± 70.2mm to 179.7 ± 145.2mm/ month during the dry season and from 173.9 ± 237.9mm/ month to 376.8 ± 357.2mm/ month during the wet season (Fig. 2A). The bar graphic shows the wet season

(November to April) and the dry season (May to October). The most recent climatic rainfall average 2015 - 2018 is visible by a dotted line. Regarding total monthly rainfall, wet seasons varied less during the study than dry seasons. The wet season showed a remarkably similar trend throughout the research period, fluctuating less than the dry seasons (Fig. 2B).

Temperature and salinity

The water temperature varied slightly between the wet and dry seasons, ranging from 25.13 to 31.59°C. However, it can be seen that the temperature variations in the dry season are minor compared to those in the wet season. They were also visible in every location. The temperature ranges from 25.13 to 31.59°C in the U.E. zone. Similar variations occurred in zona M.E. from 25.81 to 30.22 °C and were slightly different in L.E. zone from 25.21 to 30.00 °C (Fig. 3A). Salinity varied from 0 to 32.37 PSU, with 47 of 600 sampled values being 0, especially in the U.E. and M.E. zones during the wet season. Salinity ranges from 0 to 21.79 PSU in the zone. Similar variation occurred in zona ME from 0 to 32.03 PSU and slightly different in L.E. zone 20.20 to 32.37 PSU (Fig. 3B)

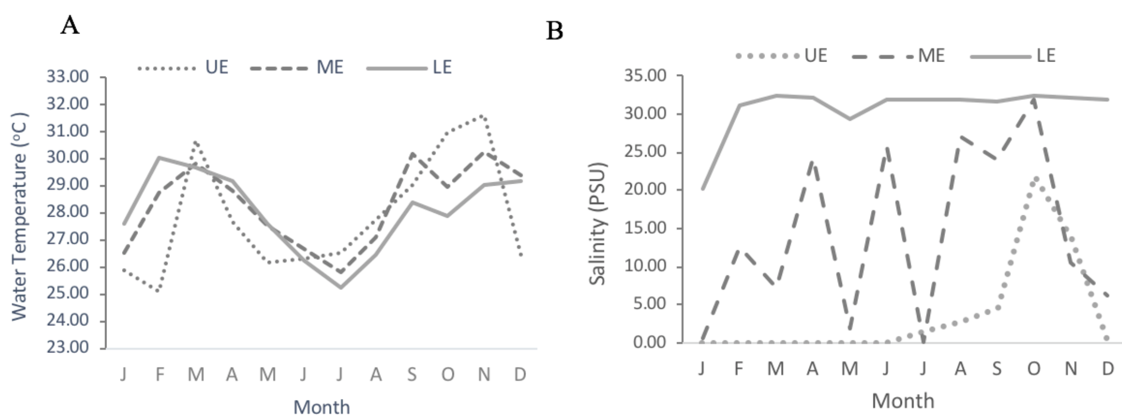

Fig. 3. A-B. Variations of temperature and salinity

Physical observation

Physical parameter observation included DO, pH, and turbidity. DO varied from 1.20 to 8.23mg/ L, with the highest average concentration in the wet season at L.E. zone. Fig. (4A) shows a graph with the normal distribution of the number of observations of dissolved oxygen values obtained (n = 600). It observed a wide range, from 1.20 to 7.43mg/ L in the wet season and 1.80 to 6.55mg/ L in the dry season at the U.E. zone. The wider distance was in the M.E. zone, and the most comprehensive distance was in the L.E. zone in both the wet and dry seasons. It range observed at the M.E. zone was from 4.06 to 6.23mg/ L in the wet season and 3.65 to 6.84mg/ L in the dry season. At LE zone, it ranged from 4.11 to 6.88mg/ L in wet season and 5.21 to 8.23mg/ L in dry season (Fig. 4B). The seasons were different, and so were the zones.

