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Spatial Variability of Water and Sediment Quality in Pond Outlet: Implications for Coastal Ecosystems in Mangrove Areas, Pasuruan, East Java

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ABSTRACT

Aquaculture expansion in Pasuruan's coastal areas raises concerns about water and sediment pollution, but the spatial variability and magnitude of these impacts remain insufficiently quantified. This study aimed to assess the water and sediment quality at pond outlets across different aquaculture systems. Samples were collected from seven intensive (high-input shrimp farming), traditional (low-input, extensive ponds), and silvofishery (integrated aquaculture with mangroves) aquaculture farms from July to September 2024, coinciding with peak farming activity. Water and sediment samples were collected from seven farms and analyzed for chemical parameters, organic matter content, and redox potential. Results of the current research record extensive spatial and temporal heterogeneity that is driven by aquaculture management and external events like the WSSV epizootic in August 2024. Ammonia concentrations increased dramatically at stations within intensive vannamei shrimp farms (5.5 mg/L), while downstream stations exhibited natural dilution and mitigation by mangroves. Sediment quality analysis demonstrated a reducing condition with redox potential values from as low as -100 mV and SOM concentrations as high as 23%. Correlation analysis highlighted intensive farming systems as the main drivers of water and sediment degradation, with mangrove belts demonstrating resistance through nutrient adsorption and filtration with COD, TSS, and organic matter as primary pollution contributors. These findings emphasize the urgent need for adopting sustainable practices, such as polyculture systems, reduced feed input strategies, the implementation of constructed wetlands, and enhanced mangrove rehabilitation around aquaculture zones, to minimize environmental impacts and preserve coastal ecosystem health.

1. Introduction

Aquaculture, particularly white leg shrimp (*Litopenaeus vannamei*) farming, is one of the main determinants in achieving Indonesia's national goal of 2 million tons of shrimp production annually by 2024 (Mustafa *et al.* 2023; Maudy and Junianto 2024). However, the rapid adoption of intensive shrimp culture systems, which prioritize high productivity through increased stocking densities and inputs, has raised significant environmental concerns. Intensive systems are not only highly vulnerable to disease outbreaks (Millard *et al.* 2021; Le *et al.* 2024) but also contribute substantially to water quality degradation, increasing nutrient loads, suspended solids, and organic matter that can negatively affect surrounding ecosystems.

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Despite the importance of aquaculture to national food security and economy, understanding of the spatial variability of pollution from aquaculture effluents remains limited. Previous studies have indicated that even low levels of prolonged contamination can significantly alter benthic community structures (Iwasaki *et al.* 2009; Qu *et al.* 2010). However, the specific impacts at the outlet zones where wastewater is discharged into coastal systems have been less explored. Evaluating the spatial patterns of water and sediment quality near aquaculture outlets is essential for developing effective management and mitigation strategies.

Coastal environments, particularly estuaries, are under intense environmental stress from high nutrient levels from natural processes as well as pond operations. These contaminants can influence benthic communities in numerous ways and have the potential to impact them heavily. Even within relatively low-contamination sites, prolonged contact may bring about drastic changes at the community level (Iwasaki *et al.* 2009; Qu *et al.* 2010). Increased nitrogen and phosphorus levels promote eutrophication, increasing primary production and organic matter deposition in sediments. While this can benefit some benthic organisms in the short term, too many nutrients can lead to oxygen loss and habitat change. High-suspended solids raise water temperature and lower dissolved oxygen (Rahman *et al.* 2020). These particles absorb solar radiation heat and transfer it to the surrounding water. Even the heavier particles can settle and smother benthic organisms and fish eggs (He *et al.* 2017).

The Pasuruan Mangrove Study Centre in East Java provides an ideal setting for investigating these interactions. The center integrates shrimp farming practices-ranging from traditional to intensive systems-and promotes silvofishery approaches that incorporate mangrove reforestation. These activities have inspired local farmers to diversify their pond activities. The Kraton area in Pasuruan, which is 22.5 hectares of the coastal area, contains 25 fish culture ponds in the coastal mangrove forest zone (Sina *et al.* 2017; Doctorina *et al.* 2024).

The long history of aquaculture activity at the Pasuruan brackish water station makes contamination evaluations challenging, so the exact separation between acute pollution and background levels is hard. The outlet area where wastewater is released into rivers or the sea is a key point of pollution (Nagaraju *et al.* 2022). More studies must be conducted to establish baseline environmental conditions as a reference point for aquaculture impact assessment. This study aimed to describe the spatial variation of water and sediment quality parameters because of various cultivation practices at the Pasuruan field practice station and to assess how much the outlet channel contaminates coastal areas.

2. Materials and Methods

2.1. Field Sampling and Data Collection

Between July and September 2024, water and sediment samples were collected from seven reference stations in Pasuruan's brackish water cultivation site (Figure 1). Stations 1–3 were near intensive vannamei ponds, 4–5 near traditional milkfish ponds, and 6–7 near the mangrove buffer zone (Figure 1, Table 1). Each station was sampled once a month to assess the spatial variability of water and sediment quality.

2.1.1. Additional Sampling During WSSV Outbreak

In August 2024, additional sampling was conducted spontaneously during an outbreak of White Spot Syndrome Virus (WSSV) in intensive vannamei shrimp culture (Table 2). While monthly sampling was planned, the outbreak occurred unexpectedly and prompted extra sampling to assess its impact on water and sediment quality in the affected areas. Three replicate water and sediment samples were collected at each station during both the routine monthly sampling and the additional sampling during the WSSV outbreak.

