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RESEARCH ARTICLE

MONITORING SUSPENDED SEDIMENT DYNAMICS AND WATER QUALITY IN A SEMI-ENCLOSED BAY FOR SUSTAINABLE COASTAL MANAGEMENT

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ABSTRACT

The study investigated how suspended sediment concentration (SSC) and environmental factors relate in the coastal waters of Lhok Paroy in Aceh Besar, Indonesia. Samples were taken from ten sampling locations at high and low tide. SSC varied from 150 mg/l to 220 mg/l when the tides went out and had a similar range of 110 mg/l to 220 mg/l when it came in. Higher SSC were found near the mouth of the river as well as in areas of high human activity. The other environmental variables also had considerable variability that was dependent on tidal phase as well as location. Luminosity ranged from 4.6 m to 8.9 m; salinity ranged from 28 ppt to 31 ppt; temperature ranged from 30 °C to 33 °C; dissolved oxygen (DO) ranged from 5.5 mg/l to 11 mg/l; and pH ranged from 6.5 to 7.9. Through Principal Component Analysis (PCA), PCA identified the strongest relationships between SSC and pH (Station 2) and SSC and temperature (Stations 3 and 4). And, negative correlations were also found between SSC and DO, and SSC and luminosity. As a result, the amount, or concentration of SSC is affected by tidal hydrodynamics, sediment resuspension and mineral interactions. The work provides insight into the complex interaction between physicochemical factors that impact water quality in tropical coastal ecosystems and helps form a scientific basis for future sediment management and environmental monitoring plans for the Lhok Paroy area.

KEYWORDS

Lhok Paroy, suspended sediment concentration, physicochemical, tides

1. INTRODUCTION

Coastal zones are one of the most active zones on the Earth's surface; these zones possess an important interface between land and water, and are fundamental to maintaining ecological equilibrium and providing for human needs (Luo et al., 2025; Paul et al., 2025). Coastal areas also serve as intricate habitats for many organisms (e.g., benthic animals, plankton, fish, mangrove trees) that contribute to the overall biological diversity and productivity of the coastal systems and provide critical economic resources through tourism, fisheries, transportation, and residential development (Zhang et al., 2025a). In addition to ecological functions, Coastal Areas have also been increasingly affected by human activity (e.g., land-use change, expanding infrastructure, aquaculture development, and tourism growth) over time and this has subsequently led to increased stress on coastal ecosystems. An example of one of the major consequences of this increased stress is an increase in the concentration of suspended materials in coastal waters (Chakraborty et al., 2023). There are different types of suspended sediments, but all provide useful measures of water quality. For example, suspended sediment concentration (SSC) is a central metric for assessing the condition of an aquatic environment. Light penetration and its resultant turbidity are affected by SSC changes. Similarly, temperature distributions are affected by increases in suspended sediments. This alters both primary production and photosynthetic rates of aquatic plants and phytoplankton (Wisha et al., 2025). The effects on the energy flows and nutrient cycles of aquatic ecosystems can lead to long-term ecological imbalances if they are not mitigated. Accordingly, to effectively manage coastal areas, an understanding of the spatial and temporal variation in SSC is essential to develop sustainable management practices that reduce anthropogenic impacts on marine ecosystems (Wang et al., 2022; Xu et al., 2025).

Suspended particulate matter in water has multiple influences from natural and anthropogenic sources of action. For example: as rivers discharge and rise and fall due to tidal activity or land being eroded from the coastline, fine sediments are released into the water column (Zhang et al., 2025b). In contrast, humans can often exacerbate the input of fine sediments into the water column through a variety of activities, including land clearing for agriculture, agricultural runoff, waste being discharged into the water, and fishery and boating operations that resuspend fine sediments within a given water body. In turn, an increase in SSC can help decrease the amount of light penetrating to the bottom of the water column resulting in a subsequent limitation of growth of phytoplankton, seagrass, and coral reef systems as all of these organisms require sufficient light to perform photosynthesis and create oxygen, which are the building blocks of the marine food web (Chen et al., 2025; Song et al., 2024). Finally, an abundance of suspended solids may attach to or accumulate nutrients, heavy metals, or other organic contaminants that have been deposited into the sediment and re-enter the water column, resulting in an ongoing degradation of water quality (Huang et al., 2022). Additionally, long-term