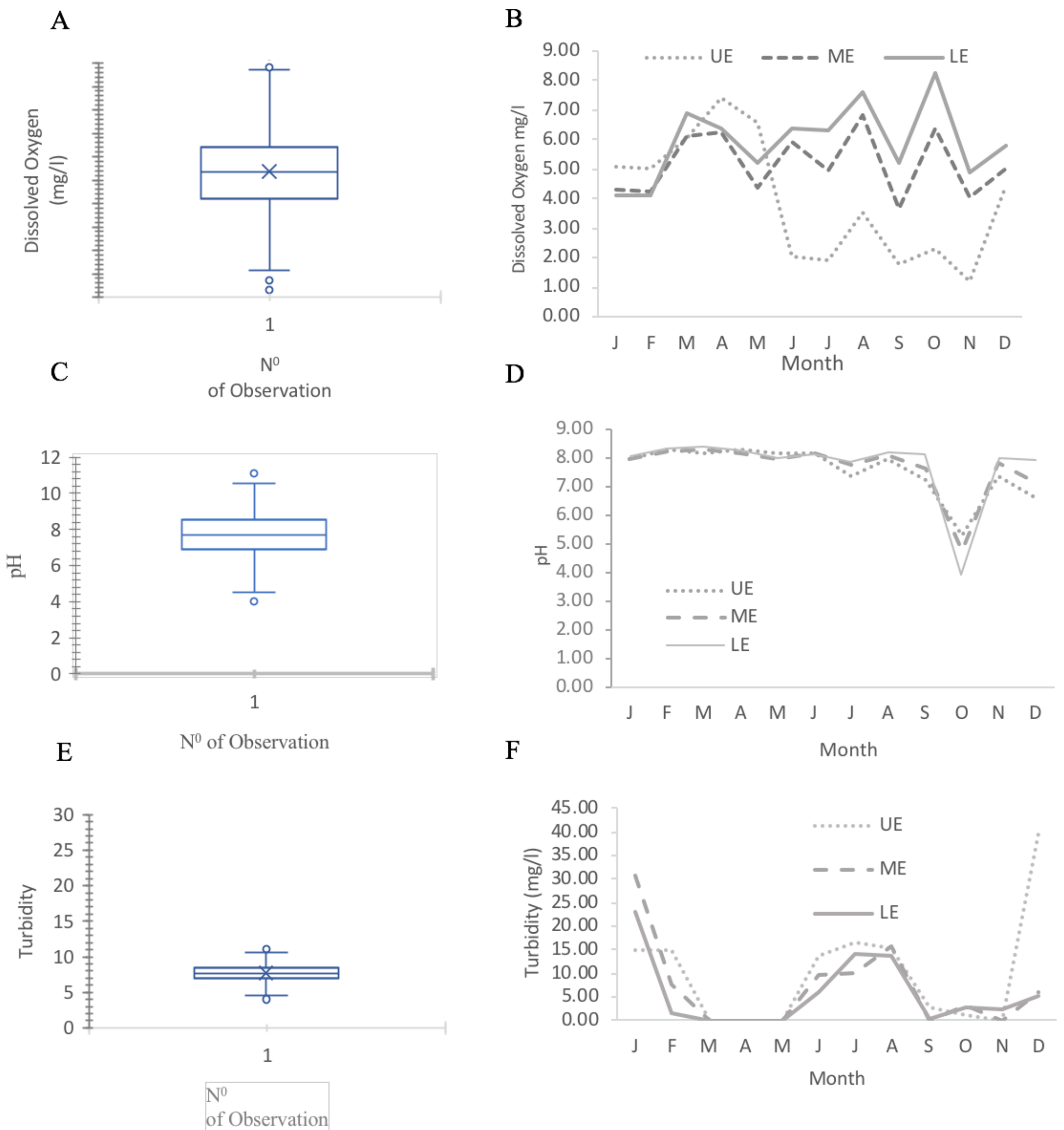

Fig. 4. A-F. Variations and standart deviation of DO, pH, and turbidity throughout the year in the Perancak Estuary

pH varied from 3.92 to 8.39, with the highest average concentration in the wet season. Fig. (4D) shows a graph with the normal distribution of the number of observations of pH values obtained (n = 600). The pH ranged in the wet season from 6.61 to 8.39 and in the dry season from 3.92 to 8.22. In the U.E. zone, the pH varied from 5.31 to 8.16 during the dry season and from 6.61 to 8.33 during the wet season. The pH variation in the M.E. zone was 4.77 to 8.16 in the dry season and 6.61 to 8.33 in the wet season. In the L.E. zone, the pH varied from 3.92 to 8.22 during the dry season and from 7.93 to 8.39 during the wet season. There was more variation across all zones during the dry season than in the wet season. The most comprehensive distance was at the L.E. zone compared to the other two. Low pH in October (Fig. 4D) in three zones (UE, ME, LE), is related to very low rainfall in that month (Fig. 2A) so that there is no leaching and regeneration in the water column. Rainfall is the most essential factor in the renewal and maintenance of water in small tropical estuaries **(Costa *et al*., 2017)**. Turbidity varied from 0 to 30.86 NTUs, showing considerable variation in the year. Turbidity variability was more significant in the wet season than in the dry season. Fig. (4F) shows a graph with the normal distribution of the number of observations of turbidity values obtained (n = 600). The turbidity ranged from 0 to 30.86 NTUs in the wet and dry seasons from 0 to 16.48 NTUs. In the U.E. zone, turbidity varied from 0 to 16.48 NTUs during the dry season and 0 to 14.93 NTUs during the wet season. The turbidity variation in the M.E. zone was 0 to 15.83 NTUs in the dry season and 0 to 30.86 NTUs in the wet season. In the L.E. zone, the turbidity varied from 0 to 13.81 NTUs during the dry season and from 0 to 23.06 NTUs during the wet season. Variations between zones are most significant in the M.E. zone, and less variability was noticed in the U.E. zone.