2.2. Water and Sediment Collection

Physical water quality parameters (Temperature, Salinity, pH, DO, Brightness) and chemical water quality (Ammonia, BOD, COD, TOM, Nitrate, Nitrite, Phosphate, and TSS) were measured in situ and tested in the laboratory. All samples were collected in polypropylene bottles and returned immediately to the lab for analysis by applying standard methods (National Oceanographic Bureau 1991). Sediment quality (Redox Potential, Soil pH, SOM) was also analyzed. Water samples were taken from 10 cm depth, and sediment samples from 0.5 m were taken. The samples were kept preserved, dried, and sieved before analysis (Husson 2013). After drying, the sediment was sieved with 2 mm mesh to remove coarse particles. Samples of wastewater were also measured directly.

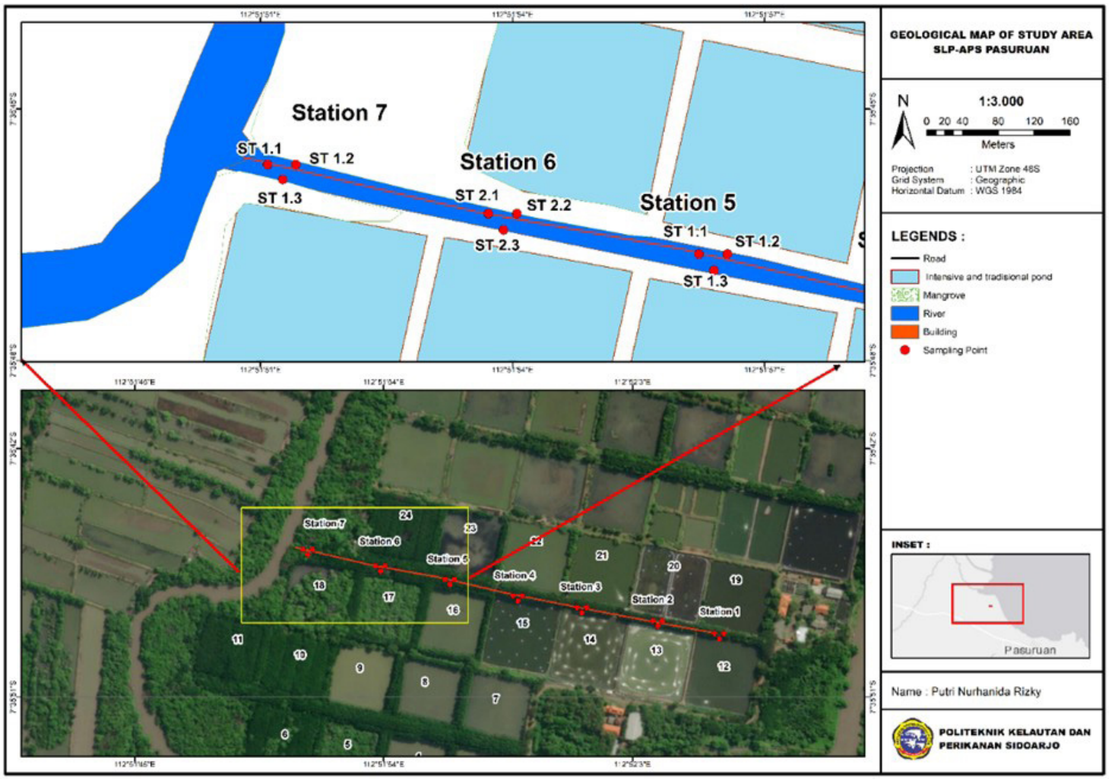


Figure 1. Geological Map of the Study Area (SLP-APS Pasuruan) showing station locations, sampling points, roads, ponds, mangroves, and buildings. The inset map shows the location within Pasuruan. Sampling points are marked with red dots, and the roads, ponds, and mangrove areas are indicated in the legend

Table 1. Pond utilization of brackish water cultivation practice station, Pasuruan

Station	Map out the aquaculture area	Utilization of ponds
1	12	Intensive vannamei shrimp
	19	Traditional crab mud (research)
2	13	Intensive vannamei shrimp
	20	Intensive Asian Sea Bass
3	14	Intensive vannamei shrimp
	21	Traditional polyculture systems of milkfish and tilapia
4	15	Reservoir pond
	22	Traditional polyculture systems of milkfish and tilapia
5	16	Sylvofishery of milkfish
	23	Traditional polyculture systems of milkfish and tilapia
6	17	Mangrove (Buffer zone)
	24	Mangrove (Buffer zone)
7	18	Mangrove (Buffer zone)
	-	Mangrove (Buffer zone)

Table 2. Time sampling of study

Time sampling	Days of culture				
	Intensive vannamei shrimps	Traditional mud crab (research)	Traditional polyculture systems of milkfish and tilapia	Intensive Asian Sea Bass	Sylvofishery of milkfish
July 15, 2024	10	Preparation	78	67	30
Aug 15, 2024	41	19	109	97	61
Aug 28, 2024	WSSV Outbreaks (98% of mortality)	32	122	110	74
Sept 15, 2024	No act	52	140	128	92

2.3. Water Quality Parameter-Ammonia (NH3)

Ammonia concentration in water samples was determined using the Nessler reagent colorimetric technique (Golterman 1991). The pH of the sample was adjusted to alkaline (>10) with sodium hydroxide. 1 ml of Nessler reagent and 0.5 ml of water sample were combined and allowed to stand for 10-15 minutes. Absorbance at 420-425 nm was measured using a spectrophotometer.