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exposure to elevated SSC will block coral polyps' ability to breathe, shorten larval survival rates, and alter the reproductive cycles of both fishes and invertebrates (Jeong et al. 2022). Ecological stress will lead to a decline in biodiversity, thus impacting the economies of coastal populations dependent on their fishing and tourism industries. Consequently, assessing SSC and its contributing factors will provide a better understanding of how human impacts combine with environmental influences to affect the condition of coastal ecosystems; this will provide a basis for establishing environmental assessment systems and implementing adaptive management procedures in coastal areas (Zhang et al., 2025c). Despite the growing number of studies on SSC dynamics in estuarine and coastal systems, field-based investigations integrating suspended sediment concentration with physicochemical parameters under contrasting tidal conditions remain limited in semi-enclosed tropical bays, particularly in Aceh, Indonesia. Moreover, few studies have applied multivariate statistical approaches to identify site-specific environmental drivers of SSC variability in such systems. Therefore, this study addresses this gap by combining in situ measurements with PCA to examine tidal-phase-dependent sediment–environment interactions in Lhok Paroy.

In order to understand how much sediment is being suspended in water and how much it relates to other things, we need to measure SSC and some other variables (such as the speed of water moving, salt concentration in water and temperature of water), all of which change depending on where you are measuring. By knowing how these different parameters act together, we can more easily identify the source of suspended sediment and how it is being moved. By knowing this information, we will also make better decisions about how to manage coastal resources. To achieve these objectives, this study aims to measure SSC related to certain environmental variables along Lhok Paroy Beach under different tidal conditions. This research project will provide data on how human activities and hydrologic conditions impact sediment movement, thus contributing to scientific data to assist in future conservation efforts and promote sustainable coastal use along the coast of Aceh.

2. Literature Review

Over the past two decades, numerous studies have been conducted on SSC in various coastal environments. SSC studies have been conducted on river dynamics using various techniques, including remote sensing and predictive modeling based on data-driven approaches. One example of such research is a study conducted in the Ganges-Brahmaputra Estuary, which used satellite SSC data collected from 1990 to 2020 to determine the long-term variability of SSC to assess river hydrological conditions (i.e., flow, rainfall, and evaporation), and how these long-term hydrological conditions are affected by global climate change in terms of sediment dynamics. By identifying how these long-term SSC trends evolve in a region with high hydrological stress, this study will provide valuable information for informed decision-making (Yang et al., 2024).

Sentinel 2 imagery, combined with field data, determined the seasonal pattern of SSC at the mouth of the West Flood Canal River (Semarang, Indonesia). The results indicate that tropical rainfall and river discharge are key factors influencing sediment distribution, revealing the impact of the seasonal hydrological cycle on SSC in tropical waters. These findings confirm the utility of monitoring local sediment dynamics using satellite imagery (Wirasatriya et al., 2023). The study of interannual variability of SSC in the Bohai Sea was conducted using the Geostationary Ocean Color Imager (GOCI). GOCI's very high temporal resolution provides more opportunities for in-depth analysis of the dynamic and complex relationships between atmospheric processes, ocean currents, and human activities. This study is part of a growing body of work examining the relationship between climate variability and the physical characteristics of semi-enclosed seas (Xie et al., 2023).

On the other hand, studies completed on the Lena River Delta indicate that hydrological change and ice melt caused by a cold climate have contributed to increased SSC within the Delta. Furthermore, studies completed in the Mezen Bay and the estuarine systems of the Mezen and Kuloy Rivers have indicated that tidal activity and estuarine dynamics are significant features of SSC variability in the surface layer. Therefore, these two studies expand the view of SSC within polar regions and cold climate estuaries (Demidenko, 2023).

As an example, in Aceh Besar Regency, Lhok Paroy Beach has been affected by the combined effects of human and natural processes such as hydrology or weathering. Coastal waters continue to be exposed to rainfall, transporting soil and vegetative debris from agricultural fields into the waters. Human activities, such as sand mining activities, small port operations, and nearshore fishing operations, have contributed to the resuspension of bottom sediment. Tidal cycles are also very important because they can further influence the fluctuations of SSC. At high tide, the influx of seawater dilutes the amount of sediment that is present, and at low tide the amount of sediment is increased due to the turbulence created by waves and currents.

Based on the above findings, the dynamics of SSC in this region are highly influenced by a combination of hydrology, weather or climatic fluctuations, and humans. However, research on SSC in coastal regions of Aceh, such as in Lhok Paroy Beach, is relatively limited. Given the high levels of human activity and the highly dynamic nature of tropical geology in this region, measurements of SSC at Lhok Paroy are critical in developing an understanding of how suspended sediments fluctuate; hence, assisting in implementing sustainable coastal management and adding to global literature regarding SSC in vulnerable tropical ecosystems due to human activities.