Table 1. Weight graph (P.C.A.) showing the contribution

Variable	The variables factor coordinates determined by correlations								
	U.E. Zone			M.E. Zone			L.E. Zone		
	Fac 1	Fac 2	Fac 3	Fac 1	Fac 2	Fac 3	Fac1	Fac 2	Fac 3
pH	0.73	0.4	-0.41	-0.5	-0.29	-0.28	-0.38	0.04	0.9
DO	0.76	-0.05	-0.36	0.26	0.35	-0.87	0.75	-0.16	-0.15
Turb.	0.38	-0.25	0.84	-0.73	0.48	-0.2	-0.23	-0.91	-0.24
Temp.	0.05	0.83	0.25	0.38	-0.87	0.18	-0.34	0.79	-0.45
Sal.	-0.95	0.16	-0.1	0.78	-0.06	-0.41	0.69	0.62	0.2
TSS	-0.95	0.14	-0.13	-0.19	-0.58	-0.66	-0.62	0.34	-0.1
Rainfall	0.12	0.83	0.23	-0.64	-0.61	-0.12	-0.9	0.03	-0.05

The cluster analysis grouped observations was recorded into three major groups (G.I., G.II, G.III). Group I was subdivided into two subgroups. Each subgroup was wet season (SG.1-1) and dry season (SG.1-2). Subgroup (S.G. 1-1) comprised sample from U.E. zone (St.1; St.2) during the dry season and subgroup. Subgroup (S.G. 1-2) comprised sample from M.E. zone (St. 3; St.4; St.5; St.6, St,7). Group II was subdivided into wet seasons (SG.2-1) and dry seasons (SG.2-2). According to the principle components analysis (P.C.A.), interrelationships between the variables can be seen in PC1 and PC2 of the data variance that is satisfactorily explained. P.C.A. should account for 70% or more of the initial variability in a data set, according to **Clarke and Warwick (2001)**. If so, it makes sense to explain the phenomenon or global structure of interactions in that way. In the U.E. zone, PC1 explained 43.94% of the total variance and was formed mainly by the variables pH and DO of the year, while PC2 and PC3 represented each 23.73 and 16.39%. PC2 was formed primarily by temperature and rainfall, while PC3 was formed mainly by turbidity (Table 1).

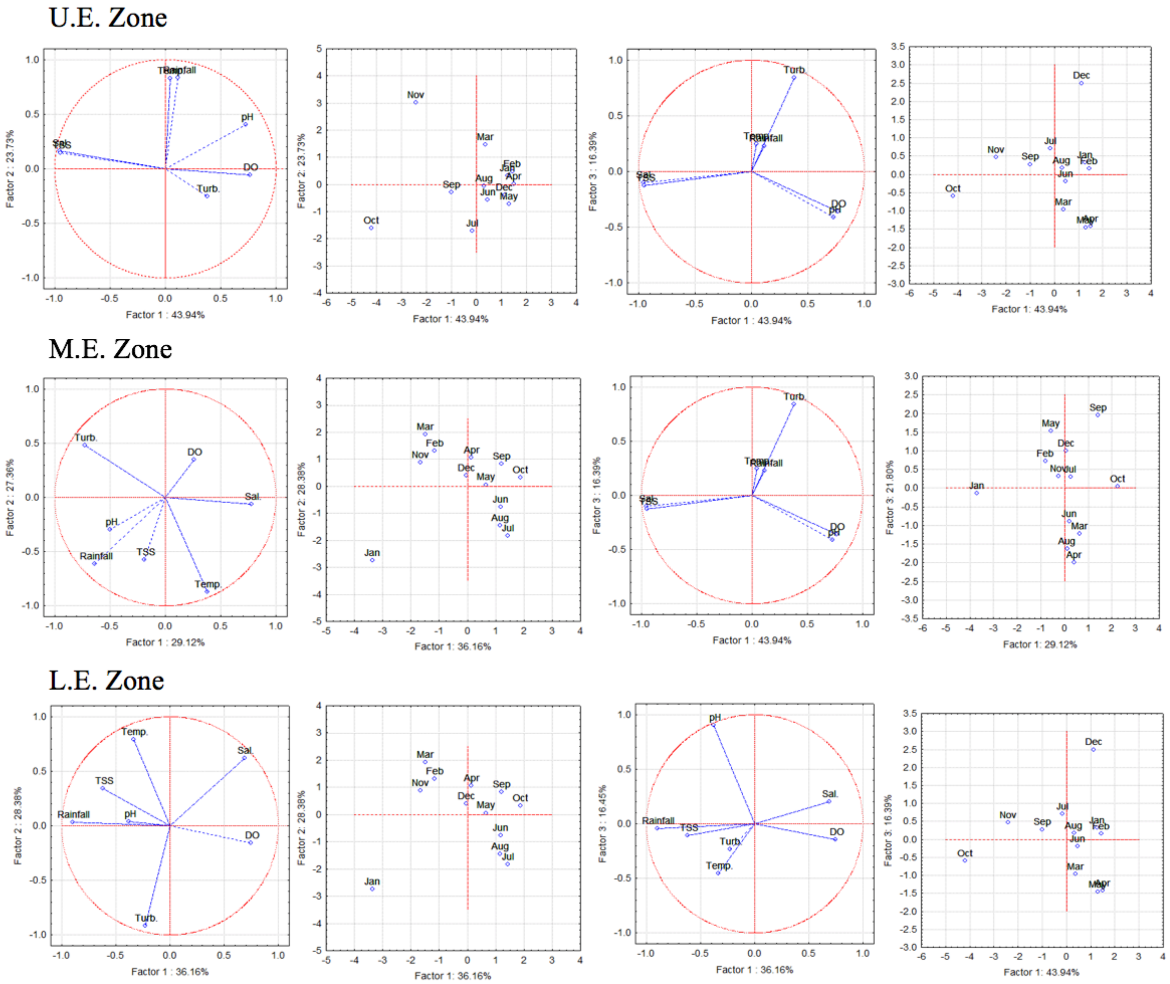

Fig. 5. Weight grap (P.C.A.) showing the distribution of environmental variables to water quality patterns and score graph (P.V.A.) Perancak estuary from January to December 2018

