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ORIGINAL RESEARCH ARTICLE

Mariculture site selection based on water quality, cultivation and ecological condition

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ABSTRACT

BACKGROUND AND OBJECTIVES: Choosing a location for mariculture is very important because it affects water quality, while problems that affect cultivation and the environment can be avoided by choosing the right location. The objective of this study is to develop a methodological strategy for integrating and analyzing spatial data, which will facilitate the identification of optimal locations for mariculture. In this context, the ecosystem approach to mariculture is analyzed with an emphasis on evaluating water quality conditions and determining primary productivity values.

METHODS: Water quality parameter data was analyzed using principal component analysis, values, and distribution of primary productivity using the kriging interpolation method using geographic information system. Spatial analysis employing Geographic Information System applications is used to evaluate the appropriateness of locations for mariculture.

FINDINGS: The distribution pattern of primary productivity is strongly influenced by the distribution of phytoplankton and the highest concentration values are located in coastal waters and small islands. The analysis identified three primary components that account for 79.64 percent of the results. The most influential factors include suspended particulate matters, nitrate, temperature, salinity, ammonia, current, and water transparency. According to the study results, the principal component values indicate that the most affected regions by pollutant pressure are agricultural lands that drain into rivers and watersheds, along with coastal residential neighborhoods.

CONCLUSION: The status of water quality is the main limiting factor in determining the location of mariculture, therefore it is necessary to relocate existing mariculture, improve agricultural cultivation techniques, and/or regulate the use of pesticides that not carried out during the rainy season. These findings may assist the appropriate authorities in the selection and oversight of mariculture sites. The innovative aspect of this study lies in its focus on adaptive management of sustainable marine cultivation, designed to align with regional conditions and promote ecological health alongside the socio-economic prosperity of local communities.

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45	5	4

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INTRODUCTION

High-quality aquatic resources are vital for preserving ecological balance and driving sustainable socioeconomic growth (Ghotbizadeh *et al*., 2022; Sin and Lee, 2020). Water quality issues have evolved into more intricate problems, largely as a result of the pressures exerted on ecosystems and the surge in population caused by urban development. The widespread decline in water quality poses a significant threat to livelihoods globally and has become a major concern for the public (Brkić *et al*., 2019). Numerous efforts have been undertaken to explore accurate information on water quality fluctuations (Chen *et al*., 2021; Wang *et al*., 2021). Assessing water quality involves utilizing hydrochemical monitoring techniques, collecting data on geological diversity, examining human activities, and implementing measures to mitigate water pollution (Liu and Mao, 2020). In recent years, numerous studies have focused on evaluating water quality, including the use of single-factor assessment methods (Wu *et al*., 2021), the water quality index (WQI) approach (Seif *et al*., 2020), the Storet method evaluates water quality by comparing data against standards tailored to its intended use, determining the status of water quality. This approach employs a scoring system developed by the United States (US) Environmental Protection Agency (EPA), categorizing water quality into four classes: meeting standards, lightly polluted, moderately polluted, and heavily polluted (Morsoleto *et al.,* 2024; Marzuki *et al*., 2022). Selecting suitable cultivation locations is a key strategy for guaranteeing the ongoing production of marine fish in the desired quantities (Arifin *et al.,* 2014). Determining the area and selecting the right cultivation technology, as well as paying attention to environmental aspects are important for the sustainability of optimal production (Wang *et al*., 2020). When choosing a location, it is essential to consider multiple environmental factors (Oyinlola *et al*., 2018), especially the influence of oceanographic parameters (Pamungkas *et al*., 2022). The concept of water productivity can be effectively utilized for the administration of water resources and the evaluation water quality. To enhance fish production and cultivation, it is essential to examine the factors influencing aquatic productivity (Mercado *et al.*, 2017). The practice of mariculture in Indonesia provides an alternative economic avenue for coastal fishing communities, playing an essential role in mitigating the strain on marine natural resources. In 2022, the total production of national mariculture reached 16.87 million tons (Nagel *et al*., 2024). In 2023, the mariculture sector is experiencing significant growth in food production, with the Indonesian Ministry of Marine Affairs and Fisheries setting a target to enhance production by 21.58 million tons (Pamungkas *et al*., 2022). Due to the community's socio-economic activities, such as the increase in agricultural land and the dumping of residential and small industrial waste into the watershed, there will be detrimental effects that diminish the ecological potential of the bay, particularly by reduction of potential areas for mariculture. So far, this problem has not been scientifically revealed, therefore this study on the integration of geographic information system (GIS) and principal component analysis (PCA) analysis is able to reveal and provide solutions, especially for the development of sustainable mariculture. Considering the ecological characteristics of water is crucial for optimizing mariculture production. According to Loka, (2015), water quality is the key and most critical factor in ensuring the sustainability of mariculture (Clavelle *et al*., 2019). The physicochemical and biological factors essential for Factors to consider in mariculture include water temperature, turbidity, salinity, potential of hydrogen (pH), dissolved oxygen (DO), ammonia, nitrates, nitrites, phosphates, and algal growth (Marzuki *et al*., 2024). So far, research on selecting locations for mariculture has only used a single water quality parameter as a factor. This research established a methodology that combines the evaluation of water quality with the assessment of primary productivity to determine optimal sites for mariculture. By utilizing the GIS and a processed image overlay system containing these factors and parameters, appropriate spatial and temporal information will be obtained (Brkić *et al*., 2019). Principal component analysis results are employed to analyze temporal changes in the spatial distribution of water quality and to identify the influencing factors. The findings are anticipated to offer a method for assessing water environmental stress, particularly in areas with continuous pollutant input (Marzuki *et al*., 2022). Apart from that, it can be used as a guide in determining location and sustainable management so that it can increase mariculture production (Marzuki *et al*., 2024). The aims of the current study

is to propose a methodological approach to the integration and analysis of spatial data to produce information for determining mariculture locations. This study examines the ecosystem approach to mariculture, focusing on the evaluation of water quality conditions and the assessment of primary productivity values. This study provides new insights into the impacts of seasonal changes on water quality and marine aquaculture continuity by considering ecological aspects to support sustainable marine ecosystem management. This study has been carried out in the Saleh Bay area, West Nusa Tenggara (WNT) Province, Indonesia in 2023.

