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Spatial Distribution Modeling of Nutrient Waste from Aquaculture Activities in Response to Increased Wastewater Discharge in Bojo Bay, Indonesia

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ABSTRACT

Bojo Bay, located in Barru Regency, South Sulawesi, Indonesia, is a coastal area experiencing increasing ecological pressures due to aquaculture expansion. The intensification of aquaculture has led to the accumulation of organic waste, with the potential to degrade water quality, trigger eutrophication, and disrupt ecosystem balance. This study aimed to model the spatial distribution of nutrient waste from aquaculture under varying production intensities in Bojo Bay. Simulations were conducted using MIKE 21 software by integrating the Hydrodynamics (HD) and ECOLAB modules to model current dynamics and key water quality parameters, including dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia, nitrate, and phosphate. Two scenarios were applied: existing conditions and a 100% increase in waste load. The results showed that intensified aquaculture significantly reduced water quality by elevating nutrient concentrations and expanding the spatial extent of waste distribution. Waste accumulation was concentrated in the inner bay during high tide, while concentrations decreased during low tide, reflecting local hydrodynamic circulation. These findings demonstrate that increased waste discharge without treatment negatively affects water quality and provide a scientific basis for developing sustainable aquaculture waste management strategies in Bojo Bay.

INTRODUCTION

Bojo Bay, located in the Makassar Strait within the administrative area of Mallusetasi Subdistrict, Barru Regency, is an Indonesian coastal zone with important ecosystem functions. Human activities such as settlement, tourism, industry, and aquaculture are widespread in this region **(Mubarak *et al.*, 2024)**. Coastal ecosystems provide critical environmental services, including food provision, erosion control, and tourism **(Gedan *et al.*, 2011; Kanan & Giupponi, 2024)**. However, the intensification of aquaculture activities in Bojo Bay has the potential to increase organic waste inputs into coastal waters, similar to conditions reported along the northern coast of Java

(Adyasari *et al.*, 2019). Excessive nutrient inputs from aquaculture—such as uneaten feed and feces—can trigger eutrophication, reduce oxygen levels, and disrupt ecosystem balance **(Tuholske *et al.*, 2021)**.

Intensive shrimp farming is a major contributor to nutrient loading. Ponds under intensive management produce suspended solids containing up to 18 times more nitrogen and phosphorus than traditional systems **(MHR, 2022)**. Such nutrient enrichment drives eutrophication, commonly manifested as algal blooms that reduce dissolved oxygen and create hypoxic or anoxic “dead zones,” threatening aquatic life. This process, driven by phosphorus and nitrogen enrichment, is further accelerated by agricultural runoff and industrial waste **(Howarth & Marino, 2006; Qin *et al.*, 2013; Sinha *et al.*, 2017)**. Similar conditions have been observed worldwide, including the Gulf of Mexico, where nitrogen accumulation has caused one of the largest hypoxic zones globally **(Pontius & McIntosh, 2024)**. Coastal eutrophication has thus become a major environmental crisis, causing ecological degradation, economic losses, and threatening marine sustainability **(Guo *et al.*, 2024)**.

Modeling water quality distribution offers an effective analytical framework to map waste dispersion and predict environmental impacts of aquaculture activities. Compared with experimental methods, modeling provides a more comprehensive representation of hydrodynamic and ecological processes and is more efficient in terms of spatial and resource requirements **(Costa *et al.*, 2003; Ali *et al.*, 2011)**. For example, studies in Tanjung Pinang Bay showed consistent nutrient distribution patterns between tidal phases, with elevated concentrations near river mouths influenced by agricultural activity **(Lestari, 2020)**.

Numerical modeling, particularly with MIKE 21 software developed by DHI Denmark, has proven highly effective for simulating aquatic system dynamics. MIKE 21 can model free-surface hydrodynamics in both spatial and temporal scales and integrates the Hydrodynamics and ECOLAB modules for water quality simulations **(DHI, 2014; DHI, 2022)**. Previous studies have successfully applied MIKE 21 to analyze nutrient and pollutant dynamics in diverse environments, including Muara Porong (Indonesia), Baisha Reservoir, and the Dongjiang River (China) **(Suntoyo *et al.*, 2015; Wu *et al.*, 2024; Guo *et al.*, 2025)**. While effective, model performance depends strongly on data quality and underlying assumptions **(Jourtani *et al.*, 2024)**.

This study addresses a research gap in aquaculture waste modeling, which has often focused solely on observed field conditions without scenario-based simulations. Here, we apply MIKE 21 to model the spatial distribution of key water quality parameters—dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia (NH_4), nitrate (NO_3), and phosphate (PO_4)—in Bojo Bay under three scenarios of aquaculture activity. The results provide a detailed assessment of nutrient dispersion patterns and identify areas most vulnerable to eutrophication, offering a scientific basis for mitigation strategies and sustainable water quality management in tropical estuarine systems.

MATERIALS AND METHODS

1. Study area

The study was conducted in Bojo Bay, Bojo Village, Barru District, South Sulawesi, Indonesia. The primary focus was on the intensive aquaculture effluent channels within the bay, which serve as the main sources of wastewater entering the coastal ecosystem. These aquaculture facilities discharge effluents characterized by reduced dissolved oxygen and elevated concentrations of ammonia, phosphate, and nitrate, originating from uneaten feed and organic waste produced by cultured organisms. The simulated study area covered the bay and its surroundings, located at approximately 119°37′ E and 4°06′ S. The research location, situated within the Sulawesi Strait region, is shown in Fig. (1).