The weight plot shows the distribution of variables, and the scores plot the distribution of replicas (Fig. 5). PC1 accounted for 29.12% of the variance in the M.E. zone, caused mainly by variations in salinity and temperature during the year. In contrast, PC2 and PC3 contributed 27.35 and 21.80% of the variance, respectively. PC2 was formed mainly by DO and turbidity (Table 1). The weight plot shows the distribution of variables, and the scores plot the distribution of replica (Fig. 5). In the L.E. zone, PC2 and PC3 each contributed 28.38 and 16.45% of the variance. In comparison, PC1 accounted for 36.16% of the variance overall and was created mainly by the year's salinity, and DO PC2 was primarily generated by salinity, temperature, and T.S.S. In contrast, pH was the primary factor in PC3 formation (Table 1).

Chemical observation and planktont abundance

Water fertility can be determined by looking at the nutritional composition of the water. The concentration of phosphate (PO_4-P), nitrate (NO_3-N), ammonia (NH_3-N), and silica (SiO_2) in a body of water can be used to determine the fertility of the water. PO_4-P varied from undetected to 0.581mg/ L in the period, with the highest average concentration in the end dry season at the U.E. and M.E. zones. The PO_4-P ranged in the wet season from undetection to 0.168mg/ l and in the dry season from 0.03 to 0.581mg/ l. The PO_4-P concentration in the L.E. zone was relatively lower than in the two other zones; even in the wet season, the concentration was almost undetectable (Fig. 6A). NO_3-N varied from 0.011 to 0.7645mg/ l. NO_3-N range in the wet season from 0.019 - 0.765mg/ l and in the dry season from 0.011 to 0.372mg/ l. The highest concentration was in the U.E. zone in the wet season, and the lowest was in the M.E. zone in the dry season (Fig. 6B). NH_3-N varied undetection to 0.504mg/ l. In the dry season, the variation of NH_3-N is higher than in the wet season. Each were undetected to 0.504mg/ l and to 0.48mg/ l. The concentration of NH_3-N recorded highest in the U.E. zone (Fig. 6C). The SiO_2 varied from 0.243 – 19.922mg/ l. In the wet season, the concentration of SiO_2 was higher than in the dry season, with values of 0.63– 19.92, 0.24 – 19.02mg/ l. The highest variation of concentration SiO_2 was at the U.E. zone (Fig. 6D). The abundance of plankton was 0 – 20 sel/l. In the dry season, an abundance of plankton was higher (1.5 – 20.30 sel/l) than in the wet season (1.20 – 8.85 sel/l. The abundance of plankton in each zone was 0 – 6.99 sel/l (U.E.), 1.65 – 20.30 sel/l (M.E.), and 1.2 – 6 sel/l (L.E.). The highest abundance of plankton was at the M.E. zone both in the wet season (2.85 – 8.85 sel/l) and dry season (1.65 – 20.3 sel/l) (Fig. 6E).

DISCUSSION

Effect of seasonal on the water quality

The J.J.A. (June-July-August) seasons in Indonesia typically see below-average monthly rainfall. Indonesia receives less rain in June and experiences low rainfall, below 153mm/ month. **As-syakur *et al*. (2013**) found a decrease in rainfall which peaked in July. Rainfall in almost all of Indonesia is less than 150mm per month. In this tropical estuary, the wet season runs from November to April, when the frequency of rainfall decreases as the season changes to the dry season. Conversely, the dry season lasts from May to October, when the frequency of rainfall increases as the season changes to the wet season. These results align with those of earlier studies such as those of **As-syakur *et al*. (2013)**, which found less rainfall during the M.A.M. season. Most of Indonesia experienced a low point in rainfall events during J.J.A. and a peak in high rainfall events during D.J.F. These circumstances are connected to the monsoons in the northwestern and southeastern. Rainfall is the most essential factor in the renewal and maintenance of water in small tropical estuaries **(Costa *et al*., 2017)**.