2.4. Water Quality Parameter-Biochemical Oxygen Demand (BOD)

Biochemical Oxygen Demand (BOD) was ascertained through respirometry with the addition of phosphate buffer and magnesium sulfate to support microbial growth. Incubation of the sample was carried out for five days at 20°C using a respirometer. BOD value (mg/L) was estimated on the basis of the difference in the dissolved oxygen content before and after incubation.

2.5. Water Quality Parameter-Chemical Oxygen Demand (COD)

Approximately 5-10 ml of wastewater sample is added to potassium dichromate ($K_2Cr_2O_7$), and then concentrated sulfuric acid (H_2SO_4) is added. It is heated at 150°C under reflux for 2 hours. After heating, the leftover dichromate is determined by titration using an ammonium ferrous sulfate (FAS) solution. COD is presented in mg/L as follows:

$$\text{COD}\left(\frac{\text{mg}}{\text{L}}\right)=\frac{(\text{Vblanko - Vsample}) \times \text{NFAS} \times 8000}{\text{Vsample}} \quad (1)$$

2.6. Water Quality Parameter-Total Organic Matter (TOM)

The analysis of Total Organic Matter (TOM) content is performed by Titrimetry by the SNI 06-6989.22:2004 standard. A 100 ml wastewater sample is treated with 0.01 N KMnO4 until a light purple color is achieved. Then, 5 ml and 10 ml of 0.01 N KMnO4 and 8 N sulfuric acid. The solution is heated to 105°C ± 2°C for 10 minutes. Titration with 0.01 N potassium permanganate is carried out until the mixture turns pink. KMnO4 usage is calculated as:

$$\text{KMnO4}\left(\frac{\text{mg}}{\text{L}}\right)=\frac{100}{1000}\{(10+\alpha)\,f - 10\} \times 31.6 \times 0.01\,p \quad (2)$$

Where a represents the volume of 0.01 N KMnO4, f denotes the normality of KMnO4, 0.01 refers to the normality of oxalic acid, and p is the dilution factor.

2.7. Water Quality Parameter-Nitrat (NO_3) and Nitrit (NO_2)

Fifty ml of the wastewater sample is treated with naphthyl ethylenediamine dihydrochloride and sulfanilic acid reagents until a purple-red color. The mixture is left to incubate at room temperature for 10 to 15 minutes, and the absorbance is read in a spectrophotometer at 543 nm. The concentration of nitrite (NO_2^-) is typically calculated using the following formula:

$$C=\frac{(A - A_o)}{(A_s - A_o)} \times Cs \quad (3)$$

Where C is the nitrite concentration in the sample in mg/L, A is the absorbance of the sample at 543 nm, A_o is the absorbance of the blank, A_s is the absorbance of the standard solution of known concentration, and C_s in mg/L is the concentration of the standard solution.

2.8. Water Quality Parameter-Phosphate (PO_4)

Fifty ml of wastewater is mixed with sulfuric acid and ammonium molybdate to form a phosphomolybdate complex. Ascorbic acid subsequently reduces the complex to blue molybdenum, which forms a color after incubation for 10–15 minutes. Blue color intensity is subsequently determined using a spectrophotometer at 880 nm.

2.9. Water Quality Parameter-Total Suspended Solid (TSS)

Five ml of the wastewater sample is transferred into a cuvette and inserted into the turbidimeter for analysis.

2.10. Nanoparticle Characterization

Redox potential is a key indicator of the oxidation-reduction conditions in sediments, influencing nutrient cycling and the degradation of organic matter. To assess this, 25 ml of air-dried sediment was combined with 50 ml of distilled water and homogenized for 5 minutes. The redox potential was measured using the potentiometric method (IKM/7.2.18/UPT-LKIL) and expressed in millivolts (mV), with positive values indicating oxidation and negative values indicating reduction. The measured potential was corrected by adding a +199 mV factor to align with the Standard Hydrogen Electrode (SHE) (Ramaley 1963; Husson 2013).

2.11. Sediment Analysis-Soil pH and SOM (Soil Organic Matter)

Soil pH was measured because it directly affects the chemical forms of nutrients and contaminants, influencing their mobility and availability in the sediment environment. A Takemura Soil Tester was used for pH measurement. A 1:1.5 soil-water suspension was shaken and allowed to settle before the pH electrode was placed in order to measure. Soil Organic Matter (SOM) content was analyzed as an important indicator of organic pollution levels and sediment quality. Soil Organic Matter (SOM) was analyzed by the Walkley-Black method, where 1 g of soil was mixed with potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4), left to stand for 30 minutes, and diluted with distilled water. Titration was achieved through the use of ferrous sulfate ($FeSO_4$) solution, and the organic carbon content was calculated from the volume of $FeSO_4$ used (Global Soil Laboratory Network 2019).

$$\text{Soil organic concentration (SOC) (\%)} = \frac{(B - S) \times M \times 0.003 \times f}{W} \times 100 \qquad (4)$$

Where B is the volume (ml) of ferrous sulfate added during the blank titration, S is the volume (ml) of ferrous sulfate added during the sample titration, M is the molarity of the ferrous sulfate solution, 0.03 is the milliequivalent weight of carbon, f is the correction factor (typically 1.3 to account for incomplete oxidation), and w is the weight of the soil sample (in grams). A conversion factor is applied to change SOC to SOM.

$$\text{SOM (\%)} = \text{SOC (\%)} \times 1.724 \qquad (5)$$

2.12. Statistical Analysis

Principal Component Analysis (PCA) and Factorial Analysis were applied to identify common patterns between the water quality and sediment parameters measured at more than one station point over four months. Pearson and Spearman correlation tests were carried out using R Studio 2024.12.0 to identify the correlations between all of the parameters across the station samples. Finally, differences between the seven stations with 16 variables were examined at once using the F-test and the Hausman test.