MATERIALS AND METHODS

Location and period

Saleh Bay is an area vulnerable to pollutant inputs. On the other hand, it has excellent mariculture potential to support the economic strength of coastal communities. Saleh Bay was designated as the research location because it is among the leading areas for mariculture food production in Indonesia. Geographic boundaries are set in the western and eastern parts of the bay, near islands, between islands, and other protected areas for mariculture activities. These locations were chosen because they are areas that represent the water conditions around Saleh Bay. By combining GIS and PCA analyses, specific environmental and ecological boundaries are defined for the study area, which is a semi-enclosed bay, allowing for the identification of parameters that lead to the decline in water quality. Spatial data in mariculture location selection; useful as a geo reference to conduct mapping based on physical and chemical parameters (water quality), cultivation and ecological conditions so that the goal of long-term mariculture development sustainability can be achieved. The analysis tools used for spatial data integration are GIS and PCA. The application of GIS facilitates the assessment of location suitability by aligning the water quality parameters of a site with predetermined standards. The application of PCA analysis allows for the evaluation of the distinct traits of each group, focusing on their physical and chemical attributes. These results can be used by relevant authorities in monitoring water quality and selecting locations for floating net cage (FNC) grouper marine cultivation systems in Saleh Bay. Water quality measurements (temperature, current, water transparency, suspended particulate matters (SPM), DO, salinity, pH, nitrate, phosphate, and ammonia were carried out at 143 points (Fig. 1). To analyze chlorophyll-a and nutrient parameters, seawater samples were collected using a 2.2 L Van Dorn horizontal water sampler at a depth of 1–3 meters (m). The application of PCA analysis can aid in uncovering and interpreting the sources of pollutants. Furthermore, PCA is capable of extracting and elucidating parameters linked to agricultural operations and settlement activities. By grouping locations with comparable water quality patterns and values, it becomes simpler to recognize the pollutant pressures stemming from the watershed as well as other anthropogenic influences. PCA results can provide information for mariculture management strategies, in this term PCA analysis is able to reveal and provide solutions, especially for sustainable mariculture development.

Data

This study involved collecting water quality data from 143 sampling stations (Fig. 1) and carried out 3 (three) repetitions (3 x 143 = 429). The determination of the location of the water quality sampling station was chosen based on the existing conditions of mariculture and the potential pollutants from the watershed. Measurements and sampling were performed three times at each station. The water quality evaluations and sampling activities concentrated on the watershed that feeds into Saleh Bay. The measurement and sampling sites are situated in the western and eastern sections of the bay, near the islands, between the islands, and other designated protected areas for mariculture activities. The assessment of water quality and sampling efforts were directed towards the river basin or watersheds (DAS) that discharge into the bay of the coastal residential area (Chipepe *et al*., 2021). The tools and methods for water sample analysis used in both the first and second surveys were identical. During the first survey, water quality was measured directly at the site, and subsequent laboratory analyses were carried out at the Marine Aquaculture Center of the Ministry of Maritime Affairs and Fisheries. In the second survey, laboratory tests were conducted at the integrated oceanographic research laboratory (LATERIO) – National Research And Innovation Agency (BRIN) (Nagel *et al*., 2024; Riany *et al*., 2023).

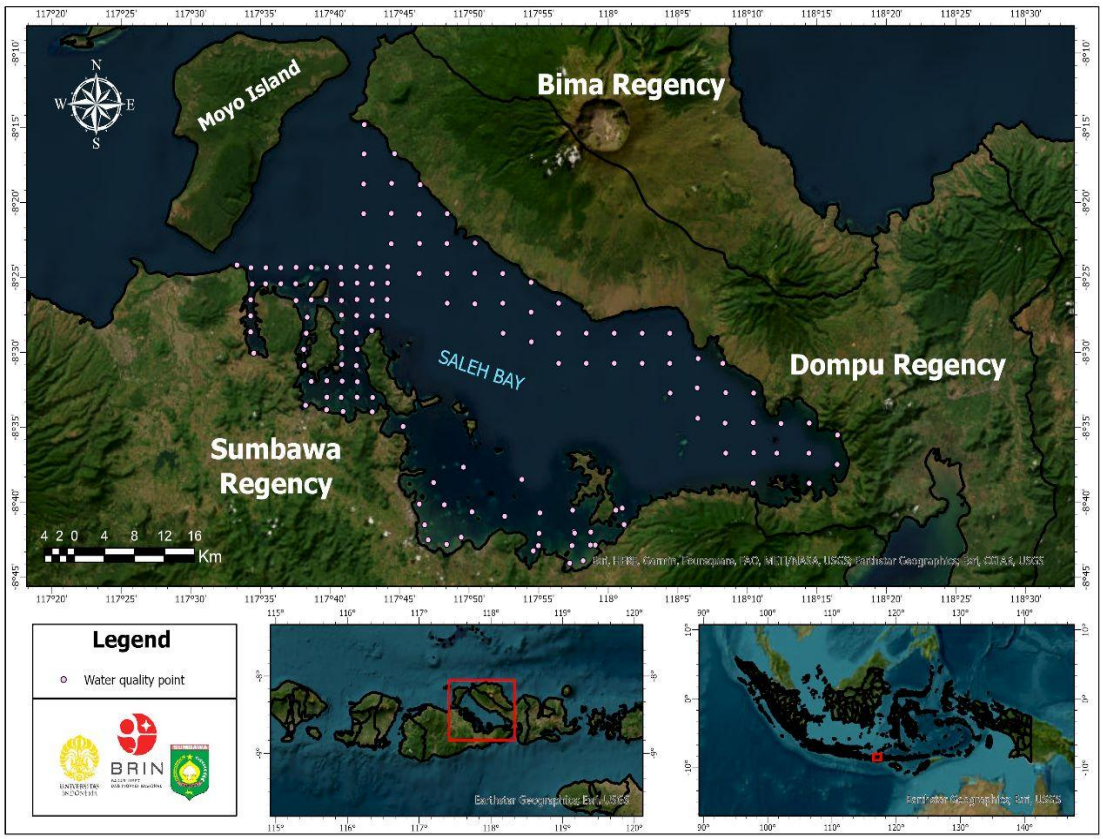

Fig. 1: Geographic location of the study area in Saleh Bay area, West Nusa Tenggara Province, Indonesia

This study uses data with two measurement periods, the first period, the author is still under the Marine and Fisheries Research Agency, Ministry of Marine Affairs and Fisheries, which uses facilities under the Ministry, namely the Marine Aquaculture Laboratory. In the second measurement period, the researcher has migrated to BRIN, which uses facilities under BRIN, namely LATERIO. The preparation and analysis methods used are the same, so that all procedures are consistent and reliable. The evaluation of water quality involves several physical parameters. Temperature is measured with a water checker, and current speed is determined using an acoustic doppler current profiler (ADCP). Depth is ascertained from bathymetric map, water transparency, measured with a Secchi disk and SPM, analyzed in the laboratory using the gravimetric method with a Millipore filter. Biological parameters, including chlorophyll-a, were measured using a spectrophotometer (Kumar *et al.*, 2023; Wang *et al.*, 2020). Chemical parameters, including DO, salinity, and pH, use a water checker, while nutrients include nitrate, phosphate, and ammonia, using a spectrophotometer (Riany *et al.*, 2023). The LATERIO - BRIN water quality laboratory conducted all of these analyses.