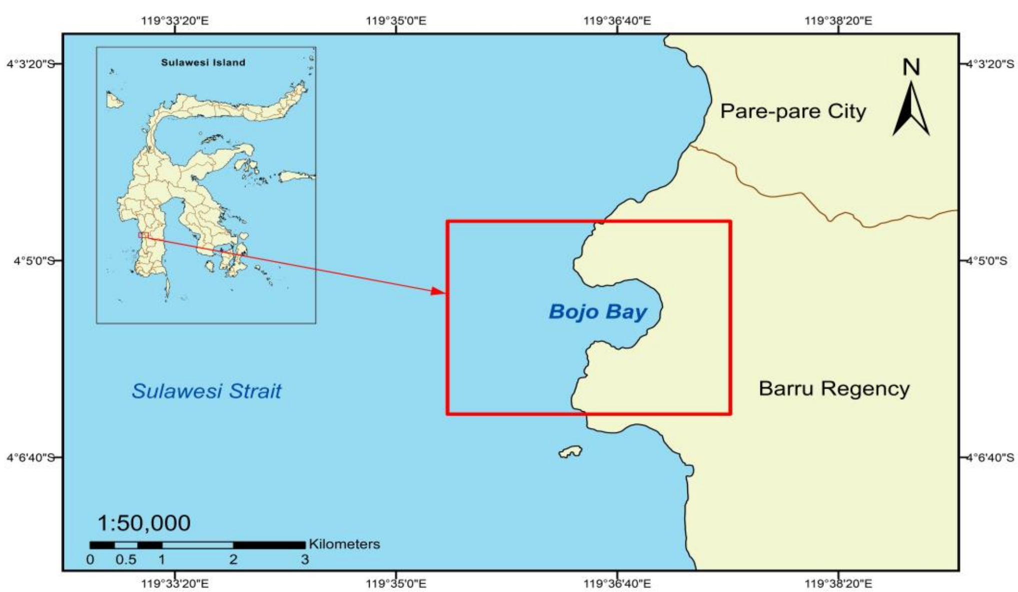


Fig. 1. Research location map showing the Bojo Bay area in Barru Regency, including the waters of the Sulawesi Strait

2. Data collection

2.1 Primary data

Field data collected included dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia (NH_4), nitrate (NO_3), phosphate (PO_4), and wastewater flow rate. DO and BOD were measured using a DO meter (AZ 8403), while NH_4, NO_3, and PO_4

concentrations were analyzed by spectrophotometry at the Chemical Oceanography Laboratory, Faculty of Marine Sciences, Hasanuddin University. Each sample was measured in triplicate to ensure accuracy and consistency.

Sampling was conducted at six observation stations representing the inner bay, bay boundary, outer bay, and two wastewater discharge channels from intensive aquaculture activities (Fig. 2). Stations were selected for their representativeness in reflecting water quality conditions in Bojo Bay. Field sampling was carried out on July 26, 2025, between 10:00 and 11:00 AM, to minimize the influence of short-term temporal variability.

2.2 Secondary data

Supporting data for the model were obtained from several open-access sources:

1. **Wind speed and direction**: ERA5 Hourly Data on Single Levels (1940–present), provided by the Copernicus Climate Change Service (C3S) via the Climate Data Store (CDS), DOI: [10.24381/cds.adbb2d47], with hourly temporal resolution for June–July 2025.
2. **Tidal data**: National Geospatial Information Agency (BIG), via [https://srgi.big.go.id/tides], with hourly temporal resolution for June–July 2025.
3. **Bathymetric data**: SIBATNAS, National Geospatial Information Agency, via [https://tanahair.indonesia.go.id].

These sources were chosen for their high temporal resolution, daily updates, and open accessibility, ensuring accuracy and suitability for water quality modeling.

3. Sampling location points

Sampling was purposively conducted at six locations in Bojo Bay (T1–T6). Four points (T1–T4) were designated for validating the water quality model, while two points (T5–T6) represented wastewater discharge channels from aquaculture ponds A and B.

- **T1**: inside the bay
- **T2**: at the bay boundary
- **T3**: outside the bay
- **T4**: near the wastewater discharge channel of Company B
- **T5**: wastewater discharge channel from Pond A
- **T6**: wastewater discharge channel from Pond B

The selection of discharge channels (T5 and T6) was based on their direct, untreated daily effluent. At each point, water quality parameters and wastewater flow rates were measured. Detailed locations are presented in Table (1) and Fig. (2).