3. Results

3.1. Physical Water Quality Parameter

The results of the study showed variability in water and sediment quality parameters across seven stations in the Pasuruan aquaculture site between July and September 2024. Statistical analysis (ANOVA) showed that variations in water quality parameters were significant ($p<0.05$) across sampling times. Moreover, the observed sharp coincided with the onset of a WSSV outbreak, suggesting a potential link between water quality deterioration and disease occurrence (Figure 2A-M). Water temperature ranged from 29 to 30°C, with the highest recorded during the sampling period in September, reaching approximately 32.5°C (Figure 2A). Water temperature ranged from 29 to 30°C, peaking at 32.5°C in September (Figure 2A). Salinity remained relatively stable at 34 ppt near intensive ponds (Stations 1–5) but was slightly lower (32 ppt) near mangrove zones (Stations 6–7). Notably, salinity spiked to 40 ppt during the WSSV outbreak in August (Figure 2B), suggesting that intensification practices affected salinity levels. The sharp increase in salinity may have stressed aquatic organisms and contributed to disease susceptibility, supporting the hypothesis of environmental stress triggering WSSV outbreaks.

Initially, pH values were stable at 7.8, which is within the acceptable range for wastewater. However, as intensive aquaculture practices continued, the pH gradually increased to 8.9 by the end of the sampling period (Figure 2C). Dissolved oxygen (DO) levels fluctuated between 3.5-4.5 mg/L in mid-July but dropped sharply to 1.5_2.0 mg/L on August 28, coinciding with the WSSV outbreak (Figure 2D). By mid-September, DO levels partially recovered (3.0-4.0 mg/L). Low DO concentrations during the WSSV outbreak suggest oxygen depletion due to increased organic matter and eutrophication, highlighting the ecosystem's vulnerability under intensive aquaculture