Recent work has also shown that either outside and/or remotely sensed classifications are widely used to characterize SSC in areas such as bays affected by the physical sediment inputs derived from land and oceanographic systems (Morgan et al., 2025). Studies have demonstrated that SSC is distributed irregularly throughout the bay, resulting in higher concentration areas located within the bay (e.g. sheltered waters and at river mouth locations) compared to areas with lower concentrations occurring along the bay margins (exposed to ocean). Seasonal variability of SSC is affected by the time of year (e.g. weather/storm activity, monsoon cycle). In addition, areas with coral reefs in the tropics such as Hantu Island and Kusu near Singapore have also demonstrated seasonal variations in the SSC value with peak concentrations occurring during the southwest monsoon months (Morgan et al., 2025). Additionally, long-term data collected at these locations have shown that average SSC values can be characterized as approximately 29 mg/l (Hantu Island) and 16 mg/l (Kusu Island); however, the seasonal variability of SSC within the two study locations has been recorded as variable (Morgan et al., 2025).

In Kendari Bay, sedimentation rate is associated with poor reef conditions, including less live coral cover when sedimentation rates are high (Afu and Subhan, 2016). In addition, high sedimentation rates in Kendari Bay have been shown to negatively affect recruitment of juvenile corals (Subhan and Afu, 2017).

Regression analysis in Lampung Bay demonstrated that sedimentation rates were negatively correlated with live coral cover, indicating that high SSC and sedimentation rate inhibit coral growth and cover (Barus et al., 2018). An analysis of the literature summarised in a systematic review (which was not bay-specific, but provided evidence of an impact of SSC) found that SSC greater than 15 mg/l to 260 mg/l produced a wide range of chronic stress, impaired growth, and/or mortality for coral reefs, however, there is some variation across locations and different types of sedimentation (Tuttle and Donahue, 2022).

3. Methods

3.1 Determination of Research Stations

This study was conducted during a single field campaign in February, 2024, during which sampling was performed under both ebb and flood tidal conditions within the same survey period. Sampling at all stations was completed within a continuous 24-hour tidal cycle to ensure comparability between tidal phases. Across the coastal waters of Lhok Paroy, a total of ten sampling stations were established (shown in Figure 1). Each sampling station was located via purposive random sampling to ensure that it represented variability in hydrodynamic conditions, river inflow, and human activity (e.g., the bottom stations closest to the mouth of the river were influenced by land-based sediment input, while offshore stations represented open water conditions). In addition to sampling in areas with river influence, some of the stations were also placed in areas that experienced both tourism and commercial fishing to assess the impact of human activities on the environment. The geographic coordinates of each station were recorded with global positioning system (GPS) to facilitate accurate and reproducible sample collection. The number of ten stations was considered sufficient to represent the spatial heterogeneity of this semi-enclosed bay, capturing gradients from river-dominated areas to offshore zones while maintaining logistical feasibility and consistent sampling coverage.

3.2 Water Sampling

The collection of water samples was done using clean polyethylene sample bottles of known volume. Each bottle was submersed to about 1 meter below the surface of the water, to obtain a representative sample from the surface layer of the water. All of the sampling was conducted, methodically, at each sampling station so that all of the samples collected at a given location had an equal chance of being contaminated. Once the water samples were collected, they were sealed tight, labelled with the sampling station codes and placed into an insulated (with ice packs) styrofoam container for transportation to the laboratory, to maintain the integrity of the samples during transport. At each station, sampling was conducted in triplicate for each tidal phase to ensure measurement reliability. The average value of the replicates was used for subsequent analysis.