Table 1. Coordinate points and sample data types

Sample Collection Point	Data Type	Coordinate Point	Characteristics	Description
1	Water Quality	4°5'24.618"S 119°36'45.690"E	Sea	Validation Data
2	Water Quality	4°5'27.288"S 119°36'27.467"E	Sea	Validation Data
3	Water Quality	4°5'30.759"S 119°36'3.037"E	Sea	Validation Data
4	Water Quality	4°5'6.729"S 119°36'3.838"E	Sea	Validation Data
5	Water Quality / Water Flow	4°4'43.099"S 119°36'28.669"E	Output Channel of the Pond	Input Data
6	Water Quality / Water Flow Rate	4°5'44.243"S 119°36'44.756"E	Output Channel of the Pond	Input Data

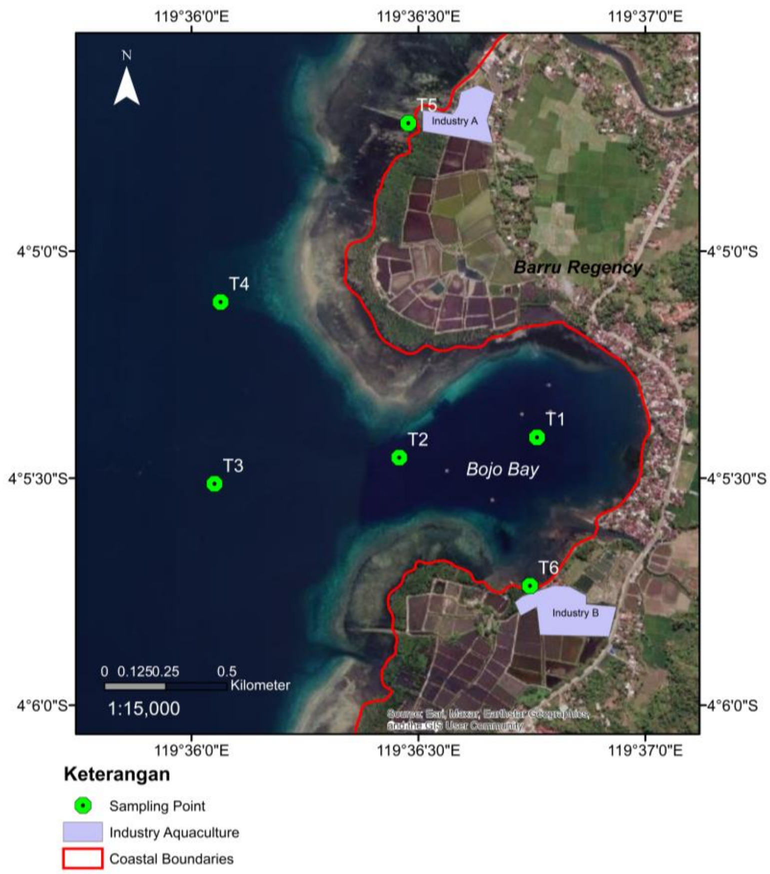


Fig. 2. Map of sampling points in Bojo Bay, Barru Regency

4. Data processing and analysis methods

4.1 Analysis of changes in cultivation waste intensity

Scenario analysis was applied to predict changes in water quality in Bojo Bay under varying intensities of aquaculture activities. Two scenarios were developed:

1. **Scenario 1 (Current conditions):** constant aquaculture activity with no changes in waste discharge, representing present conditions.
2. **Scenario 2 (Increased intensity):** a 100% increase in aquaculture activity, assuming that higher production would generate greater waste discharge and consequently degrade water quality.

This approach allowed the evaluation of how changes in waste load influence the spatial and temporal distribution of key water quality parameters. The detailed assumptions underlying each scenario are provided in Table (2).

Table 2. Scenarios for wastewater discharge intensity in aquaculture

Scenario	Assumptions on Changes in Aquaculture Activity Factors	Percentage of Total Wastewater Discharge
Scenario 1 (Actual conditions)	✓ No change in the number of farming units ✓ Feed intensity remains constant	0
Scenario 2 (Increased Cultivation Intensity)	✓ Significant increase in the number of cultivation units ✓ Increase in feeding intensity ✓ Without waste management	+100

4.2 Modeling the distribution of water quality parameters based on scenarios

Water quality distribution was modeled using MIKE 21 by integrating the Hydrodynamics (HD) and ECOLAB modules. The HD module simulated physical processes, including currents, tides, and wind, while the ECOLAB module modeled water quality parameters such as dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia, nitrate, and phosphate.

The modeling process consisted of:

1. Defining boundary conditions,
2. Developing a bathymetric mesh,
3. Inputting field data into the HD and ECOLAB modules,
4. Running simulations, and
5. Validating model outputs against observed field data.

Once the model was validated, water quality distribution analysis was carried out under the two aquaculture intensity scenarios. The overall flow of the modeling process is illustrated in Fig. (3).

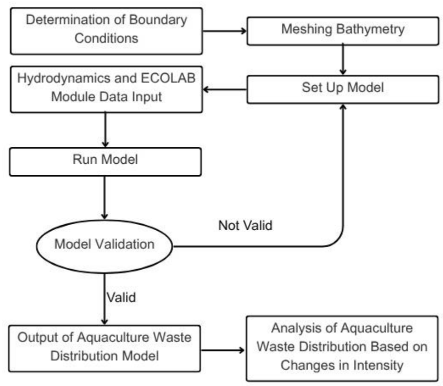


Fig. 3. Waste modeling flow diagram

4.3 Model validation

The ECO Lab model was validated using the Mean Absolute Percentage Error (MAPE), as field sampling was conducted only once at a single point. MAPE (Eq. 1) quantifies the error between model predictions and observed data, with smaller values indicating closer agreement between simulated and actual conditions. In simple terms, a low MAPE value reflects high predictive accuracy of the model. The equation for calculating the MAPE value is as follows:

$$MAPE = \sum_{i=1}^{n} \left| \frac{At - Ft}{At} \right| \times 100\% \qquad \text{(Equ.1)}$$

Where:
At = Actual value
Ft = Modeled value

The use of MAPE in evaluating prediction results avoids bias caused by differences in the magnitude of actual and predicted values. The interpretation criteria for MAPE values are presented in Table (3) **(Wei, 2006)**.