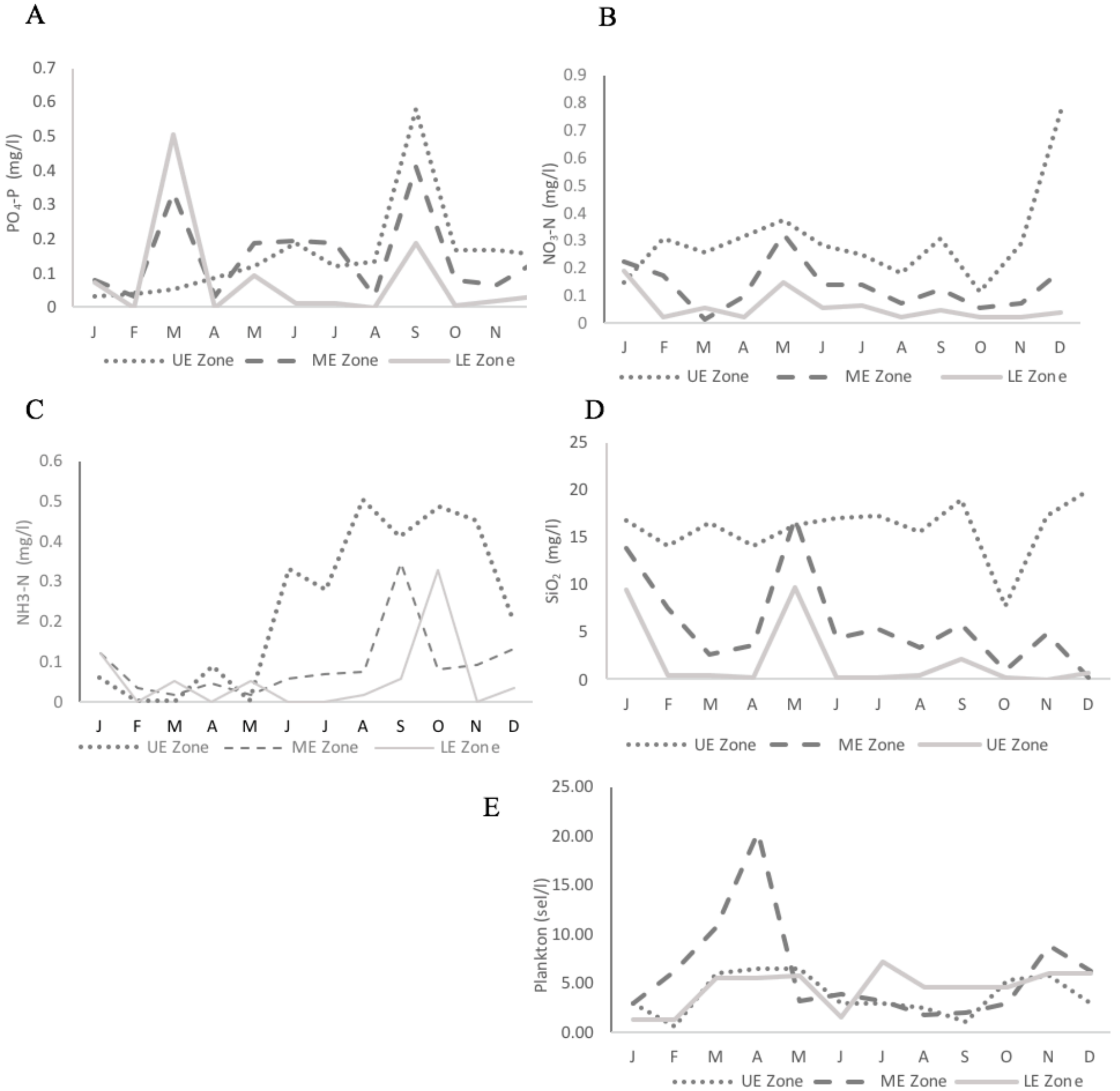

Fig. 6. A-E. Variations PO_4-P, NO_3-N, NH_3-N, SiO_2 and plankton

Water temperature was greatly influenced by the season **(Nuzula *et al.*, 2017)**. This estuary is located on southern Bali island, facing both the Indian Ocean and the Bali Strait. The southeast monsoon circle impacts this area in June, July, and August. The water temperature in southern Java, Bali, and Nusa Tenggara is often colder during the southeast monsoon, incorporating this during the southwest monsoon **(Ningsih *et al.*, 2013; Rintaka *et al.*, 2020)**. In this study, Perancak Estuary's mean water temperature peaked during the transitional season and decreased over the wet and dry seasons. Another study in different tropical estuaries said the average water temperature is highest in the transition season, followed by the wet and dry seasons **(Costa *et al.*, 2017)**. L.E. zone, which is immediately adjacent to the Indian Ocean and Bali Strait, has the lowest temperatures than other zones (Fig. 3A). Although there was much variation between months within the same season, the distinction between seasons was evident. This estuary is tropical, encouraging year-round high water temperatures **(Costa. *et al*., 2017)**. Water temperature in tropical estuaries is influenced by rainfall and air temperature, as seen in Fig. (2A). Water and air temperatures are lower in the dry season than in the wet season. Water temperature in the estuary is influenced by runoff and monsoon **(Wang *et al*., 2021)**. This element may impact how easily gasses dissolve in water, reducing their availability in chemical and biological processes **(Wu *et al*., 2016; Bugica *et al*., 2020; Duque *et al*., 2020)**. Because of the impact of ocean tides, zone L.E., which is immediately next to the open sea, has the highest salinity and is classified as a seasonal river. Salinity varied with zone and season, which defined the estuarine gradient **(Barletta & Dantas, 2017)**. In the dry season, decreasing freshwater enters the estuary locally (in zona L.E.), with the most significant marine influence on this zone of all month. According to a different study, an area had a salinity gradient, with the maximum salinity in the outer sites and the lowest in the inner sites during the dry season, followed by the transitional and wet seasons **(Duque *et al*., 2020)**. Abiotic factors such as salinity and water temperature are crucial in determining the dispersion of aquatic biota and the formation of ecoclines **(Montagna *et al*., 2013; Dolbeth *et al*., 2016; Bugica *et al*., 2020)**. Over time, abrupt and significant changes in these characteristics may degrade environmental quality **(Costa *et al*., 2017)** and change the distribution and composition of biota **(Zhou *et al*., 2017)**. Modification of highly ecologically significant regions regarded as nurseries, increase the amount of plastic and microplastic pollution in estuaries, as well as the impact of dilution of wastewater **(Telesh *et al*., 2010)**, organic pollutants **(Possatto *et al.,* 2011; Blaber *et al*, 2013; Ivar do Sul *et al*., 2013; Ismanto *et al*., 2023)**, substances' intake and accumulation by the biota **(Roselli *et al*., 2013; Hamdhani *et al*., 2024; Zakiah *et al*., 2024)**.