Data analysis

Physicochemical parameters of water

The PCA is one of the ordination and reduction analysis te The application of PCA analysis allows for the evaluation of each group's traits through the analysis of chniques (Zhang *et al.*, 2020). PCA analysis is used to determine the character of each group based on physical, chemical, and biological parameters. To date, PCA has been commonly employed and is viewed as a vital component in the field of quantitative ecological analysis (Rahimah *et al.*, 2020). PCA is a method of descriptive statistics

designed to visually represent data and enhance the information extracted from a data matrix. The data matrix in question consists of observation stations as individual statistics (rows) and water quality parameters as qualitative variables (columns). Prior to performing PCA, an analysis of variance is conducted initially. In principle, PCA uses Euclidean distance (the sum of the squares of the differences between individuals/rows and corresponding variables/ columns), using Eq. 1 (Guo *et al*., 2018):

$$D^2\left(i,i'\right)=\sum_{j=i}^{n}\left(xij-xi'j\right)^2 \quad (1)$$

Where,

D^2 = distance of Euclid

i,i' = station (on line i)

$From\,the$ = water quality parameter (index in column, varies from 1 to p)

X_{ij} = number of columns j for all rows i

The smaller the Euclidean distance between two observation stations, the more similar their characteristics are. Conversely, a greater Euclidean distance reflects more significant disparities in the physicochemical water parameters observed between the two stations. The classification of principal components is based on loading values categorized as strong (>0.75), moderate (0.75–0.50), and weak (0.50–0.30) (Wijanarko, 2022). Factor loading can be utilized to determine the importance of a variable when compared to its counterparts within a component. Positive values on each factor indicate a strong influence, while negative values signify a weaker influence (Clavelle *et al*., 2019).

Value and distribution of primary productivity

Primary productivity values in the waters of Saleh Bay, using a formula developed, using Eq. 2 (Nusapril *et.al*. 2017):

$$PP = 22.74 + (95.536\ (0.1442 + 0.615\ C) \quad (2)$$

Where,

PP = primary productivity as primary productivity value (mg C/m^3/h)

C = surface chlorophyll-a concentration

The distribution of primary productivity was carried out using spatial analysis using the kriging interpolation method in ArcGIS software. The kriging method represents spatial differences and values between all spatial data samples in a semivariogram. Utilizing the kriging method for interpolation results in a data range that is nearly equivalent to the range of the existing data samples (Xiao *et al*., 2016). The basis of kriging is to obtain a set of weights that can be used to combine observed values at nearby locations to estimate values at the target location. The selection of weights aims to minimize the variance associated with estimation errors, under the condition that the estimated values represent a linear combination of the observed values. The interpolation results are then presented in the form of a map of the distribution of primary water productivity in Saleh Bay.

Suitability of mariculture

The data analysis used consists of spatial analysis using the GIS application (Bemani *et al*., 2021; Francisco *et al*., 2019). The method for utilizing fish resources in the study area is evaluating the suitability of the location by matching the location's water quality parameters with the specified criteria. The results of the study are expressed as a match percentage of coinciding water quality parameters, from which conclusions are derived to evaluate the use of land for mariculture purposes. This analysis utilized the weighted overlay approach, which involves the spatial technique of superimposing various maps that pertain to the factors influencing the assessment. The overlapping process of parameters for mariculture consists of physical-chemical parameters. Identifying the best location for grouper fish mariculture involves a thorough evaluation of multiple parameters, guided by criteria that support recommended mariculture activities, based on the outcomes of the weighted overlay method. The results of coding for each parameter is continued by determining the score according to the criteria in Table 1. Score 3 for the very suitable class, score 2 for the suitable class and score 1 for the unsuitable class. By considering the criteria and limiting factors, the suitability of land for grouper fish mariculture in Saleh Bay has been determined (Fig. 5). The criteria employed are derived from the outcomes of parameter extraction conducted through PCA analysis. The distribution of primary productivity was carried out using spatial analysis with the kriging

Table 1: Criteria for water quality parameters for mariculture

Parameters	Weight	Suitability Classification and Scores			Basis on scoring	Saleh Bay condition	Sources
		Highly suitable (3)	Suitable (2)	Largely unsuitable (1)			
Physical							
Temperature as degree Celsius (°C)	10	28-30	25-27 & 31-32	<25 & >32	Parameters that can have a stronger influence as a limiting factor for mariculture is given a higher weight	The northern waters of Saleh Bay are more dynamic than the southern part, this affects the physical parameters in the area	Zhang *et al.*, 2020; Loka, 2015
Current speed As meter per second (m/s)	15	0.2-0.5	0.1-0.19	<0.1 & >0.60			Zhang *et al.*, 2020
Depths (m)	15	8-15	16-25	<8 & >25			Roy and Saikia, 2023
Water transparency (m)	10	>3	1-3	<1			Roy and Saikia, 2023
SPM as milligram per liter (mg/L)	10	<25	26-50	>50			Chipepe *et al.*, 2021
Chemical							
DO (mg/L)	10	>6	4-6	<4		There are river basins (DAS) that empty into the bay, this affects the chemical parameters of the water	Kumar *et al.*, 2023
Salinity as part per thousand (ppt)	10	30-35	20-29	<20 & >35			Zhang *et al.*, 2020
pH	5	6.5-8.5	4-6.4; 8.5-9	<4 & >9.5			Zhang *et al.*, 2020
Nitrate (mg/L)	5	0.9 – 3.2	0.7-0.8 & 3.3-3.4	<0.7 & >3.4			Loka, 2015
Phosphate (mg/L)	5	0.2-0.5	0.6-0.7	<0.2; >0.8			Farantika *et al.*, 2020
Ammonia (mg/L)	5	<0.2	0.2 – 0.5	>0.5			Kumar *et al.*, 2023