Table 3. MAPE value criteria

MAPE Value	Description
>10%	Very Good
10% - 20	Good
20% - 50	Fair
> 50%	Poor

Noted : **Wei (2006)**.

RESULTS AND DISCUSSION

1. Setting up a model for aquaculture waste distribution

1.1 Modeling of boundary conditions and bathymetric meshing

Water quality modeling in Bojo Bay employed three types of boundary conditions: coastal boundaries, pond drainage channels, and tides. Two main aquaculture sites were included as point sources of pollution, while tidal data were obtained from local references. Bathymetric modeling was performed using the MIKE Mesh Generator, producing 2,425 elements and 1,382 grid points. Visualizations of the boundary conditions and the generated mesh are presented in Fig. (4).

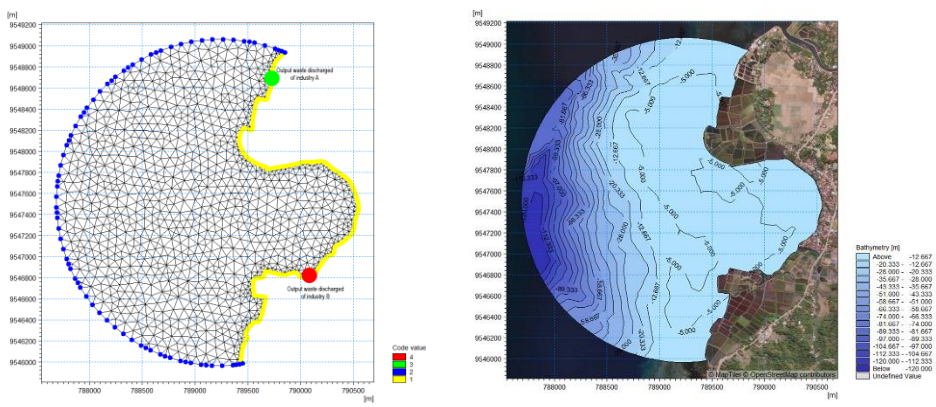


Fig. 4. Boundary conditions and bathymetric mesh results

Bathymetric modeling indicated that the Bojo Bay study area has a depth range of 0– 120m, classifying it as shallow water. The bathymetric mesh data were used as the model domain. The simulation was run over a 15-day period (24 June–8 July 2025) with 360 time steps at 1-hour intervals. The Hydrodynamic (HD) and ECO Lab modules were applied to simulate water circulation and water quality dynamics.

Data Measurement and Model Validation

Water quality measurements were conducted at points 1–4 (Fig. 1) and used for model validation. Measurements were taken on 26 June 2025 between 10:00 and 12:00. The observed parameters are presented in Table (4). Model outputs were compared with field observations using the Mean Absolute Percentage Error (MAPE) equation. The MAPE values were predominantly low, with an overall accuracy >50%, categorizing the model as “good.” Based on this validation, the model was considered reliable and used to predict the distribution of aquaculture-derived waste in Bojo Bay.

Table 4. Water quality measurement data

Parameter	Quality Standard (mg/L)	Point 1	Point 2	Point 3	Point 4
Dissolved Oxygen (DO)	>5	9.9	9.84	9.81	9.69
Biochemical Oxygen Demand (BOD)	20	6.6	5.99	5.96	6.0
Nitrate (NO3)	0.015	0.182	0.165	0.217	0.197
Phosphate (PO4)	0.015	0.079	0.036	0.029	0.033
Ammonia (NH4)	0	1.075	1.284	1.032	1.194

Note: Quality Standard Source Indonesian Government Regulation No. 22 of 2021.

5. Hydrodynamic model

Hydrodynamic simulations were carried out to analyze water dynamics under the influence of tides, wind, and flow discharge. In Bojo Bay, bathymetry, wind forcing, tidal oscillations, and aquaculture effluents were identified as the main drivers of water elevation and current patterns. The resulting current simulations are critical for predicting the direction and dispersion of pollutants through advection and diffusion processes **(Nie, 2020)**.