The oxygen contents were higher in zone L.E. of the estuary (Fig. 4B), where there is a more significant influence of marine waters, more oxygenated. DO was substantially connected with salinity; estuarine circulation may regulate the spatial distribution of low-oxygen waters **(Mudge *et al*., 2007)**. In addition to salinity, temperature influences DO solubility and biological activity in water and frequently results in variations in DO **(Zhi *et al*., 2021)**. In contrast, the lowest dissolved oxygen concentrations are found in zone U.E. (Fig. 5B), which is directly adjacent to inhabited regions. The direct release of waste that consumes oxygen, such as domestic waste, into these deep pathways is thought to cause the current oxygen shortage **(Mudge *et al.*, 2007)**. Dissolved oxygen concentrations were greatly influenced by rainfall because It occurs in tropical areas and is essential for water renewal and dilution (Figs. 2A, 4B) **(Delpla *et al.,* 2016)**. During the wet season, DO concentrations increase in almost all zones. The most increased DO concentrations were in zone L.E. because the oxygenation and dilution process between seawater and rainwater occurred in this zone. Some studies document an oxygen increase associated with higher rainfall **(Li *et al*., 2015; Zhi *et al*., 2021)**. Conversely, dissolved oxygen was generally low in practically all zones during the dry season. When there was little rainfall, the DO was deficient, below 4mg/ l, because there was no rainwater diluting mechanism. The level of

DO recommended for aquatic conservation is about 4-5mg/ l, occasionally more severe due to anthropic disturbances **(Osode *et al*., 2009)**. Dissolved oxygen solubility is affected by salinity, and it decreases with increasing salinity **(Onabule *et al*., 2020)**.

pH decreased during the wet season; It was greatly influenced by rainfall (Fig. 4D). pH fluctuations are relatively small from the transition season to the dry season, and the pH drops when the wet season begins. This drastic decline pattern occurred in all zones. Even though it has the same pattern in all zones, the pH value increases in zones near the sea because of the impact of the ocean tide. pH. and salinity were lower during monsoon than intermonsoon seasons **(Proum *et al*., 2018)**. pH and salinity increased expectedly seaward due to tidal forcing and freshwater dilution at opposite ends of the estuary. Turbidity presented higher values in the wet season when the water column is unstable, with higher resuspension of particles and higher flow of sediment and particulate matter carried by runoff. High rainfall causes more runoff from the land, which raises turbidity and can shift primary production **(Devlin *et al.*, 2008; Costa *et al*., 2017)**. Given that the estuary is situated in a tropical region, variations in solar radiation were most likely not a deciding factor **(Kronvang *et al.,* 2005)**. Almost all zones have considerable turbidity during the wet season. During the wet season, turbidity was highest in the M.E. and L.E. zones, where both zones were still influenced by tidal currents. The convergence of tidal currents and rainfall runoff intensifies the process of agitating sediment particles. Total suspended solids (T.S.S.) contribute to turbidity by limiting the contribution of light penetration into the water. T.S.S. concentrations are often higher in zone III estuaries with a wide tidal range (Fig. 4F). There are two possible reasons for the increased T.S.S. and turbidity during the wet season: First, a significant amount of material from the upstream may have entered the estuary due to the increased river flow, and second, the increased river flow may have eroded the solid river bank, producing new sediment that deposited and settled in the estuary. A higher estuary turbidity maximum was seen during the wet season compared to the dry season in almost all the rivers observed **(Fernandes *et al*., 2018)**. Season, tidal currents, and erodible rock types influence the forming of maximum estuary turbidity. Turbidity is directly impacted by freshwater flow, with a decrease in turbidity occurring with an increase in freshwater flow. Elevating freshwater flow also causes dispersed particulate matter to be transported seaward **(Onabule *et al*., 2020)**.