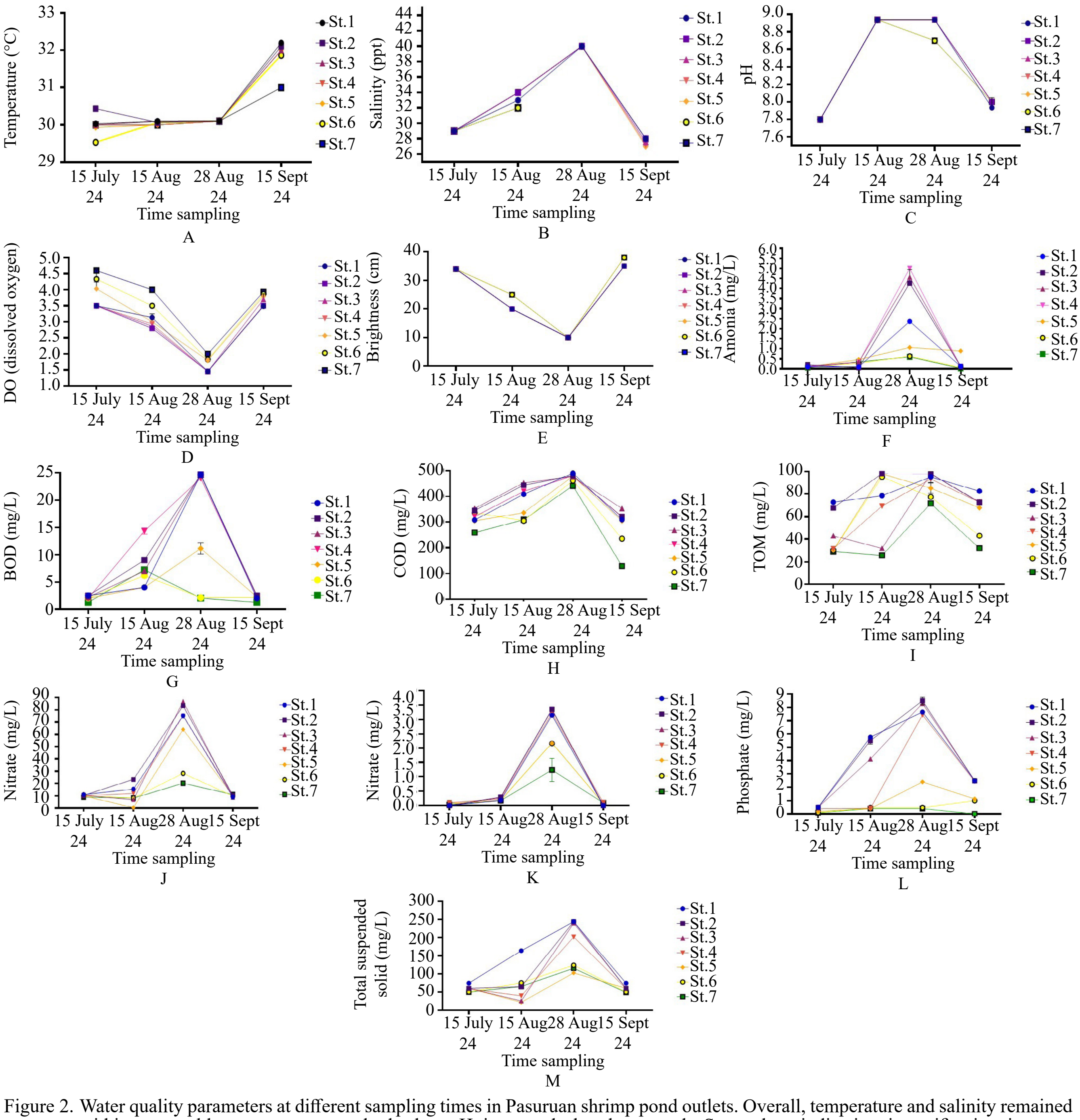


Figure 2. Water quality parameters at different sampling times in Pasuruan shrimp pond outlets. Overall, temperature and salinity remained within acceptable wastewater standards, but pH increased sharply towards September, indicating intensification impacts. Dissolved oxygen (DO) dropped significantly during August, coinciding with a WSSV outbreak, while TSS and ammonia peaked simultaneously, suggesting eutrophication and increased organic pollution. Improvements were noted by mid-September. Wastewater standards: Temperature 28–30°C; Salinity 26–32 ppt; pH 6–9; DO >4 mg/L; Brightness 30–50 cm; Ammonia <0.1 mg/L; BOD <3 mg/L; COD <100 mg/L; TOM <90 mg/L; Nitrate <75 mg/L; Nitrite <2.5 mg/L; Phosphate <0.1 mg/L; TSS <200 mg/L.*Significant events, such as ammonia spikes and WSSV outbreaks, are indicated in the time sampling graph by italicized letters corresponding to specific time points

pressure. Water clarity, as measured by brightness, started at 33 cm on July 15 and declined steadily, reaching a low of 10 cm on August 28 due to increased suspended solids. By mid-September, water clarity improved to 35-38 cm, with Station 6 consistently showing slightly higher values during the study period (Figure 2E).

3.2. Sediment Quality Parameter

Redox potential in sediment samples fluctuated between –40 and –100 mV across stations, indicating overall reductive conditions typical of aquaculture wastewater systems (Figure 3A). Station 2 showed the most significant fluctuations, reaching as low as –100 mV during the WSSV outbreak on August 28, suggesting heightened anaerobic activity. Stations 1–4 exhibited similar trends (–40 to –80 mV) throughout the study period. The highest redox potential (–40 mV) was recorded in mid-September, coinciding with a period of reduced aquaculture activity, suggesting partial recovery of sediment conditions. During the WSSV outbreak, a notable drop (–60 mV) was observed, particularly in Stations 4–7, indicating that the buffer zone (mangrove area) was also affected by organic loading from pond effluents.

Soil pH in outlet channels remained generally acidic throughout the study period, ranging from pH 5 to 7 (Figure 3C). The low pH values are consistent with typical brackish environments influenced by both aquaculture activities and mangrove soil characteristics. The acidic conditions suggest a vulnerability of the sediment to further acidification processes, which can influence nutrient solubility and pathogen survival, potentially exacerbating disease risks during intensive farming periods.

Soil organic matter (SOM) content showed a significant increase during August 2024, with values rising well above the typical <5% baseline. Stations 2 and 7 recorded the highest SOM levels, reaching 23% on August 28 and August 15, respectively (Figure 3B). By September 15, SOM levels declined substantially to 1–2% across all stations, indicating a recovery phase. The sharp rise in SOM during August corresponds closely with the timing of the WSSV outbreak, suggesting that excessive organic loading from aquaculture effluents played a key role in degrading sediment quality. Elevated SOM could foster anaerobic conditions, favoring the proliferation of opportunistic pathogens in sediment environments.

3.3. Spatial and Temporal Water Quality Hotspots

Spatial variation of wastewater quality along the Pasuruan outlet channel ranges from very polluted (red, St.1) to low pollution (blue, St.6 and St.7).