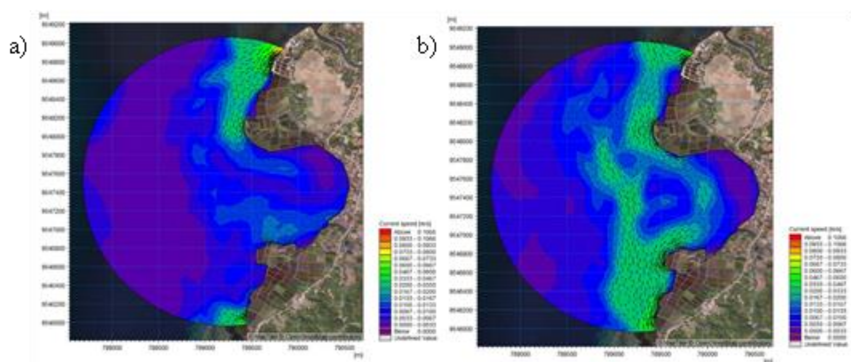


Fig. 5. Current patterns in Bojo Bay (a) toward low tide on day 5 at timestep 107 and (b) toward low high tides on day 15 at time step 348

Based on Fig. (5), it can be seen that the current pattern on day 5 at timestep 107 is toward ebb, with a water level of 0.4 m, and on day 15 at timestep 348 toward flood, with a water level of 1.2 m. During low tide, the current pattern in Bojo Bay moved from south to north, and the currents within the bay also flew northward. Conversely, during high tide, the currents moved from north to south.

6. Model of aquaculture waste distribution

Water quality simulations were conducted using the ECOLAB module integrated with the Hydrodynamic (HD) module in MIKE 21, accounting for advection, diffusion, and chemical–biological reactions. The modeled parameters included dissolved oxygen

(DO), biochemical oxygen demand (BOD), ammonia (NH_4), nitrate (NO_3), and phosphate (PO_4).

Two scenarios were developed:

1. **Scenario 1 (Baseline):** actual conditions, used as the calibration reference.
2. **Scenario 2 (Increased intensity):** a 100% increase in wastewater discharge to represent intensified aquaculture.

The analysis focused on the spatial distribution of parameter concentrations over a 15-day period, with particular emphasis on day 5 and day 15, as well as point 1 (inner bay), to assess the system's response to elevated waste loads.

7. Comparison of DO parameters between scenarios 1 and 2

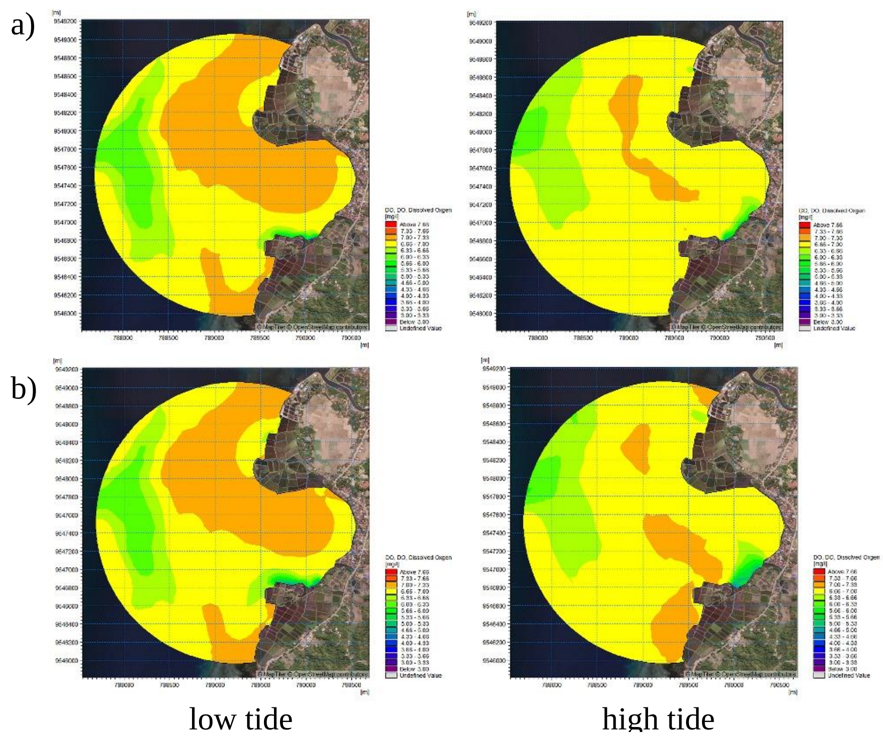


Fig. 6. Results of DO parameter modeling (a) Scenario 1 (b) Scenario 2

Fig. (6) presents the modeling results of DO distribution toward low tide (left) and toward high tide (right) for each scenario. Blue-green indicates low DO concentrations, while orange-red indicates higher DO concentrations. The DO concentration values obtained from the modeling results within the bay are as follows: S1 (a) during the ebb phase, DO in the central area of the bay showed a value of 7.06mg/ L, and during the flood phase, it shows a value of 6.81mg/ L. Furthermore, at S2 (b), the values were 7.05mg/ L during low tide and 6.75mg/ L during high tide.

In Scenario 1, DO concentrations were relatively stable during low tide and increased during high tide, indicating that water conditions were still supportive of biota. In contrast, Scenario 2 showed a decrease in DO, particularly during high tide, with low concentration areas spreading upstream and into the middle of the bay. This indicates a significant impact of pond discharge on DO decline. This decline aligns with the findings of **Xiao *et al.* (2023)**, who linked low DO levels to high organic matter content and biochemical oxygen demand. Advection, diffusion, and organic degradation processes further exacerbate DO conditions, particularly in scenarios of pond intensification **(Bhuiyan *et al.*, 2024)**.