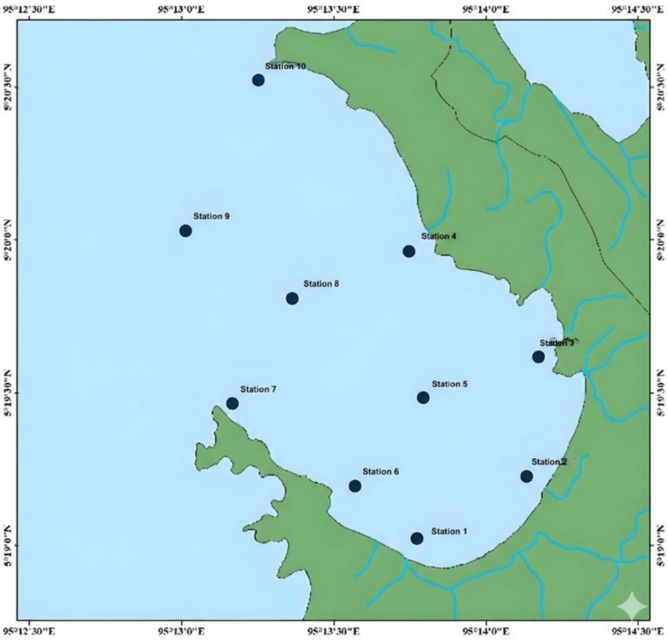

Figure 1: Research location map of Lhok Paroy waters showing ten sampling stations

3.3 Measurement of SSC

Measurement of SSC was performed using the Gravimetric Method according to the established protocol (SNI 06-6989.3-2019). The initial step in this process was preparation of the filter medium. The filter medium consisted of filtration apparatus and filter paper which were rinsed with distilled water prior to use (Jiang et al., 2020). Filter paper was then prepared by placing on a petri dish, oven dried at 103 °C to 105 °C for one hour, cooled in a desiccator, and weighed (initially W_0). For measurement, the filter paper was moistened with a small amount of distilled water, and then one litre of the homogenised water sample was filtered through the filter paper using a vacuum filter (i.e., filtration was completed). After filtration was completed, the filter paper was rinsed three times with 10 ml of distilled water to remove any residual salts and impurities from the filter paper and filter paper was then dried, cooled in a desiccator, and re-weighed (final W_1). The difference between W_1 and W_0 was the mass of suspended solids in the water sample and was used to calculate SSC (mg/l) (Tao et al., 2025).

3.4 Measurement of Luminosity

The Secchi disk (a circular plate divided in half between black and white) was utilized to measure luminosity (water transparency). The Secchi disk is attached to a marked (calibrated) rope and lowered into the water until it can no longer be seen, this depth being determined as d_1. It was then raised until it was again visible, this depth being determined as d_2. The average of d_1 and d_2 is considered to be the luminosity for each sampling station (Ji et al., 2024).

3.5 Calculation of SSC

To assess the distribution of SSC values based on the measured data, the following formula $SSC\left(\frac{mg}{l}\right) = \frac{W_1 - W_0}{V}$ was utilized in accordance with the National Standardization Agency (SNI 06-6989.3-2019), where W_0, W_1, and V are weight of filter paper before filtration (mg), weight of filter paper with dry residue (mg), and volume of water sample (ml), respectively.

3.6 Statistical Analysis

Principal Component Analysis (PCA) was conducted to explore multivariate relationships between SSC and environmental parameters under high and low tide conditions. All variables were standardized using z-score transformation prior to analysis to remove scale effects. PCA was performed based on the correlation matrix. The first two principal components were retained for interpretation based on the cumulative percentage of explained variance. The orientation and length of variable vectors were used to interpret relative associations among variables. Statistical analysis was performed using SPSS version 26.

4. Results And Discussion

4.1 SSC

The measurement results indicated that SSC values varied among sampling sites during both ebb and flood tides. Ebb tide SSC values ranged from 150 mg/l to 220 mg/l, while flood tide SSC values ranged from 110 mg/l to 220 mg/l. Average SSC was found to be higher during ebb tide (196 mg/l) than flood tide (161 mg/l) in Table 1. This evidence suggests that sediment resuspension and transport processes are primarily influenced by tidal movements. The reduction in water volume (i.e., through ebb tide) and increased current velocity, can cause previously settled sediments to be resuspended into the water column once again. SSC values at sites closest to estuaries (i.e., Stations 1 and 2) exhibited the highest levels due to sediment inputs from both river discharge and tidal mixing; therefore, these areas are subject to significant sedimentation from land-derived sources (e.g., runoff, land-use practices). Moreover, high SSC levels are often found in these areas due to the influence of runoff containing soil particles, organic material and human waste (Li et al., 2023; Poirier et al., 2017; Zou et al., 2025). In contrast, sites farther away from the influence of land-derived sediment sources generally exhibited lower SSC; therefore, these sites are characterized by lower sediment inflows due to stronger water mixing and dilution. Therefore, the spatial distribution of suspended materials in coastal areas is primarily influenced by tidal dynamics as well as land-derived inputs (Vowels et al., 2025).