interpolation method in ArcGIS software. The kriging technique illustrates the spatial variations and values of all spatial data samples through a semi-variogram. The interpolation method using the kriging method produces a range of data that is close to the range of existing data samples. The basis of kriging is to obtain a set of weights that can be used to combine observed values at nearby locations in estimating values at target locations. The selection of weights aims to minimize the variance associated with the estimation error, while ensuring that the estimated value remains a linear combination of the observed data. The interpolation results are then presented in the form of a map of the distribution of primary productivity of waters in Saleh Bay. To enhance the GIS results, PCA analysis was performed, effectively uncovering the parameters that are responsible for the decline in water quality. One of the functions of this method is to solve multi-criteria problems such as optimal location selection or suitability modeling (Cárdenas *et al.*, 2021). Weighted Overlay is one of the facilities in ArcGIS that combines various kinds of input in the form of grid maps with weighting (weighted factor) (Marzuki *et al.*, 2021). Utilizing raster data, this approach operates with the smallest unit being pixels, enabling the scoring and weighting process for each pixel according to its respective value. Overlay some rasters use a common measurement scale and weigh each according to its importance (Koehn *et al.*, 2022). In the use of weighted overlay, all input rasters must be integer. Rasters floating-point must first be converted to an integer raster before it can be used in

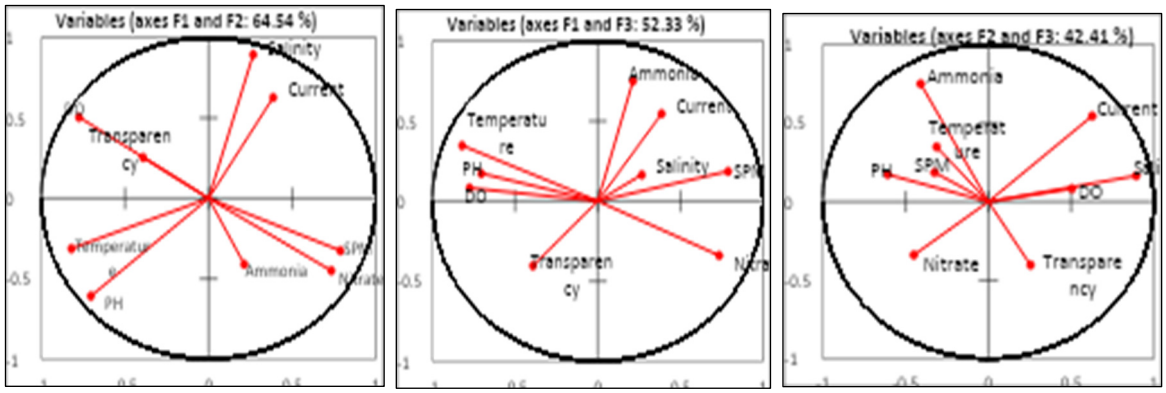

Fig. 2: Components loading for PC1, PC2 and PC3 after rotation

Table 2: Descriptive statistics of original PCs

Sampling locations	F1	F2	F3
Eigenvalue	3.35	2.46	1.36
Variability (%)	37.23	27.31	15.10
Cumulative %	37.23	64.54	79.64

weighted overlay. Each value class in the input raster is assigned a new value based on the evaluation scale (Sin and Lee, 2020). Each inputted raster is weighted according to its importance or described by percentage, the sum of the percent influence weights must be 100 (Yuan *et al*., 2023). Table 1 presents the guidelines for the weighting and scoring of water quality parameters. These parameters are key parameters in determining the suitability of selecting a marine cultivation location, especially in supporting the growth of grouper fish.

RESULTS AND DISCUSSION

Water quality assessment by principal components analysis

Using PCA, the attributes of the research location at a given time are described based on environmental parameters derived from water quality data obtained from 143 stations (Fig. 1). The first two principal components (F1 and F2) are the most critical factors, accounting for over 50.00 percent (%) of the variance in Saleh Bay's water quality. F1 contributes 37.23%, while F2 accounts for 27.31%. Analyzing the eigenvalues and variability percentages of the principal components F1, F2, and F3 is crucial for understanding the primary parameters that impact water quality. Components F1, F2, and F3, respectively, describe 37.23%, 27.31%, and 15.10% of the total variance with significant loading on the variables SPM, nitrate, current, DO, salinity, and ammonia, as shown in (Table 4 and Fig. 2). The proactive assessment of these parameters reveals the correlation that contributes to the reduction in water quality. This PCA analysis can reveal and provide solutions, especially for sustainable mariculture development. These findings highlight the significance of the first two eigenvalues compared to the others (Table 2). The main components (F1, F2, and F3) explained 79.64% of the total variance observed in the water quality data set (Table 2 and Fig. 2). Eigenvalues >1 are considered significant (Table 2).

Variable SPM and nitrate are positively correlated while temperature is negatively correlated with the first principal axis (F1) (Table 3). The formation of the first principal axis (F1) is greatly affected by these three environmental parameters, whereas salinity and ammonia play a role in shaping the second principal axis (F2). Ammonia, current speed, and brightness play a more prominent role in shaping the third principal axis (F3). Observations originating from all locations contributed more to the formation of the first principal axis (F1), while most of the observations

Table 3: Correlation matrix (pearson) between water quality parameters

Variables	Temp. (°C)	Current speed (m/s)	Transpa-rency (m)	SPM (mg/L)	DO (mg/L)	Salinity (ppt)	pH	Nitrate (mg/L)	Ammonia (mg/L)
Temperature (°C)	**1**	-0,2926	0,1125	-0,4390	0,4792	-0,4170	0,8163	-0,5464	0,1528
Current speed (m/s)	-0,2926	**1**	-0,1323	0,1810	0,0091	0,6951	-0,5009	-0,1321	0,1820
Transparency (m)	0,1125	-0,1323	**1**	-0,3569	0,2631	0,1190	0,1305	-0,2430	-0,2555
SPM (mg/L)	-0,4390	0,1810	-0,3569	**1**	-0,7526	-0,0155	-0,2863	0,5743	0,3801
DO (mg/L)	0,4792	0,0091	0,2631	-0,7526	**1**	0,2345	0,2119	-0,7920	-0,3198
Salinity (ppt)	-0,4170	0,6951	0,1190	-0,0155	0,2345	**1**	-0,6712	-0,2512	-0,1501
PH	0,8163	-0,5009	0,1305	-0,2863	0,2119	-0,6712	**1**	-0,2934	0,2024
Nitrate (mg/L)	-0,5464	-0,1321	-0,2430	0,5743	-0,7920	-0,2512	-0,2934	**1**	0,1223
Ammonia (mg/L)	0,1528	0,1820	-0,2555	0,3801	-0,3198	-0,1501	0,2024	0,1223	**1**