8. Comparison of BOD parameters between Scenarios 1 and 2

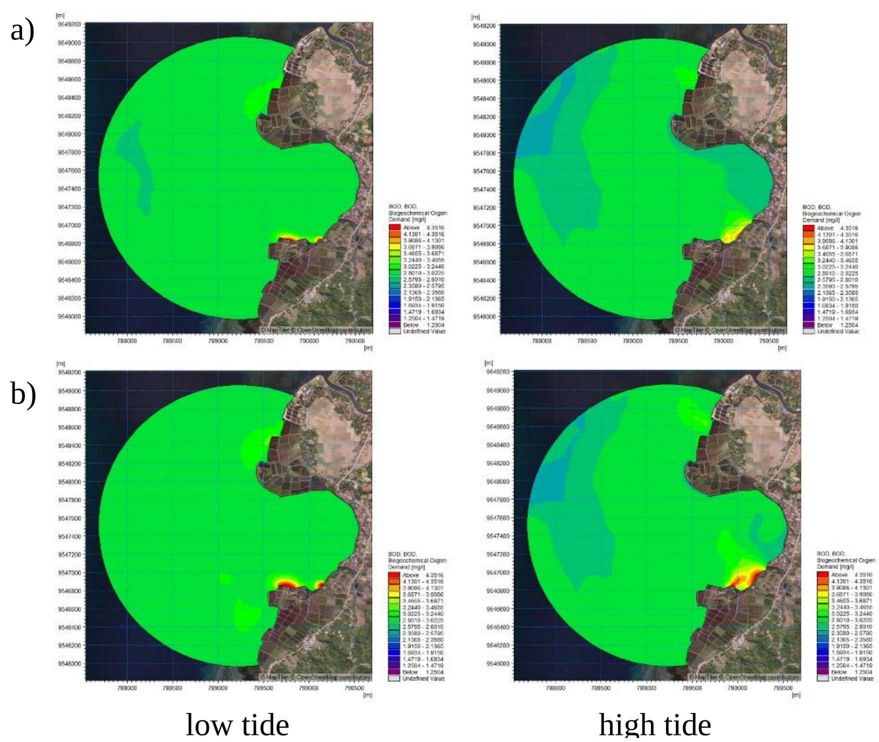


Fig. 7. BOD parameter distribution model toward low tide (left) and toward high tide (right) (a) Scenario 1 (b) Scenario 2

Fig. (7) presents the results of BOD distribution modeling during low tide (left) and high tide (right) for each scenario. Blue-green colors indicate low BOD concentration, while orange-red colors indicate higher BOD concentrations. The BOD concentration values obtained from the modeling results in the bay are as follows: S1 (a) during low tide, the BOD concentration in the central part of the bay was 2.96mg/ L, and during high tide, it was 2.76mg/ L. Furthermore, in S2 (b), the BOD concentration was 2.97mg/ L during low tide and 2.82mg/ L during high tide.

In scenario 1, BOD distribution during low tide is limited around the ponds, indicating the influence of natural decomposition and dilution by currents. During high tide, wastewater tends to be trapped in the bay area due to northward currents. Scenario 2 shows a similar pattern during low tide, but during high tide there is an increase in BOD distribution towards the center of the bay, indicating the influence of greater wastewater discharge. The decrease in BOD in Scenario 1 reflects natural recovery through diffusion and dilution **(Gomolka *et al.*, 2022)**, but this mechanism tends to weaken in Scenario 2, so increased wastewater discharge risks expanding pollution in the long term.