Table 1: SSC Measurement Results

Station	SSC (mg/l)	
	Ebb	Flood
Station 1	220	130
Station 2	210	130
Station 3	200	200
Station 4	210	220
Station 5	220	180
Station 6	180	190
Station 7	190	110
Station 8	180	130
Station 9	150	130
Station 10	200	190
Average	196	161

The minimum SSC was observed at Station 9 with concentrations of 150 mg/l (during ebb tide) and 130 mg/l (during flood tide). This station is at the bay mouth, where freshwater input is diminished by the hydrodynamic energy of seawater causing increased dispersion and dilution of suspended particles (Sun et al., 2025; Wang et al., 2025). Offshore decreases in SSC indicate that sedimentation occurs as flow rates decrease and particles settle due to gravity. The relatively high values at Station 4 and Station 5 during flood tide indicate strong mixing through wave and current action, which has caused the resuspension of sediments that were originally deposited on the seabed. The differences between the stations also reflect the role of human factors such as fishing, tourism and land-based sources of pollution, which can disturb bottom sediments and increase turbidity (Shen et al., 2025). Data supports the suggestion that Lhok Paroy's SSC is controlled by the interaction between hydrodynamics of the tides, river delivered sediment, and human activities on the coast. These results emphasise the importance of ongoing monitoring of sediment transport to manage coastal ecosystems and prevent further degradation of water quality and aquatic organisms due to increased sedimentation (Zhao, 2026; Zong and Hadley, 2025).

4.2 Environmental Parameters of Lhok Paroy Coastal Waters

The monitoring of multiple environmental characteristics in the Lhok Paroy water systems indicated that there were dynamic changes in the parameter as a result of changing tides. The water brightness (luminosity) is defined as the amount of light entering the water column; therefore, during high tides the overall range for the luminosity value, which can be found between 4.6 to 8.9, was generally more for high tide and less for low tide. The luminosity value is affected by several environmental and physical conditions which include the depth of water, the amount of suspended materials in the water, and the amount of light provided from the sun. As seawater entered the estuaries, seawater diluted existing suspended materials and thus improved visibility within several of the recording stations during high tide. Nevertheless, a few monitoring stations, such as the 10th station, were characterized by an increase in luminosity that coincided with an increase in SSC (suspended sediment concentration (Table 2). It is likely that these anomalously bright values are due to coastal cliff erosion and the large quantities of fine sediments being released into the water column due to coastal cliff erosion (Chakraborty et al., 2024; Matos et al., 2024; Wang et al., 2024). Approximately 90% of the solid materials from the coastal cliffs which have eroded from the coastal cliffs enter marine water as solid sediments; these sediments contribute to turbidity in the surrounding locations. Overall, the spatial patterns in luminosity indicate that light penetration into the Lhok Paroy water must have been determined collectively by tidal mixing, sediment resuspension and the geomorphology of each site. As such, transparency could be a sensitive indicator of hydrodynamics and sediment processes at all sites along this coastal system (Morales-Marín et al., 2025).

Table 2: Results of Other Parameter Measurements

Parameter	Ebb	Flood
Luminosity (m)	5.95 ± 1.41	5.71 ± 1.30
Salinity (ppt)	30.20 ± 1.23	30.30 ± 0.67
Temperature (°C)	31.40 ± 1.07	30.90 ± 0.99
DO (mg/l)	7.60 ± 1.80	6.62 ± 0.92
pH	7.10 ± 0.46	6.95 ± 0.35

The key physicochemical parameters of aquatic habitat quality are salinity, temperature, and dissolved oxygen (DO). Tidal fluctuations and freshwater runoff affect salinity levels at three different sites in Lhok Paroy, where the salinity recorded in Lhok Paroy ranged from 28 ppt to 31 ppt. Salinity was lowest at Station 1, the station nearest to the estuary, indicating that during times of high river flow there was a significant amount of freshwater entering the system. The salinity reading taken near Station 1 is well within the accepted range for Indonesian coastal waters and indicates there is an adequate supply of freshwater at that station. Thermal readings for all three locations were also relatively stable, ranging from 30°C to 33°C. The small amount of variability in these temperatures indicates that the shallow coastal waters of Lhok Paroy are well-mixed, and therefore, the temperature differences between ebb and flood tides are likely the result of differences in the timing of measurements and solar radiation rather than tidal currents. These stable temperature ranges promote the growth of phytoplankton and benthic organisms adapted to tropical coastal environments (Bazrafshan et al., 2025; Jiang et al., 2020; Vowels et al., 2025). DO also fluctuated distinctly between 5.5 mg/l to 11 mg/l on the two sampling days during high tide versus between 5.6 mg/l to 8.4 mg/l at low tide. These changes were attributed to mixing intensity, organic matter decomposition and influx of oxygenated freshwater. High DO levels close to the estuarine areas indicate that nutrient input and river discharge aerate the location resulting in increased levels of oxygen, conversely offshore stations generally exhibited lower DO levels because they are diluted and have no stratification (Chakraborty et al., 2023; Wisha et al., 2025; Zhang et al., 2025a).