Table 4: Rotated factor loading for the 3 PCs

Parameters	F1	F2	F3
Temperature (°C)	-0.8208	-0.3128	0.3475
Current speed (m/s)	0.3861	0.6275	0.5458
Transparency (m)	-0.3921	0.2550	-0.4042
SPM (mg/L)	0.7886	-0.3253	0.1865
DO (mg/L)	-0.7753	0.5050	0.0818
Salinity (ppt)	0.2665	0.8942	0.1652
pH	-0.7044	-0.6084	0.1730
Nitrate (mg/L)	0.7340	-0.4506	-0.3397
Ammonia (mg/L)	0.2127	-0.4091	0.7501

from the western part of the strait contributed more to the formation of the main axis (F2) (Fig. 2).

F1, F2, and F3, respectively, describe 37.23%, 27.31% and 15.10% of the total variance, significant loadings were observed for the variables SPM, nitrate, current, DO, salinity, and ammonia, as presented in Table 4 and illustrated in Fig. 2. The active loading parameters underscore the factors that negatively impact water quality, resulting from social activities within the DAS area and the clearing of land for aquaculture in the northern part of the bay

In the observation plot depicting the initial two principal axes (F1xF2) (Fig. 3), it is evident that the distribution largely stems from the western area of the bay, concentrated in quadrant IV, where high concentrations of suspended particulate matter (SPM) and nitrate are observed. Mariculture in the eastern part of the bay, clustered in quadrant 2, is characterized by high DO concentrations and clearer waters. In the western section, observations are partially allocated to quadrant 3, which is distinguished by high pH and temperature levels. Meanwhile, other observations are clustered with those from the central-western region, demonstrating elevated SPM and nitrate levels. Fraction mariculture from this location is distributed in quadrant I with high salinity and currents and besides that SPM and nitrate are also high (Marzuki *et al*., 2024).

Primary productivity

Primary productivity measurement uses an algorithm equation developed by Nusapril *et al*. (2017). Based on the spatial distribution of primary illustrated in Fig. 4, the coastal areas exhibit the highest primary productivity, with concentrations surpassing 52 milligrams per cubic meter per hour (mgC/m3/h). Conversely, in the high seas, primary productivity values are observed to be between 34.2 – 42.4 mgC/m3/h. This indicates that water flows from rivers and watersheds which carry minerals, organic materials, and sediment from upstream rivers to the sea affect the productivity

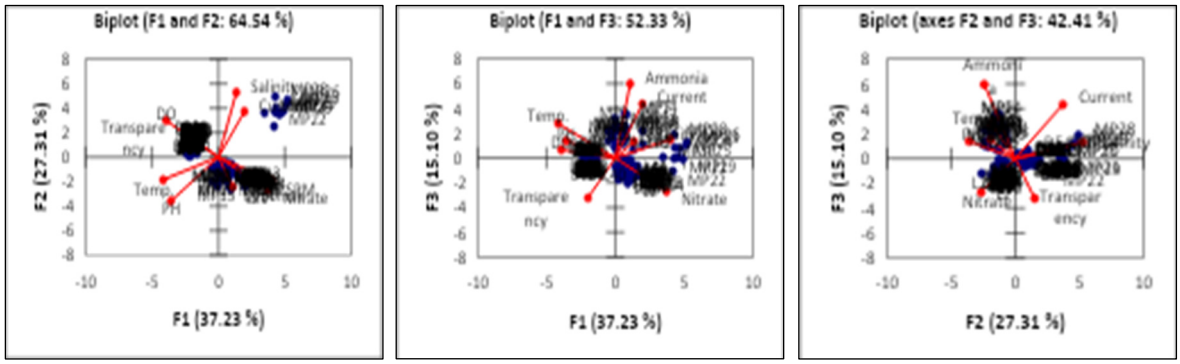

Fig. 3: Main axis observation plots (F1xF2), (F1xF3) and (F2xF3)