9. Comparison of NH4 parameters between scenarios 1 and 2

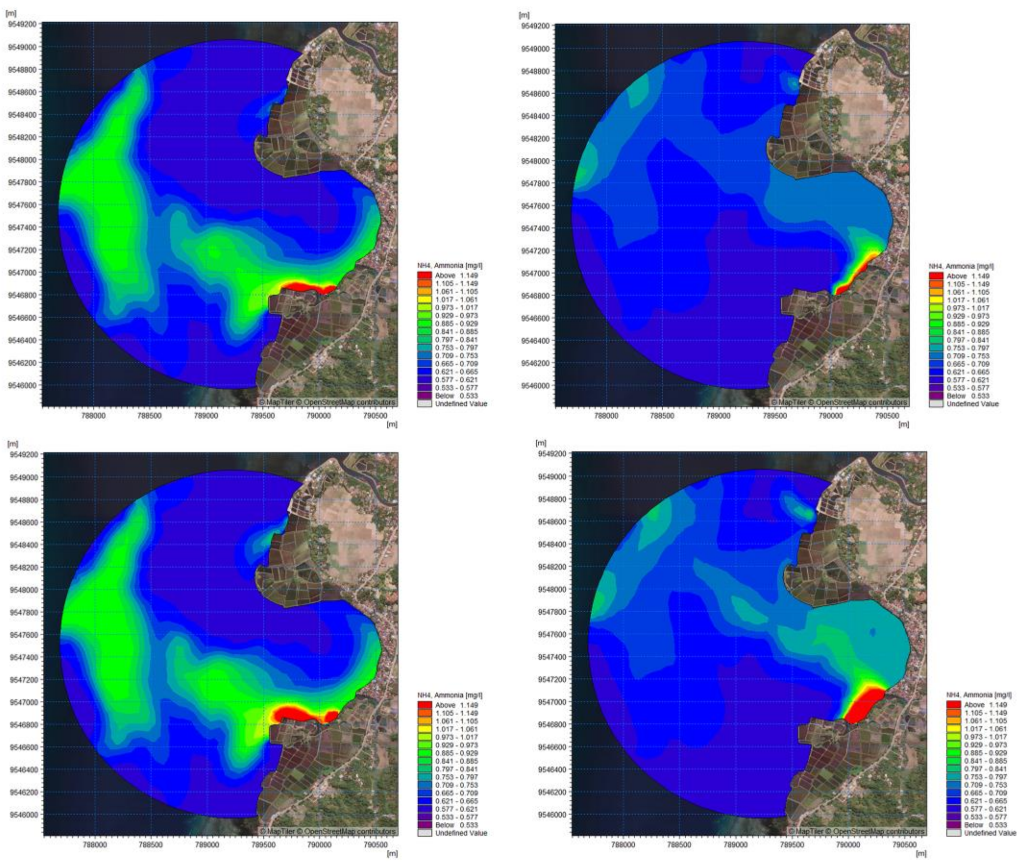


Fig. 7. Results of NH4 parameter modeling (a) Scenario 1 (b) Scenario 2

Fig. (8) presents the modeling results of NH4 distribution during low tide (left) and high tide (right) for each scenario. Blue-green indicates low NH4 concentrations, orange-red indicates higher NH4 concentrations, while green-blue indicates lower concentrations. The NH4 concentrations obtained from the modeling results within the bay are as follows: S1 (a) during low tide, NH4 in the central part of the bay showed a value of 0.616mg/ L, and during high tide, it showed a value of 0.727mg/ L. Further modeling results in S2 (b) recorded 0.622mg/ L during low tide and 0.770mg/ L during high tide.

In scenario 1, ammonia distribution during low tide is concentrated around the ponds, indicating natural dilution or conversion to other forms of nitrogen. During high tide, currents pushed ammonia northward, causing accumulation in the bay. Scenario 2 showed higher NH4 concentrations, indicating that nitrogen loads from the ponds exceed the water's capacity to neutralize them. Currents influence NH4 distribution through nitrification, where ammonia is rapidly converted to nitrate **(Mosier *et al.*, 2022)**. Increased pond activity prolongs the duration and accumulation of NH4, which originates from feed residues and organic waste **(Suwoyo *et al.*, 2019)**.