The chemical pH level of the ocean should also be noted as an important indicator of chemical stability and ecosystem vitality. In Lhok Paroy, the pH readings were within the range of 6.6 to 7.9 during high tide, and 6.5 to 7.6 during low tide, indicating slightly alkaline to neutral conditions which would be ideal for many marine organisms to thrive. Changes in pH levels are largely affected by biologic processes, particularly, the photosynthetic activity of phytoplankton, and by the mixing of the various water masses via tides (Chen et al., 2025; Wisha et al., 2025; Zhang et al., 2025a). At high tide, the incoming seawater with a higher buffering capacity generally raises the pH level, while organic material and CO_2 build-up near low tide as a result of respiration and/or decomposition can slightly reduce the pH level (Ji et al., 2024; Tao et al., 2025; Xiao et al., 2018). Therefore, the interaction between the availability of nutrients, productivity of phytoplankton, and tidal mixing determines the short-term variability of acidity in the region. The equilibrium or balanced pH (hydrogen ion concentration) is critical for controlling biochemical processes, promoting optimal metabolic activity of aquatic species, and maintaining appropriate levels of activity within the pools of available enzymes (Vowels et al., 2025; Zhao et al., 2026). Thus, the combination of changes in luminosity, salinity, temperature, DO, and pH indicates an active and dynamic coastal system that is easily changed by both natural hydrodynamic processes and man-made activities. Knowing how these variables interact will provide insight into the ecological functioning of the coastal waters of Lhok Paroy and serve as a foundation for sustainable management of water quality and sedimentation within the area.

4.3 Relationship between Environmental Parameters and SSC Based on PCA Analysis

The use of PCA was utilized to establish the associations among the environmental parameters, as well as identify those parameters that exert the greatest influence on SSC during high tide. The variable distribution can be seen in Figure 2a, while Figure 2b presents a distribution of the sampling stations based on the first two principal components (F1 and F2). F1 and F2 together account for 72.03% of the total variance of the data. Those parameters which are positioned further from the zero axis have a proportionally greater contribution to the variability in the data, indicating they have a greater degree of influence on the data set. DO, temperature, pH and SSC were located in the same quadrant, indicating that they are affecting each other through interrelated processes during high tide. For example, at Station 1, there was a significant positive correlation between DO and temperature, in that, as the temperature increased, so did the DO levels. This is because there is a high level of solar radiation in estuarine zones, and due to the shallow depths of the waters, the direct rays of sunlight facilitate increased photosynthesis by phytoplankton and aquatic macro flora. The photosynthesis process results in an increase in DO levels through the release of O2 into the water (Chakraborty et al., 2024; Luo et al., 2025; Matos et al., 2024). Temperature is not independent of the water temperature, it can be affected by metabolic activity, so therefore, due to high water temperature (33°C) along with high DO concentration (11 mg/l) at the Station 1, it can be deduced that solar intensity and photosynthetic productivity play an integral role in the maintenance of oxygen level during the high tide cycle in the waters of Lhok Paroy (Wisha et al., 2025).

During high tide, the first two principal components explained 72.03% of the total variance (F1 = 42.13%; F2 = 29.89%). Variables positioned close together and oriented in similar directions on the PCA biplot indicate positive multivariate associations, whereas variables oriented in opposite directions suggest negative associations. SSC and pH were aligned along the positive F1 axis, while luminosity and salinity were positioned in the opposite quadrant, indicating contrasting spatial gradients. Dissolved oxygen and temperature were more strongly represented along F2.

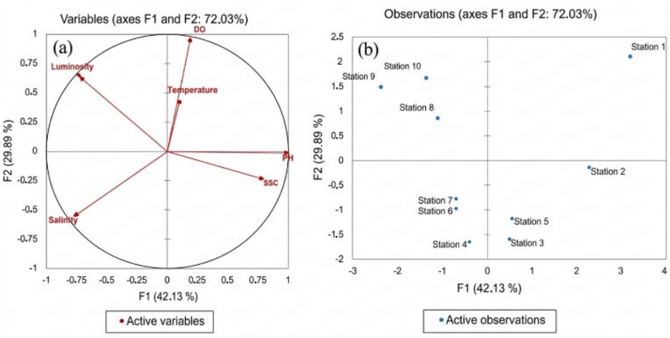

Figure 2: SSC analysis results using the PCA method during high tide; (a) parameter distribution (b) research station distribution.