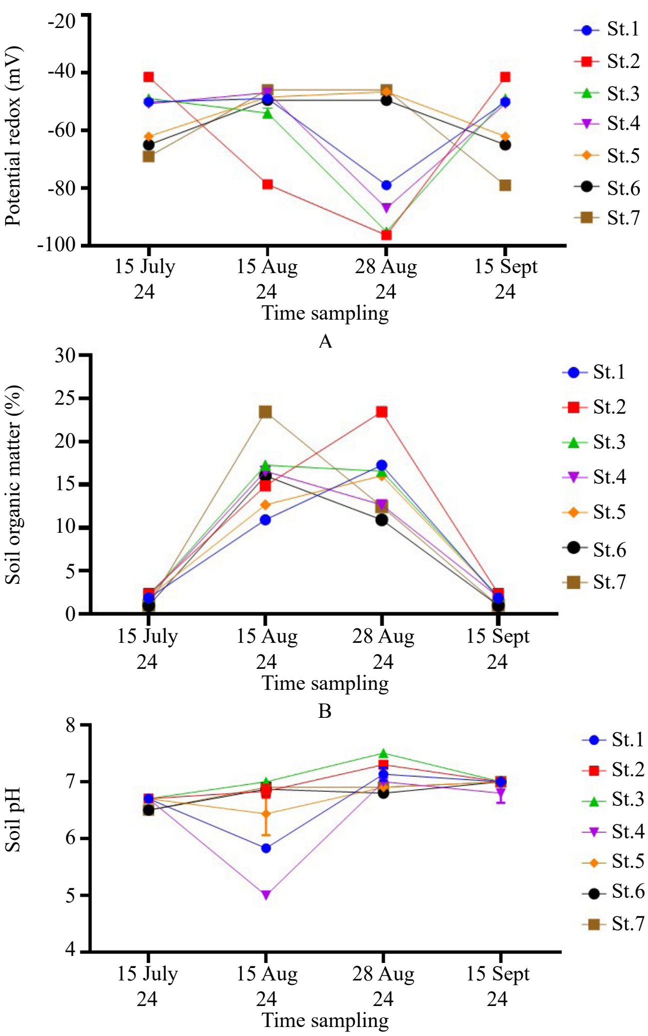


Figure 3. Sediment quality parameters at different sampling times in Pasuruan shrimp pond outlet channels. Redox potential fluctuated between -40 to -100 mV, indicating dominant reducing conditions throughout the study period. The sharpest reduction (-100 mV) occurred at Station 2 during the WSSV outbreak (August 28), suggesting intensified organic matter decomposition. Soil organic matter (SOM) levels were exceptionally high (15–23%) during August, particularly at Stations 2 and 7, which may have contributed to oxygen depletion and pathogen proliferation. Soil pH ranged from 5 to 7, indicating mildly acidic conditions typical of mangrove-influenced sediment. SOM and redox conditions improved towards September, reflecting a recovery trend after the outbreak event. Significant events, such as ammonia spikes and WSSV outbreaks, are indicated in the time sampling graph by italicized letters corresponding to specific time points

Stations 2 and 3 are polluted (orange), while Stations 4 and 5 are slightly polluted (green). Pollution is higher during intensive Vannamei shrimp culture due to the discharge of effluent with organic waste, chemicals, and nutrients (Figure 4).

3.4. Principal Component Analysis

Physical-chemical parameters, such as water quality and sediment quality, rely on redox potential, soil pH, and BOT/SOM. PCA accounts for 83.017% of the variation. BOD, COD, nitrate, nitrite, and phosphate are indicators of water pollution. At the same time, redox potential, soil pH, and BOT/SOM are the parameters that have a significant role in aquaculture pond sediment pollution.

The biplot (Figure 5) identifies two dominant components: COMP 1, which clusters Stations 4, 5, and 6, and COMP 2, which clusters Stations 1, 2, 3, and 7, which shows dissimilar spatial variation between these station groups. COD is perfectly positively correlated with the level of pollution, while TSS is negatively correlated. Also, Salinity, Temperature, Brightness, Dissolved Oxygen, NH_3, NO_2, pH, and Redox Potential cluster together, a sign of their interconnected influence on water quality.

3.5. Correlation Analysis of Water and Sediment Parameters

The effect analysis by F-test did not reveal any significant differences in the parameters. To examine the relations between parameters at each station, an analysis was conducted along seven stations with time-differentiated sampling (Figure 6).