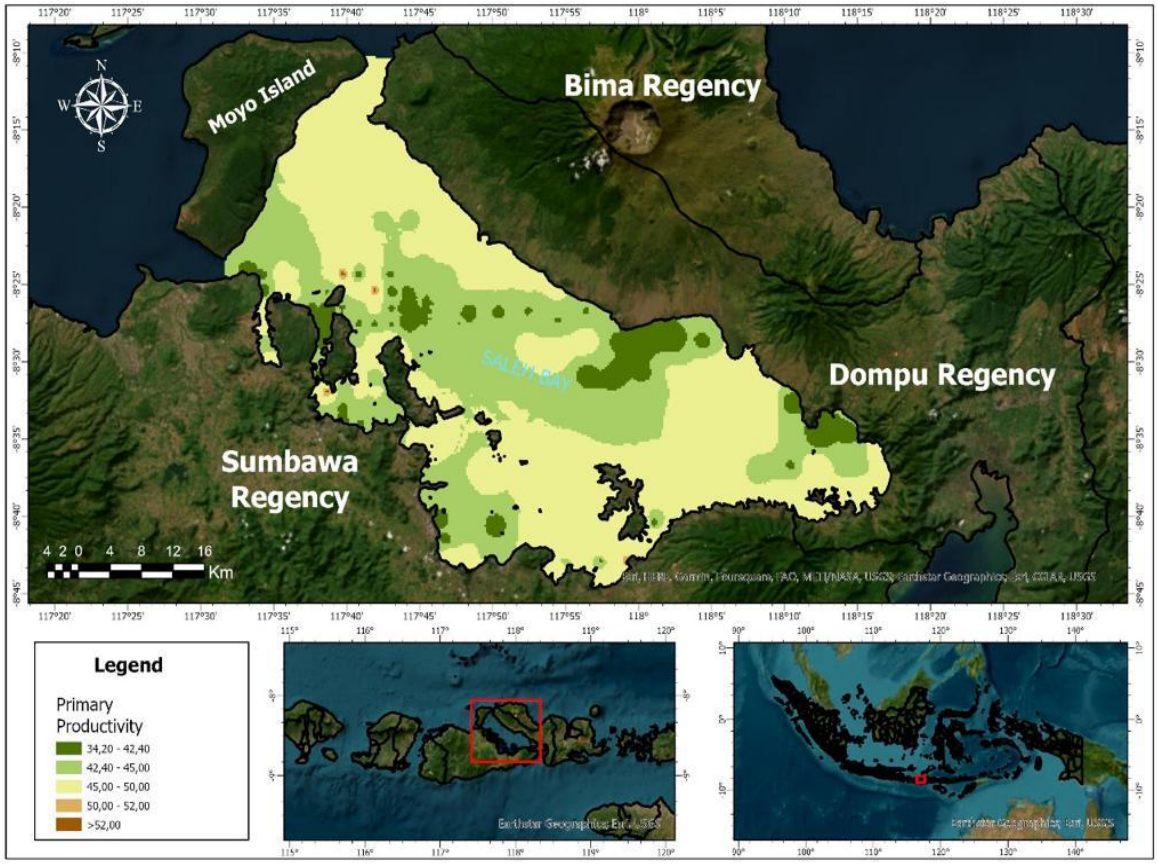

Fig. 4: Spatial distribution of primary productivity in Saleh Bay in 2023

of the research area. In aquatic ecosystems, suspended particles, nitrates, and chlorophyll-a levels are vital indicators that are closely associated with primary productivity. They play a key role in shaping the environmental conditions necessary for the growth and activity of primary producers, including phytoplankton. These parameters not only provide insights into environmental conditions but also highlight their impacts on ecological balance and social aspects of communities. The relationship among these three factors significantly contributes to larger environmental issues, notably the decline of

aquatic ecosystems that jeopardize biodiversity and vital ecological functions. This situation negatively impacts the quality of life for communities that rely on aquatic resources for their livelihoods, clean water, and food supply. Furthermore, it can result in socio-economic disputes, particularly regarding water allocation among agricultural, fisheries, and domestic users. The chlorophyll-a concentration in the open sea waters north of Sumbawa (Moor *et al.*, 2022). Variations in chlorophyll-a concentration follow three distinct patterns: a maximum range of 0.21-0.74 mgC/m³/h occurs during the West Season (November-February), chlorophyll-a concentrations reach a minimum range of 0.12-0.15 mgC/m³/h. In Transition Season I (March-April), concentrations increase, with a second peak observed from mid-East Season to early Transition Season II (July-September), ranging between 0.21-0.36 mgC/m³/h (Fernandes *et al.*, 2022). There is a positive relationship between seasonal changes in chlorophyll-a concentration and primary productivity, especially in areas adjacent to the mouth of the watershed. Based on the spatial distribution of primary productivity (Fig. 4), the highest primary productivity value is found around the coast, which is >52 mgC/m^3/h, while in the open sea the primary productivity value ranges from 34.2 - 42.4 mgC/m^3/h. This implies that the transfer of water from rivers and watersheds, which carries minerals, organic substances, and sediments downstream to the sea, plays a significant role in determining the productivity of the study area. Primary productivity patterns are largely shaped by the spatial distribution of phytoplankton. This is consistent with the chlorophyll-a concentration analysis, which shows the highest levels in coastal waters (Yen *et al.*, 2021) that. This condition is in accordance with that stated in the rainy season, a positive relationship is obtained between chlorophyll-a (Chl-a) concentration and DO and temperature (Fernandez *et al.*, 2022) and has a strong negative correlation with correlation of phosphate ions (PO_4^{3-}) (Zhang *et al.*, 2022) where in shallow waters the interaction of waves, currents, and upwelling (Wang *et.al.*, 2023), causes turbulence and hydrodynamic conditions (Shi *et al.*, 2023). When wind generates surface currents, they tend to move away from the coastline, resulting in a reduction of water mass in that area. As the surface water is displaced further, the resulting gap is subsequently replenished by water from the thermocline layer beneath. This turbulence prevents coastal waters from being thermally stratified (Nuzapril *et al.*, 2017). This phenomenon is called upwelling. When upwelling occurs, the characteristics of the waters on the surface will change. Generally, warm surface water characteristics are observed; however, during upwelling events, the sea surface temperature drops below the usual levels. This phenomenon is accompanied by elevated salinity and a significant increase in nutrients and plankton in the surface waters. The existence of plankton will be a factor in increasing the productivity of marine cultivation in the waters of Saleh Bay. Consequently, its productivity is elevated in comparison to similar offshore waters, owing to the plentiful nutrients available from runoff and recycling. The fertility of a body of water will reflect the high and low productivity of local waters. The selection of the most suitable location for grouper fish mariculture development is achieved by integrating multiple parameters, guided by criteria that reflect best practices in mariculture, based on the outcomes of the weighted overlay method (weighting system).

Feasibility of sea space for mariculture

The optimal location for grouper fish mariculture development is determined by combining all parameters according to criteria derived from mariculture activities, as recommended by the results of the weighted overlay method (weighting system) (Cardenas *et al.*, 2021). After coding each parameter, the next step involves assessing the score in accordance with the criteria presented in Table 1. A score of 3 is for a very suitable class, a score of 2 is for a suitable class and a score of 1 is for a class that is not suitable.

By considering the criteria and limiting factors, land suitability for grouper fish mariculture in Saleh Bay has been determined (Fig. 5) where concentration of primary productivity is moderate. The rate of biomass production by aquatic organisms, especially phytoplankton, is known as primary productivity. This measure is crucial for assessing the health and productivity of aquatic environments. Optimal conditions foster a stable food chain and reduce the likelihood of eutrophication. Variations in the spatial distribution of primary productivity are used as a reference in determining the location of mariculture. The spatial distribution of primary productivity shows