Figures 2a and 2b of the PCA diagram illustrates DO and SSC's inverse correlation (i.e., opposite directions of their respective vectors). Therefore, as SSC increases, DO decreases. The most noticeable example of this was observed at Station 1 during low tide, when DO was recorded at 8 mg/l and SSC was at a comparatively low 130 mg/l. In contrast, when the water has less SSC (i.e., clearer water), sunlight will penetrate further, thus allowing a greater amount of phytoplankton and macrophytes to photosynthesize efficiently, leading to increased DO. Conversely, an increase in SSC from sediment resuspension or runoff will cause greater light attenuation, which decreases the amount of photosynthetic oxygen produced, resulting in lower levels of DO. The PCA clustering indicates that these two variables (luminosity and salinity) are in close proximity to each other indicating a moderate correlation between them, which may be a result of tidal mixing and influent freshwater that enters the estuary (Sun et al. 2025, Wang et al. 2025, Zhao et al. 2026). The stations which were located toward the outer coast (Stations 8, 9, and 10) were found on the opposite axis of SSC, indicating that the slope of sediment is low and clear water exists in terminal areas. These results indicate that hydrodynamic processes (i.e. flow and momentum) and sediment distribution play a direct role in the oxygen dynamics within coastal ecosystems. The identification of how SSC interacts with other variables provides insight into the ecological stability and productivity of Lhok Paroy's coastal waters.

During low tide, the first two components explained 65.61% of the total variance. SSC and pH were closely aligned, suggesting a strong multivariate association under low tidal conditions. Temperature showed alignment with SSC at certain stations, while salinity displayed an opposite orientation, indicating a potential inverse pattern. These results highlight spatial structuring of sediment–environment interactions driven by tidal phase, without implying direct mechanistic causation.

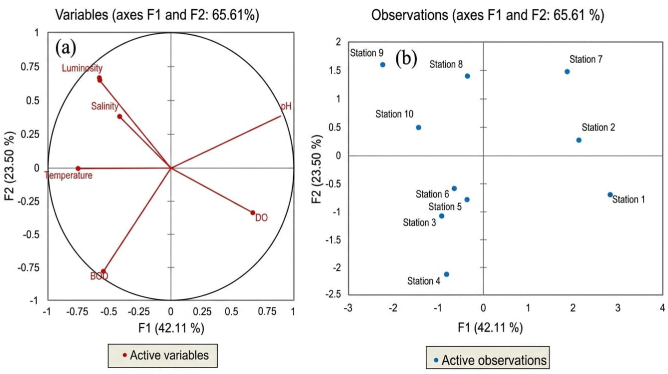

Figure 3: SSC analysis results using the PCA method during low tide; (a) parameter distribution (b) research station distribution

PCA of the environmental parameters during the low tide (Figures 3a and 3b), displays the relationship between environmental parameters or how the sampling stations relate to the environmental parameters. The first two axes (F1, F2) of the PCA account for a total of 65.61% of the total variance indicating that the majority of the environmental parameters can be represented along these two axes. Station 2 appears to have the strongest correlation between SSC (210 mg/l) and pH (7.7) indicating a statistically significant positive correlation. This suggests that as concentrations of suspended sediments increases, the pH also increases. It is hypothesized that this positive relationship is associated with the buffering capacity of the suspended sediments, particularly due to carbonates and metal oxides, which may be able to neutralize acids and raise the pH (Luo et al., 2025; Paul et al., 2025). The affinity between SSC and pH measurements logged at Station 2 show that hydraulic dynamics and sediment chemistry interactively affect the physicochemical balance of the Lhok Paroy coastal system (Wang et al. 2022; Zhang et al. 2025b).