The nutritional composition of the water includes phosphate (PO_4-P), nitrate (NO_3-N), ammonia (NH_3-N), and silica (SiO_2). The amount of nutrients in estuary waterways is influenced by rainfall that carries anthropogenic material from the land. The increasing rainfall in November-December (Fig. 2A), leading to an increase in turbidity (Fig. 4F), NO_3−N (Fig. 7A), PO_4-P (Fig. 7B), and SiO_2 (Fig. 7D). Apart from that, the high turbidity and SiO_2 during the wet season were caused by the erosion of sediment material on the river banks. The highest increasing turbidity, NO_3−N, and PO_4-P were at the U.E. zone, which is an area close to settlements. It is followed by the M.E. zone (areas near fish farming, agriculture, and mangrove ecosystem). Increasing NO_3−N (Fig. 7A) and decreasing (NH_3-N) (Fig. 7C) were related to the nitrification process of organic matter in these waters. The main elements influencing the overall amount of nutrients entering the Perancak estuary are anthropogenic activities like household trash, port fertilizer loss, and vegetation cover. Water quality influences the density of mangrove species (Fig. 3). Water quality parameters in the M.E. zone (mangrove areas) fluctuated relatively high, especially for PO_4-P, NO_3-N, SiO_2, and plankton (Fig. 6). The high NO_3−N concentration in the water column is a powerful determinant of sediment biogeochemistry in the estuary **(Perez-Rodriguez *et al.*, 2024)**. Meanwhile, the lowest concentrations of turbidity and NO_3−N were found in the L.E. zone, which is close to the open sea and the Bali strait. The main elements influencing the overall amount of nutrients entering the Perancak estuary are anthropogenic activities like household trash, port fertilizer loss, and vegetation covered. The nutrients that rivers receive vary depending on whether they are natural (runoff, precipitation, decomposition, and sediment load), artificial (recharged water, fertilizer application, and vegetation covering), social, or industrial (sewage effluents and population urbanization) **(Wu *et al.*, 2021)**.

The international literature, which adopts more conservative limits and considers < 2mg L−1 as the limit for hypoxia, served as the foundation for our study. Hypoxia in coastal waters is characterized by dissolved oxygen levels of less than 2mg L−1 and oxygen saturation values of less than 30% **(Dai *et al.*, 2006)**. Hypoxia is frequently associated with low pH and DO **(Gobler *et al.*, 2016)**. It can arise from natural or human-induced sources **(Mudge *et al.*, 2007; Zhang *et al.*, 2010; Roselli *et al.*, 2013)**. Several hypoxia occurrences were discovered in this investigation, occurring for 19 observations out of 600 observations at the U.E. zone, precisely at P.R.C. 1, considering that the location is very close to residential areas. The low DO (0.98 - 1.94mg/ l) (Fig. 4B) and low pH (until 4.75) (Fig. 4B) values in June to July and September to early October are related to the low rainfall (Fig. 2A). The lower rainfall in these months causes household waste to be trapped in this location. Meanwhile, DO was lower in November when there was peak rainfall after the lowest rainfall in October (Fig. 2A), causing large amounts of anthropogenic runoff from land to be trapped in that location. Seasonal variability and human communities in coastal ecosystems trigger hypoxia **(Low *et al.*, 2021)**. Several hypoxic events were found in the E.U. zone, specifically in P.R.C. 1, which were also caused by the nitrification process, an increase in NO_3−N (Fig. 6B) followed by a decrease in NH_3-N (Fig. 6C). Hypoxia in this zone is caused by nitrification and organic pollution from residential areas and cultivation ponds around river flows. Additionally, during these times, the absence of rainfall in the basin and locally significantly impacted river flow and water replenishment. The equilibrium between production, consumption (respiration and other chemical reactions), and exchange with the atmosphere controls dissolved oxygen concentrations in surface waters **(Uriarte *et al.,* 2004)**. The oxygen in the water is nearly entirely consumed due to the decline in regeneration. Furthermore, there was less flow during the dry season, which led to less turbulence and, ultimately, less diffusion from the atmosphere. One expected impact of a continuous decrease in water quality is hypoxia **(Qian *et al.*, 2018)**. Numerous hypoxia cases occur throughout the world. They have already been published in scientific publications. The warm and shallow waters of tropical estuaries threaten the ecosystem vulnerable **(Corbari *et al.*, 2016)**. Eventually, hypoxic conditions will cause a decline in biological diversity and abundance **(Jeppesen *et al.*, 2018)**. Hypoxia can change juvenile fish's growth rate and mortality **(Ram *et al.*, 2014)**. It might impact their eating, sleeping, and other behaviors **(Weinke *et al.*, 2018)**. Moreover, it can produce methane **(Gelesh *et al.*, 2016)**. Global warming and ocean acidification worsen hypoxia **(Zhang *et al.*, 2010)**. The above changes suggest permanent changes in the environment and, ultimately, a breakdown of resilience on an ecosystem base. The samples used for this study's analysis were from the estuary's main channel zones (U.E., M.E., and L.E.), where water is thought to have the finest renewal and oxygen production opportunities. So, almost all the DO readings fell under a natural safety threshold (Fig. 4B). Smaller tidal creeks and less turbulent sections of the drainage system that make up the estuary have a greater-than-average likelihood of already implementing hypoxia **(Ramos *et al.*, 2011)**. Therefore, Estuary Perancak should continue to be monitored if the frequency, extent, and duration of these hypoxic episodes increase. This will raise concerns about the sustainability of water resources.