10. Comparison of NO3 parameters between Scenarios 1 and 2

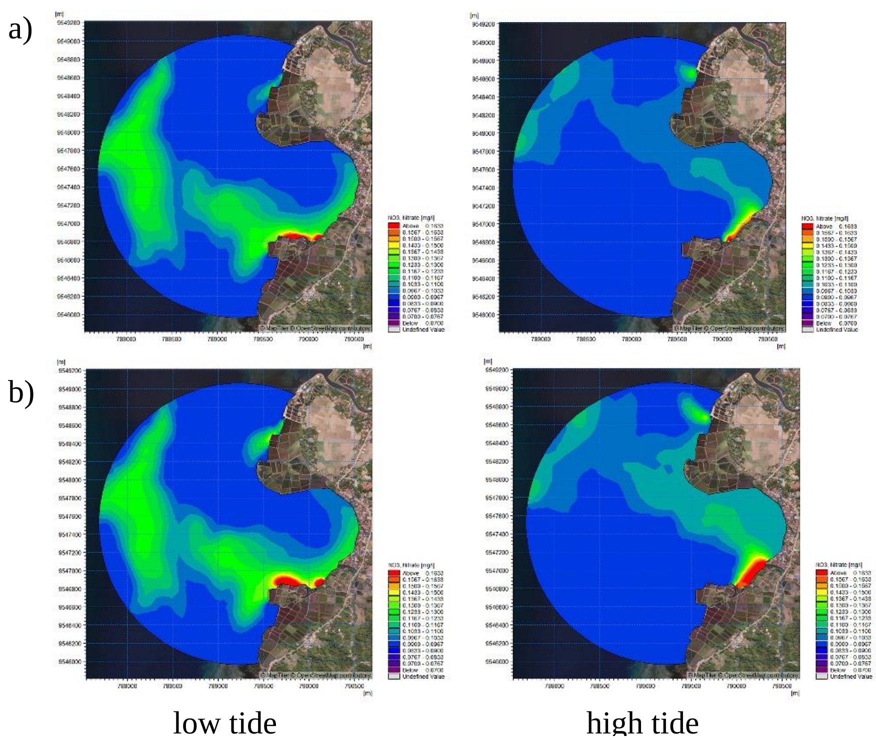


Fig. 8. Results of NO3 parameter modeling (a) Scenario 1 (b) Scenario 2

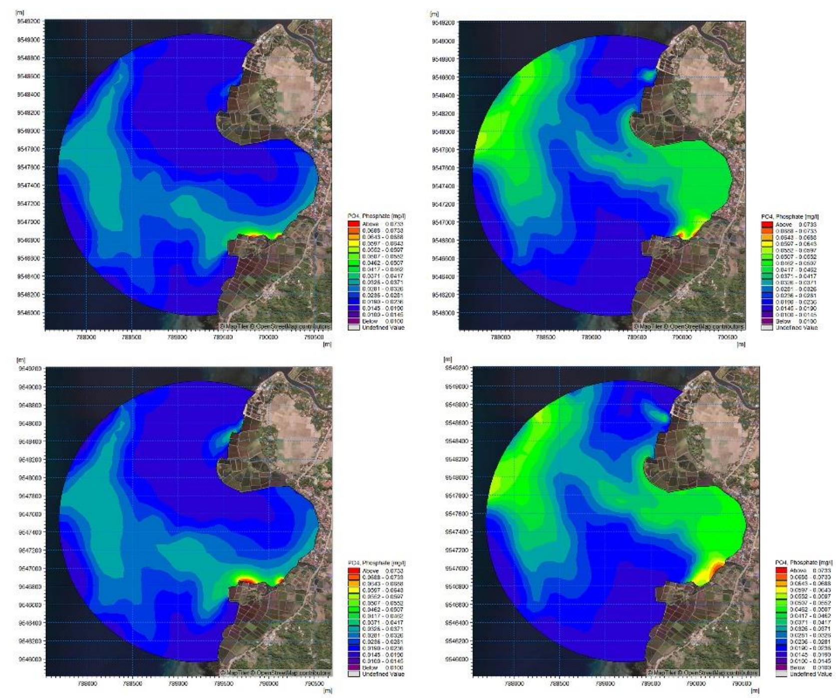
Fig. (9) presents the results of NO3 distribution modeling during low tide (left) and high tide (right) for each scenario. Blue-green indicates low NO3 concentrations, orange-red indicates higher NO3 concentrations, while green-blue indicates lower concentrations. The NO3 concentration values obtained from the modeling results within the bay are as follows: S1 (a) during low tide, NO3 in the central part of the bay shows a value of 0.092 mg/L, and during high tide, it showed a value of 0.097mg/ L. Further modeling results in S2 (b) revealed 0.093mg/ L during low tide. During high tide, the value is 0.101mg/ L.

Scenario 1 demonstrated that nitrate distribution moved southward during low tide and increased during high tide due to currents carrying waste into the bay area. Despite inputs from ponds, natural circulation and denitrification processes remained effective in reducing concentrations. In Scenario 2, increased waste discharge caused the nitrate distribution to expand, and during high tide, accumulation occurred that was not fully degraded. Overall, high cultivation intensity increases nitrate concentrations, potentially triggering eutrophication if left uncontrolled. Research by **Herbeck *et al.* (2021)** note that although nitrogen contributions from global aquaculture are smaller than those from rivers, their impact is significant in closed coastal areas with intensive cultivation activities.

11. Comparison of PO4 parameters between Scenarios 1 and 2

a)

b)



low tide high tide

Fig. 9. Results of PO4 parameter modeling (a) Scenario 1 (b) Scenario 2

Fig. (10) presents the results of PO_4 distribution modeling during low tide (left) and high tide (right) for each scenario. Blue-green areas indicate low PO_4 concentrations, while orange-red areas represent higher concentrations. The modeled PO_4 concentration values in the bay are as follows: in Scenario 1 (a), PO_4 in the central part of the bay measured 0.019mg/ L during low tide and 0.044mg/ L during high tide. In Scenario 2 (b), concentrations were 0.020mg/ L during low tide and 0.047mg/ L during high tide.

In Scenario 1, phosphate distribution during low tide showed moderate concentrations flowing southward, while during high tide it shifted toward the center of the bay with wider coverage. Scenario 2 showed an overall increase in phosphate concentrations with a similar distribution pattern, but more widespread and dominant in the central area of the bay. A comparison between the scenarios revealed that the central part of Bojo Bay is particularly vulnerable to phosphate accumulation due to intensified aquaculture activities. This highlights the limitations of the water system in mitigating additional phosphate loads, thereby increasing the potential for eutrophication. Studies by **Sari *et al.* (2020)** and **Crooks *et al.* (2021)** support these findings, indicating that intensified aquaculture and inorganic nutrient inputs can trigger a decline in coastal water quality.

CONCLUSION

This study successfully developed a water quality distribution model for Bojo Bay using the MIKE 21 software, which integrates the Hydrodynamics (HD) and ECOLAB modules. The model simulates the spatial distribution of key water quality parameters BOD, DO, ammonia, nitrate, and phosphate based on two scenarios of changes in the intensity of aquaculture activities. The simulation results indicate that: Aquaculture activities influence water quality in Bojo Bay, particularly during high tide, with wastewater discharge at point 6 (pond B) tending to accumulate in the bay area. During low tide, wastewater discharge at (pond A) moved toward the bay area. Hydrodynamic factors significantly influenced the distribution pattern of pollutants carried by currents. The modeling results indicate that water quality can reduce the concentration of pollutants discharged into the sea from aquaculture wastewater. while a 100% increase in wastewater discharge can decline the water quality and can move deeper in the waters of Bojo Bay. The scenario-based approach provided insights that can be used as a basis for decision-making in aquaculture management and planning mitigation strategies for pollution in Bojo Bay in the future.

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