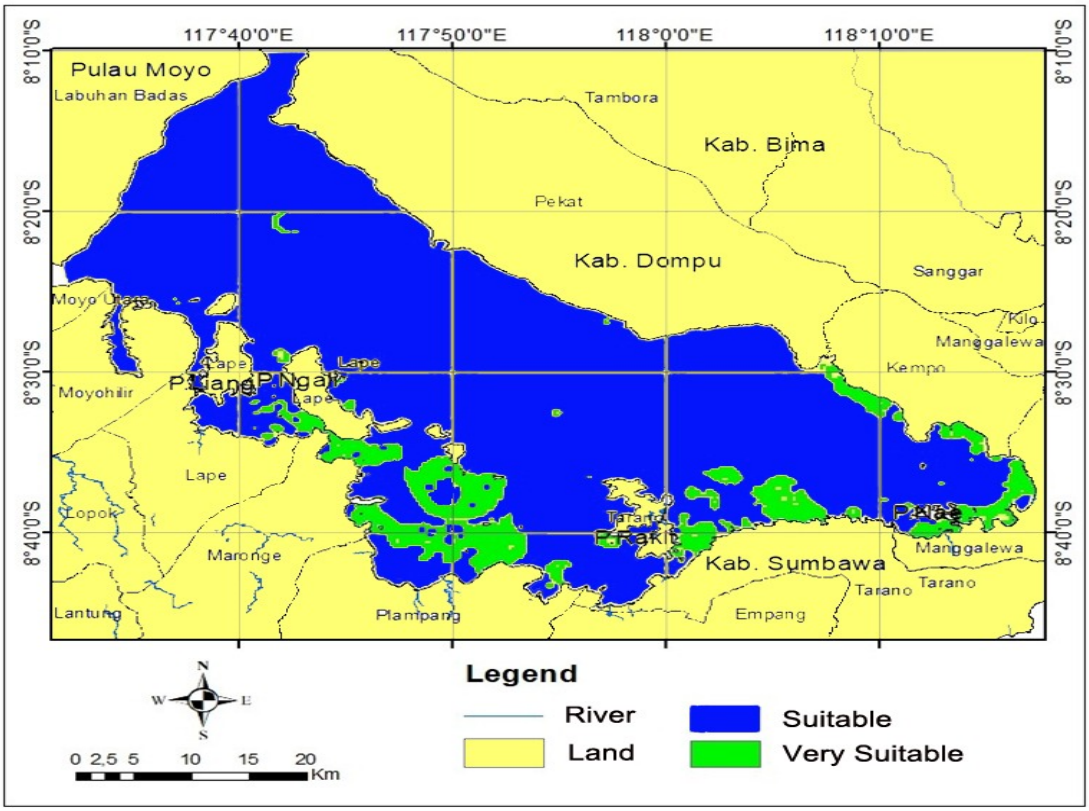

Fig. 5: Map of feasibility locations for mariculture in Saleh Bay

that the highest primary productivity value is around the coast, compared to the open sea. Therefore, the suitability of dominant mariculture is in the southern part of Saleh Bay. The ideal zone is marked in green. This region occupies a minor portion of the waters in Saleh Bay. It lacks any constraints that might influence the habitat needs of fish, thereby providing excellent conditions for mariculture (Nuzapril *et al.*, 2017). Based on Fig. 5 the results of the analysis show that in general the location of Saleh Bay is very suitable for use as mariculture for grouper fish (Guo *et al*., 2018). Some species from grouper fish like snapper, pufferfish and barramundi, are the most suitable for cultivation in accordance with the ecology condition in Saleh Bay. The primary constraint in mariculture is water quality. Assessments of water quality, which include both physical and chemical parameters, demonstrate that these waters are appropriate for mariculture operations. Several oceanographic characteristics are very important in determining the ideal location for mariculture including depth and current (Ahmed *et al.*, 2019). The current movement has the effect of destroying and washing away the construction of rafts, cages, and other supporting facilities. The current speed in the waters of Saleh Bay is 0.06 – 1.9 m/s and has a relatively small strength so this value range is still in the good category for mariculture activities. The location of mariculture should not be placed where the current speed is above 1 m/s (Wang *et al*., 2020). Evaluating land suitability requires careful consideration of water depth as a significant factor. The speed and depth are related to the availability of nutrients which are important factors in mariculture to help chlorophyll synthesis in surrounding waters, tidal conditions help the mobilization of marine nutrients (Sinsona and Juinio, 2018). Nutrient mobilization driven by tidal conditions is vital, particularly because the movement of marine life in mariculture is constrained. Low tide periods present a reduced availability of nutrients compared

to those experienced during high tide (Busch, *et al*., 2020). The results of combining Dishidros depth data and field measurements show a depth range of 0.3 – 324 m. For mariculture activities, the ideal water depth at low tide, measured between the bottom of the cage and the seabed, is 4-5 m (Wang *et al*., 2020). GIS analysis via weighted overlay shows that the water area with a total area of 2900.97 hectare (ha) has a very suitable mariculture area development area of 272.61 ha or 9.4% of the total water area of the Bay. It is expected that the growth of mariculture enterprises will prioritize sustainable practices and ongoing. Therefore, the full utilization of the existing potential should be avoided, and a buffer area should be created to lessen the effects of deteriorating environmental conditions (Garlock *et al*., 2024). This buffer zone can be established by adjusting the number of cage units. Additionally, the placement of the optimal number of floating net cage units in the mariculture zone should not exceed 10% of the ideal area. By combining GIS and PCA methods, this study offers a unique approach to ecology by combining spatial and temporal variations in water quality and could be applied to other regions with similar environment condition. The findings of the study reveal that seasonal fluctuations have a considerable influence on water quality and the viability of marine aquaculture, especially in pinpointing the dynamic factors that influence environmental conditions. The influence of the season, especially during the rainy season, will significantly affect the quality of water in the bay, this is due to runoff from the watershed that carries pollutants. The significant presence of suspended particulate matter and nitrate in the northern area, resulting from local community activities and the development of fishponds in Saleh Bay's northern part, poses potential risks to mariculture. In rainy season, it is suggested to relocate the mariculture farms to diffeerent locations. The potential long-term environmental impacts of relocating mariculture farms to different locations is related directly to mariculture production which will increase because the new location chosen is a pollutant-free area. The relocation is not a year-round measure; it is implemented exclusively during the rainy season to mitigate runoff from land that has the potential to carry harmful pollutants and toxic materials, thereby protecting mariculture activities from negative impacts. The proposed methodological approach for spatial data integration and analysis can be adapted to improve sustainable management and increase mariculture production in other areas with similar ecological and environmental conditions by being able to adjust the characteristics of the area, if it is in a bay area as in this study, then consideration of watersheds, activities on agricultural land and settlements needs to be considered. The assessment focused on physical-chemical parameters. To substantiate the spatial outcomes, PCA analysis was performed, which effectively highlighted the parameters responsible for the decline in water quality. The integration of GIS-PCA proved effective in determining the allocation of ecologically based marine cultivation space and could be applied to other regions with different environment conditions.