Two variables are highly correlated in many locations where data were collected from low tidal waters, especially in Stations 3 and 4 where temperature and SSC were the two major influences. The positive correlation between temperature and SSC indicates that as water temperature increases, SSC also tends to increase (Paul et al., 2025). This relationship is likely due to increased particulate agitation and sediment resuspension as a consequence of increased water temperature and increased current flow, both of which are common in shallow coastal waters. Higher SSC levels also absorb more solar energy, thereby increasing surface water temperatures and creating a positive feedback loop (Zhang et al., 2025b). This interaction can decrease oxygen solubility and reduce oxygen availability to aquatic animals and organisms that require consistent DO concentrations for survival. Furthermore, salinity was identified as the primary driver of sediment concentration at Stations 6 and 7, with salinity showing a negative correlation with sediment concentration (Jiang et al., 2020). This observed inverse correlation is generally explained by flocculation, where higher salinity increases the agglomeration of suspended particles, leading to their settling on the seafloor. Increasing salinity causes the coagulation of smaller sediment particles, which then settle on the seafloor, thereby reducing sediment concentration in the aquatic environment (Jiang et al., 2020). These results demonstrate the role of salinity as a regulator of sediment retention and water clarity. Simultaneously, the PCA results indicate that the spatial distribution and physicochemical characteristics of SSC during low tide can change through the relationship between temperature, salinity, and sediment transport in shaping or influencing coastal water quality.

The PCA analysis provides a novel way to understand how various environmental parameters are related to SSC and how they relate to coastal water quality through a multivariate statistical approach. Lhok Paroy has not been analyzed using multivariate statistics before, where SSC and other environmental variables (e.g. turbidity, chlorophyll) have been previously examined (Ji, et al, 2024; Xiao, et al, 2018; Zou et al, 2025). This study is unique because it provides a new way to conceptualize sediment chemistry and hydrodynamics in the context of tidal influence through their site-specific parameter dominance (i.e. strong positive relationship between SSC and pH at Station 2, and temperature and SSC interaction at Stations 3 and 4). In contrast to previous studies that have examined either sediment transport or water quality indicators on their own, the present study is able to link these two types of analyses through the use of a multivariate analysis in order to demonstrate that these interrelationships create a complex set of dynamics in coastal ecosystems. In addition, by identifying those stations with the least effect from other variables (Stations 5, 6, 7, 8 and 10), a new baseline has been created for the identification of stable versus sensitive areas for sediment dispersion. The proposed approach will aid in recognizing the two-fold function of SSC as an environmental measure and as a determinant of other water quality variables (Zhao et al., 2026; Zong and Hadley, 2025). Additionally, it is shown that tidal forces, sediment types and the buffering by minerals result in the entire ecological resilience of the coastal systems. Therefore, this study not only provides empirical data for coastal management in Aceh but also offers a new methodological approach to assess the elements affecting sediment-parameter interactions through the use of PCA. This type of information will be essential in developing sustainable monitoring systems and early warning indicators for sedimentation and eutrophication in tropical estuaries.

Lhok Paroy also functions as a fishing ground for local artisanal fishermen that use handline and trap nets to fish for reef fish located throughout the bay's coral ecosystem. While some fishing methods that operate passively may be perceived to have less impact on the environment, they can nevertheless have significant impacts on reef ecosystems, particularly those associated with coral. Handline fishing can lead to fishing line becoming entangled on corals, with fishing lines (especially those that are lost or discarded) being caught on either branching or soft coral; this leads to tissue abrasion and partial colony death, as well as contributing to algal growth on the damaged portions of the reefs. Trap nets that have been placed in coral reef areas can physically contact juvenile coral colonies and the surface of the reef. Such contact can break or scar the skeleton of the coral, particularly in sensitive taxa such as Porites and mushroom corals, while also mobilising sediment when trap nets are being moved, which can smother organisms that inhabit the shallow portion of the reef (Suebpala et al., 2021).

5. Conclusion

The study of suspended sediment concentration (SSC) and relevant environmental factors in Lhok Paroy's coastal waters indicated that tidal effects play a major role in both sediment transport and water quality within the area. Tides significantly affect how SSC correlates with environmental parameters, with SSC correlating well with dissolved oxygen, temperature, and pH during high tide; however, only salinity, luminosity, and temperature were correlated with SSC during low tide. PCA results show that each sampling station had individual dominant environmental characteristics based on both natural and anthropogenic influences; therefore, Higher SSC correlates with decreased water clarity and dissolved oxygen, while increased salinity and luminosity correspond to less sediment-laden waters. Thus, this research has gained new insights into how various physicochemical processes work together to create and influence coastal environments, as well as how sediment transport, tidal processes, and mineral buffer systems are key to controlling water quality. These new research findings underscore the importance of continuous monitoring and integrated management approaches to protect the functions of dynamic coastal environments like Lhok Paroy.

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