Interdependence of variables

Inter-monthly sampling helps determine how rainfall variations affect the water quality. The samples must be carefully planned for in order to detect cyclical phenomena, which are only detectable on more extended temporal periods, and in order to identify long-term, permanent changes brought on by anthropogenic intervention, a comparable but less intense sampling design is advised for this estuary's water quality study **(Karydis *et al.*, 2013)**. One of the main factors influencing the amount and quality of estuary water is the amount of rainfall that falls locally and across the entire river basin **(Corbari *et al.*, 2016)**. While it momentarily lessens the sunlight penetrating the water column, it restricts primary production **(Cloern *et al.*, 2014)**. Freshwater inputs facilitated the movement, dilution, and diffusion of contaminants and effluents, as well as the rise in the amount of dissolved oxygen that was accessible **(Zhang *et al.*, 2010)**. A decrease in water quality is also noted during the dry seasons, primarily due to the absence of rain-induced water regeneration **(Dai *et al.*, 2006)**. The most significant variables related to water quality in Zona U.E. were temperature and rainfall, highlighted in their essential contribution to forming the PC2 axis. The majority of variables in the other two zones were slightly different, where turbidity was the most crucial variable in zone M.E., whereas temperature was more crucial in zone L.E. (Fig. 5 & Table 1). Temperature and salinity are the primary limiting factors for the assemblages of demersal fish **(Dantas *et al.*, 2010; Ramos *et al.*, 2011)**.

Implication for ecosystem health managerial

Water quality is an essential issue in tropical estuary ecosystems **(Anwar *et al.*, 2020)**. Communities develop in areas close to water, where people can quickly obtain food, as estuaries offer the services that communities need and encourage larger populations **(WHO, 2014)**. Water quality declines when population development combines insufficient social welfare and natural resource management. Rainfall is essential in maintaining and regenerating water quality and improving it **(Karydis *et al.*, 2013; Corbari *et al.*, 2016)**, even though it is temporary because it does not last throughout the year. Based on the results of this research, water quality conditions in the tropical estuary of Perancak depend on rainfall. The importance of rainfall in renewing water resources is also observed in other estuaries. **Horrison (2004)** studied 109 estuaries in South Africa and **Mérigot *et al.* (2016)** observed the same for four estuaries in Brazil. Water management is essential for the sustainability of ecological services **(Karydis *et al.*, 2013; Corbari *et al.*, 2016)**. However, variations in the amount of rainfall and the patterns of freshwater discharge from basins can lead to an increase in freshwater flows, alterations in flow rates, and an increase in sedimentary loads (increase T.S.S. and turbidity), all of which have the potential to change the morphology of the ecosystems and natural biogeochemical cycles, which in turn can affect habitats. Perancak tropical estuary is subject to much human activity. Like many other tropical estuaries, this estuary is heavily influenced by residential areas, natural mangroves, mangrove plantings, abandoned shrimp ponds, fish ponds, and polyculture ponds, as well as active shrimps ponds with semi-intensive or intensive cultivation systems **(Rahmania *et al.*, 2015; Gusmawati *et al.*, 2016; Valera *et al.*, 2016)**. Fish farming, ports, agriculture, recreation, and household garbage are some of the primary activities along Muara Perancak that can potentially deteriorate estuarine habitat quality and cause potentially hazardous water contamination. The organic matter, nitrogen, and phosphorus that are abundant in aquaculture wastewater will seep into the nearby mangroves and coastal waterways **(Islam *et al.*, 2004; Hastuti *et al.*, 2018; Rintaka *et al.*, 2019)**, causing consumption of dissolved oxygen in the water. The predicted trend of change in the global climate due to human activity includes several events: rising sea levels; acidification; loss/replacement of habitats (species migration, invasion of exotic species); expansion of the tropics; and water heating (change in chemical kinetics of reactions in the estuary, stratification of the water column, hypoxia) **(Zhang *et al.*, 2010; Madsen *et al.*, 2014)**. The importance of tropical estuaries will become increasingly apparent in the future, requiring a thorough understanding of the function of healthy ecosystems. Furthermore, there is a growing need for water resources, making surface water quality a top priority **(WHO, 2014; Dunn *et al.*, 2019; Elliott *et al.*, 2019)**.

CONCLUSION

The sample used in our study allows the detection of monthly fluctuations in water quality, the primary cause of which was differences in rainfall patterns. It also supported earlier ecological research showing that river and estuary aquatic ecosystems provide conditions for maintaining biological resources. Despite occasional hypoxia, water quality in the study area was generally acceptable. This incident should be interpreted as a reminder of the sensitivity of the environment to human intervention in this and other similar situations. Estuary areas are included in river area mitigation initiatives to reduce impacts on aquatic ecosystems and maintain environmental quality. Important for settlement management and land and water use (regeneration of riverside vegetation, soil restoration, and waste treatment before discharge). These actions are necessary to maintain the environmental services provided by estuaries. Water quality is influenced by changes in regional rainfall patterns and increased use of water resources in river basins that have limited resources. Rainfall plays an important role in maintaining healthy ecosystems and promoting seasonal flow, especially in areas where flow controls exist. The dry season is especially important when water quality decreases significantly due to increased pH and minimal water regeneration. Our results imply that regions most vulnerable to environmental and social change and misuse of water resources should focus more on modifying seasonal rainfall patterns, as this will influence future water availability.

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