CONCLUSION

This study, proposed methodological developments in determining the location of mariculture for grouper fish. This strategy is rooted in the demand for sustainable and efficient aquaculture practices. The recommended approach is adept at detecting and analyzing changes over time in the spatial distribution of water quality parameters. The findings indicate that the key water quality parameters influencing the determination of mariculture locations are SPM, nitrate levels, temperature, salinity, ammonia concentration, current speed, and water transparency. Each of these parameters has a distinct role in supporting the life cycle of grouper fish, ensuring optimal growth and minimizing mortality. The levels of nitrates and concentrations of ammonia are crucial factors, as they influence both water quality and the well-being of fish. Excessive nitrate levels may induce physiological stress in fish, impair their immune responses, and make them more prone to illnesses. Such effects can obstruct growth by interfering with oxygen metabolism and diminishing the efficiency of feed utilization. Unionized ammonia (NH_3) is very toxic to fish, because it can damage gills, interfere with respiratory function, and poison the nervous system, in this case Ammonia will increase the energy requirements for detoxification, thereby reducing the energy available for growth. Based on the impacts caused, the application of knowledge in sustainable mariculture management is urgently needed with several suggestions for implementation, namely: routinely measuring nitrate and ammonia

levels to ensure they are below safe thresholds, feed management to minimize waste, and using a polyculture approach with species that can absorb excess nitrogen, such as aquatic plants or algae. Moreover, the examination of the spatial distribution of primary productivity revealed significant insights. The results demonstrate that primary productivity is elevated in coastal regions in contrast to the open sea. This pattern suggests that coastal regions, with their higher nutrient availability and biological activity, are more favorable for mariculture. However, this advantage is coupled with challenges such as increased susceptibility to pollutant loads from land-based sources. Therefore, careful site selection and management are crucial. Coastal regions are characterized by elevated primary productivity; however, they are also more vulnerable to pollutant influx from terrestrial sources. Therefore, it is essential to select sites judiciously, employing a data-driven methodology to strike a balance between productivity and sustainability. Several factors should be taken into account, including: i) steering clear of areas in close proximity to rivers or waterways that transport runoff from agricultural, industrial, or residential sources, ii) opting for sites with medium to deep depths to promote effective water mixing and pollutant dilution, iii) ensuring that the selected location has stable current speeds to facilitate the removal of excess nutrients from the cultivation zone. Oceanographic parameters, such as depth and current patterns, play a vital role in determining the ideal location for grouper fish mariculture. Depth influences the availability of light, temperature gradients, and the movement of nutrients, all of which are critical for supporting marine ecosystems. Current patterns, on the other hand, affect oxygen supply, waste dispersion, and nutrient cycling. These factors collectively determine the suitability of a site for establishing mariculture operations. Sustainability is a critical consideration in mariculture development. Maintaining equilibrium between economic gains and environmental conservation is crucial. When grouper fish mariculture is managed properly, it can yield substantial economic benefits. However, ineffective management practices may cause detrimental environmental effects, such as pollution of water bodies, destruction of habitats, and a reduction in biodiversity. Therefore, the implementation of sustainable practices is essential. Collaboration among stakeholders, including government agencies, researchers, local communities, and industry players, is necessary to achieve sustainable mariculture. Policies and regulations should be established to guide mariculture development, ensuring compliance with environmental standards. This study introduces methodological improvements that establish a comprehensive framework for selecting appropriate locations for grouper fish mariculture. By incorporating water quality, oceanographic parameters, and sustainability principles, this approach can support the development of a thriving and environmentally responsible mariculture industry. Continued efforts to improve agricultural practices, reduce pollution, and utilize technological innovations will further strengthen the prospects of sustainable mariculture in the future. To improve water quality in upstream areas, it is advisable to implement better residential waste management practices, regulate cropping patterns, and intensify agricultural methods by managing pesticide use and water consumption. For downstream regions, it is essential to rotate mariculture farm locations to reduce pollutant accumulation and to conduct periodic water quality assessments to mitigate drastic changes due to high pollutant levels. Additional recommendations, namely; Implementation of the integrated multi trophic aquaculture (IMTA) model with a combination of shellfish and seaweed, specifically for mariculture locations at the mouth of the bay.

AUTHOR CONTRIBUTIONS

T. Arifin, the author in charge of the study, design and conceptualization of the manuscript, conducting investigations, curating data, securing funding, performing literature reviews. Yulius contributed to acquisition of data, analysis and interpretation of data, drafting of the manuscript, and statistical analysis. M. Ramadhan, contributed to the design, conceptualization and conducting investigations. O. Johan, contributed to acquisition of data, drafting of the manuscript, obtaining funding and supervision. D.P. Gunawan, contributed to conception and design, acquisition of data, and drafting of the manuscript. A. Heriati, contributed to acquisition of data, obtaining funding, supervision. E. Mustikasari, contributed to acquisition of data, obtaining funding, and supervision. R. Rahmania, contributed

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest between fellow authors and affiliates and other parties related to the publication of this manuscript. Ethical issues, including similarity and informed consent, falsification, data violation and/or duplication, multiple publication and/or submission and redundancy, have been fully considered by the authors.

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ABBREVIATIONS

<	Greater than
>	Smaller than
^{o}C	Degree celsius
%	Percent
ADCP	Acoustic doppler current profiler
Chl-a	Chlorophyll-a
DAS	Watersheds
DO	Dissolved oxygen
Eq.	Equation
EPA	Environmental protection agency
F2	Second main axis
F3	Third main axis
FNC	Floating net cage
IMTA	integrated multi trophic aquaculture
GIS	Geographic Information System
Ha	Hectare
LATERIO	Integrated oceanographic research laboratory

LPDP	Indonesia endowment fund for education agency
m	Meters
m/s	Meter per second
mg/L	Milligrams per liter
mgC/m^3/h	Milligrams concentration per meters cubit per hour
NH_3	Ammonia
PC1	First principal component
PC2	Second principal component
PC3	Third principal component
PCA	Principal component analysis
PEMDA	Regency Government
pH	Potential Hydrogen
PO_4^{3-}	Phosphate ions
PP	Primary productivity
ppt	Parts per thousand
SPM	Suspended particulate matters
US	United states
WNT	West Nusa Tenggara
WQI	Water quality index

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