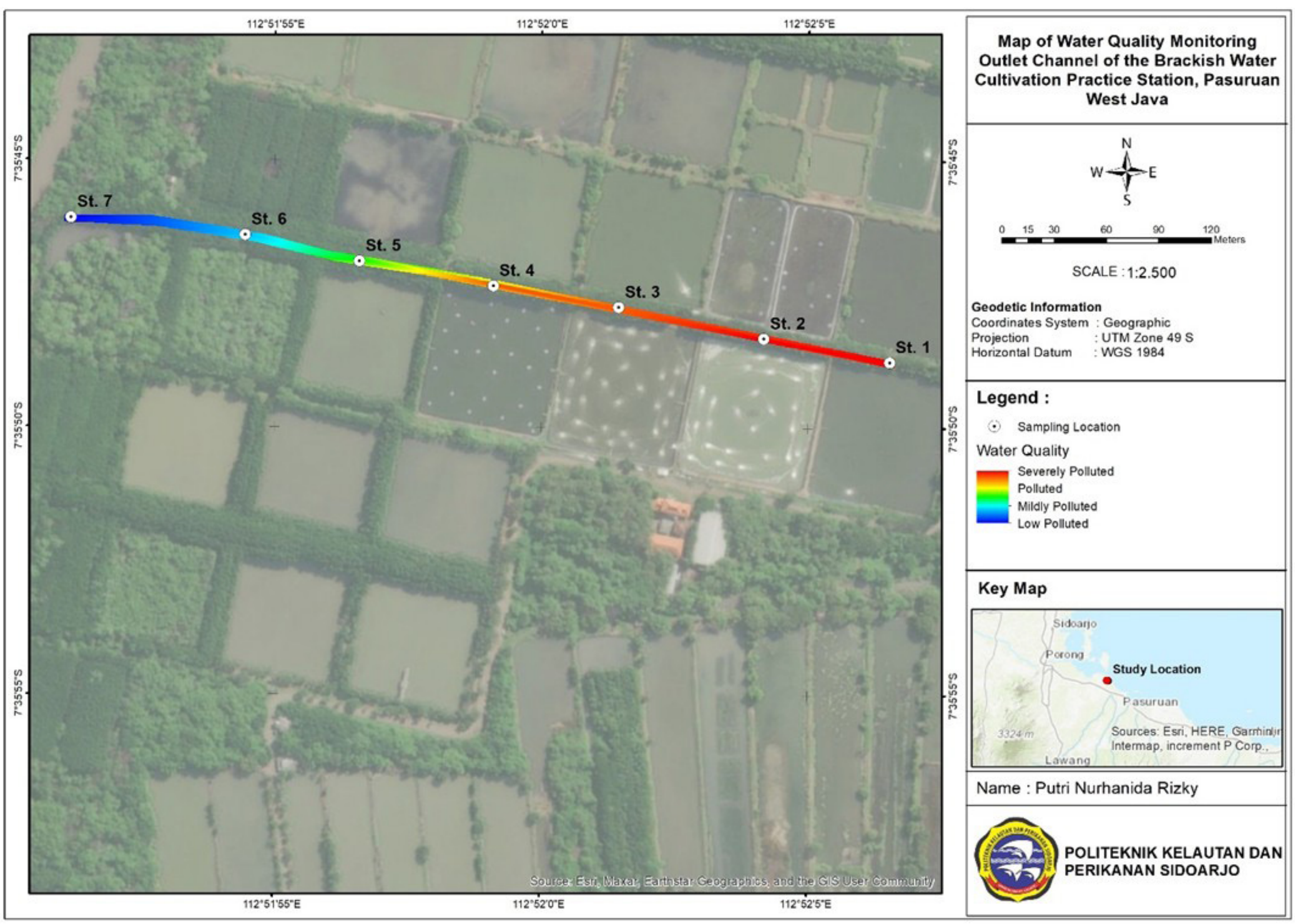
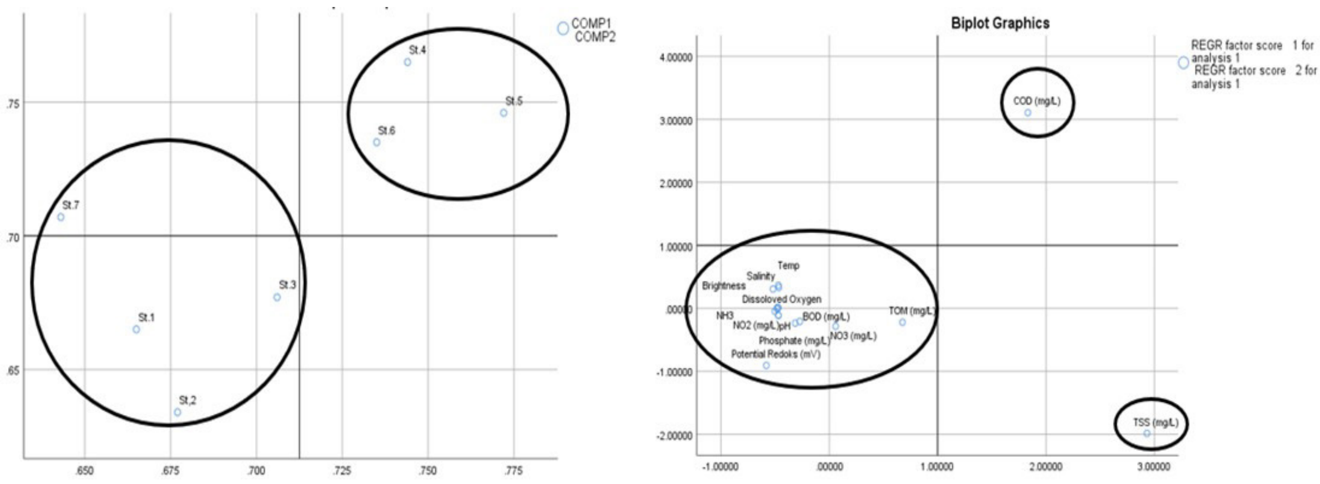


Figure 4. Map of water quality monitoring for the outlet channel of the brackish water cultivation practice station, Pasuruan, West Java. Spatial variation along the outlet channel shows that Station 1 is very polluted (red), stations 2 and 3 are polluted (orange), Stations 4 and 5 are slightly polluted (green), and Stations 6 and 7 are low pollution areas (blue). Pollution levels are notably higher during the intensive Vannamei shrimp culture period, attributed to the discharge of effluent containing organic waste, chemicals, and nutrients



A B

Figure 5. Biplot of PCA analysis. (A) The points represent different site samples (S1.1, S2.1, etc.), and (B) the blue dots represent REGRE factor scores for water and sediment quality.

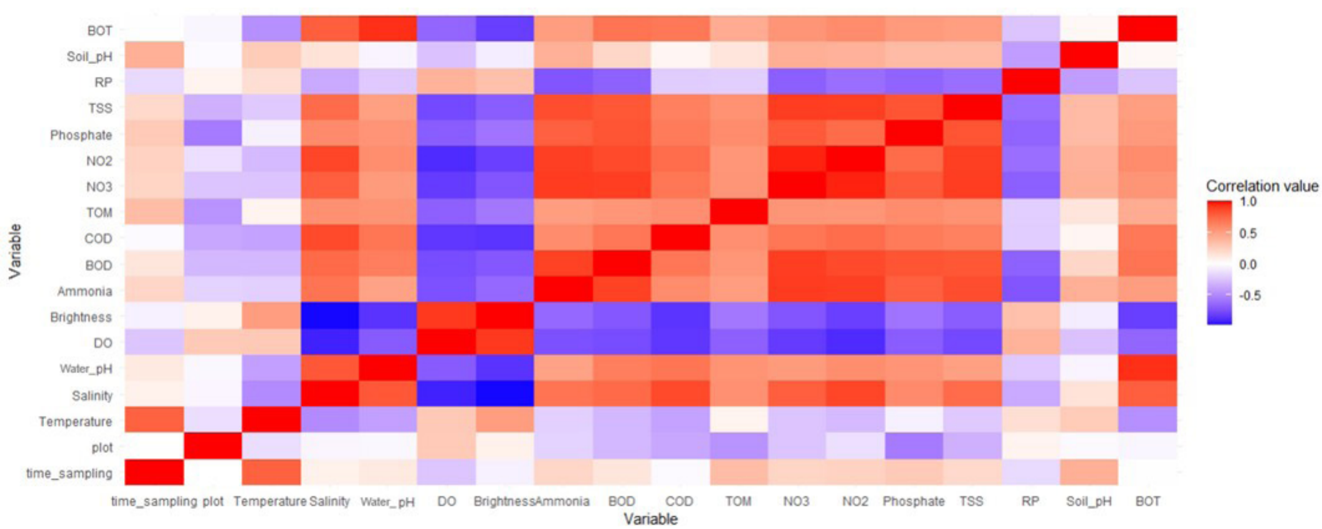


Figure 6. Heatmap pearson correlation displaying the correlation between water and sediment parameters in each station at different times in sampling

Spatial analysis reveals correlations of water quality parameters. Elevated pH correlates with increased salinity and decreased oxygen levels. Rising dissolved oxygen correlates with increased BOD, COD, and TSS and rising ammonia due to microbial activity. Rising BOD, COD, and ammonia affect biochemical processes by raising pH and resulting in the deposition of organic matter in sediment.

4. Discussion

During September–October 2024, air temperature in Pulokerto and across other regions in Indonesia was exceptionally high, thereby affecting water temperature in open flows. Elevated water temperatures reduce the capacity of oxygen to dissolve, disrupting aquatic metabolic processes and accelerating the decomposition of organic matter. Microbial activity in aquaculture ponds is highly pH-dependent and nitrifying bacteria that thrive at a near-neutral to alkaline pH level of 7–8 (Hayatsu *et al.* 2021). However, this study found that wastewater was acidic, which inhibited ammonia decomposition and increased the risk of toxicity. A severe ammonia spike (5.0–5.5 mg/L) at Stations 1–4 on August 28 far exceeded the safe level of 0.1 mg/L, indicating extreme pollution with significant health risks to shrimp.

Total Organic Matter (TOM) accumulation in the outlet channels originated mainly from shrimp farming waste, which microbial processes later converted into nitrate. However, excess nitrate contributes to eutrophication. Intensive shrimp farming also elevated phosphate concentrations, which are sensitive to variations in temperature, oxygen levels, and aquatic plant dynamics (Beiras 2018). Furthermore, high Total Suspended Solids (TSS) during the peak period of aquaculture operations raised turbidity, decreasing the brightness of water from 33 cm to 10 cm on August 28 before it improved around mid-September.

The sediment quality deteriorated through organic matter deposits. Readings of redox potential (Eh) indicated anaerobic conditions with a minimum of (-95 mV) on 28th August during the WSSV outbreak. Following the outbreak, sediment degradation slowed, and water chemistry began to recover. Nonetheless, mitigation measures such as probiotic treatments successfully prevented the detection of WSSV at the outlet (Esparza-Leal *et al.* 2009; Cox *et al.* 2023).

Sediment and wastewater contamination were worse during peak farming season, particularly at stations 1–3 near intensive ponds. Natural dilution and mangrove filtration as biofilters occurred at downstream stations (4–7), eliminating surplus nutrients like ammonia. Principal Component Analysis (PCA) showed significant pollution markers, with Chemical Oxygen Demand (COD) as an indicator of organic pollution and Total Suspended Solids (TSS) linked to turbidity (Lyimo & Mushi 2007; Pérez *et al.* 2021).

Dissolved Oxygen (DO) deficiency (1.5 mg/L) during the WSSV epizootic prevented organic matter degradation. Peaks in Biochemical Oxygen Demand (BOD), COD, and TOM were connected with high organic wastes, noting pollution risks. Mangroves, tidal conditions, and erosion of soil played a role in suspended particles for stations 4–7 and equated with TSS measurements. Importantly, mangroves also sustained nitrification, oxidizing ammonia to nitrate and reducing pollution risks (Wulandari *et al.* 2022).

Similar impacts of aquaculture effluents on coastal environments have been reported in other regions. For instance, Pérez *et al.* (2021) documented that intensive shrimp farming in Brazil led to substantial reductions in dissolved oxygen and elevated nutrient loads, findings consistent with those observed in Pulokerto. Cox *et al.* (2023) observed sediment degradation surrounding shrimp ponds in Thailand, aligning with the elevated TOM and negative redox potential identified in this study. These comparative results highlight the widespread environmental risks associated with intensive aquaculture, emphasizing the urgent need for sustainable practices.

To mitigate these impacts, farmers should implement effluent treatment systems, such as sedimentation ponds, constructed wetlands, or biofiltration units, before discharging wastewater into coastal outlets. Regular water quality monitoring and rotational aquaculture practices are also recommended to minimize organic buildup. Policymakers could promote these initiatives by providing incentives for farmers who comply with best aquaculture practices (BAP) and establishing stricter effluent regulations.

Strengthening mangrove conservation is particularly critical. Mangroves are highly effective biofilters, capable of removing up to 90% of suspended solids and nutrients from aquaculture effluents (Alongi 2021). The restoration and maintenance of mangrove buffers along outlet channels would not only enhance water and sediment quality but also increase the overall resilience of coastal ecosystems against future environmental disturbances.

In conclusion, this study confirms that the intensive culture of vannamei shrimp has a large impact on the water and sediment quality of outlet channels, with heightened risks of eutrophication, hypoxia, and disease outbreaks. Waste management improvements, mangrove conservation, and stronger regulatory frameworks are essential to safeguard coastal ecosystems while maintaining shrimp production. Implementing these strategies will be crucial to achieving a balance between economic development and environmental stewardship in aquaculture zones such as Pulokerto.

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