Mapping the impact of seasonal estuary closure on macrozoobenthos community structure and diversity in the Kungkai Baru Estuary

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Abstract. Estuaries are dynamic ecosystems that support diverse biological communities and provide essential ecological services. This study investigates the effects of seasonal estuary closure on the structure and diversity of macrozoobenthos communities in the Kungkai Baru Estuary, Indonesia. Macrozoobenthos samples were collected from 21 purposively selected stations across three zones (estuarine mouth, mixing zone, and upstream) during the West (open estuary) and East (closed estuary) seasons. Environmental parameters, including salinity and pH, were measured in situ to assess their influence on macrozoobenthos diversity and abundance. Results revealed significant seasonal variations, with higher diversity and abundance during the West season due to reduced salinity and more alkaline pH conditions. The East season exhibited lower diversity and dominance of salt-tolerant species, driven by elevated salinity. Spatial analysis showed that upstream regions, with stable pH and organic-rich sediments, supported more extraordinary biodiversity than the downstream areas. Statistical analysis confirmed a positive correlation between macrozoobenthos abundance and pH, and a negative correlation with salinity. These findings underscore the importance of managing salinity and pH to sustain estuarine biodiversity and provide insights into conservation and management.
Key Words: estuarine biodiversity, habitat variability, salinity, pH, estuarine ecosystems.

Introduction. Estuaries play vital roles in ecological and socio-economic systems, serving as productive habitats that support diverse species and contribute to nutrient cycling, sediment transport, and energy flow. These ecosystems also provide critical services, such as nursery grounds for fish and habitats for macrozoobenthos, which are essential for maintaining biodiversity and ecosystem functions (Chaudhuri et al 2012; Dolbeth et al 2021). In the Kungkai Baru Estuary, seasonal closures during the East Season prevent the mixing of riverine and marine waters, significantly altering water quality and habitat conditions. Despite their ecological importance, estuarine ecosystems in Bengkulu remain underexplored, particularly concerning macrozoobenthos communities.

Macrozoobenthos are widely regarded as bioindicators due to their sensitivity to environmental changes, such as shifts in salinity and pH (Novais et al 2015), organic matter content and sediment grain size characteristics (Muskananfola et al 2020). They contribute to nutrient cycling and sediment aeration, playing a fundamental role in the energy flow within estuarine food webs (Dias et al 2016). However, the lack of studies focusing on macrozoobenthos in the Kungkai Baru Estuary presents a gap in understanding how seasonal dynamics and environmental factors affect their diversity and distribution. Insights from research in other regions, such as South Sumatra, have shown that environmental conditions, including water quality and chlorophyll levels, critically influence the abundance and diversity of aquatic species (Andriwibowo et al 2021).

This study addresses these gaps by analyzing macrozoobenthos diversity and community structure during the east and west seasons, alongside in situ measurements of environmental parameters, such as pH, and salinity. Statistical analysis using correlation methods will explore relationships between environmental factors and macrozoobenthos diversity. By integrating seasonal and spatial perspectives, this research seeks to provide a comprehensive understanding of the ecological dynamics within the Kungkai Baru Estuary.

The findings of this study will have practical applications in the conservation and management of estuarine ecosystems, including sustainable fisheries management and mitigating the impacts of environmental changes. Using macrozoobenthos as bioindicators can offer critical insights into the health of estuarine habitats, aiding efforts to maintain biodiversity and ecological integrity. Furthermore, the results will support the development of science-based policies to ensure the resilience of tropical estuaries in the face of natural and anthropogenic pressures.

Material and Method

Description of the study sites. The research was carried out in the Kungkai Baru Estuary, situated in Seluma Regency, Bengkulu Province, on the western coast of Sumatra, Indonesia. This estuary is located along the Indian Ocean coastline and acts as a transitional area where freshwater from inland rivers mixes with saline seawater (Figure 1). The Kungkai Baru Estuary frequently experiences seasonal closure due to sand deposition during the east season, whereas it remains open mainly during the west season. These seasonal variations significantly influence the estuary's hydrological and ecological dynamics. The east season, characterized by the closure of the estuary, occurs from June to August, limiting water exchange between the river and the sea. In contrast, from December to February, the west season is marked by an open estuary, facilitating the active mixing of freshwater and seawater.

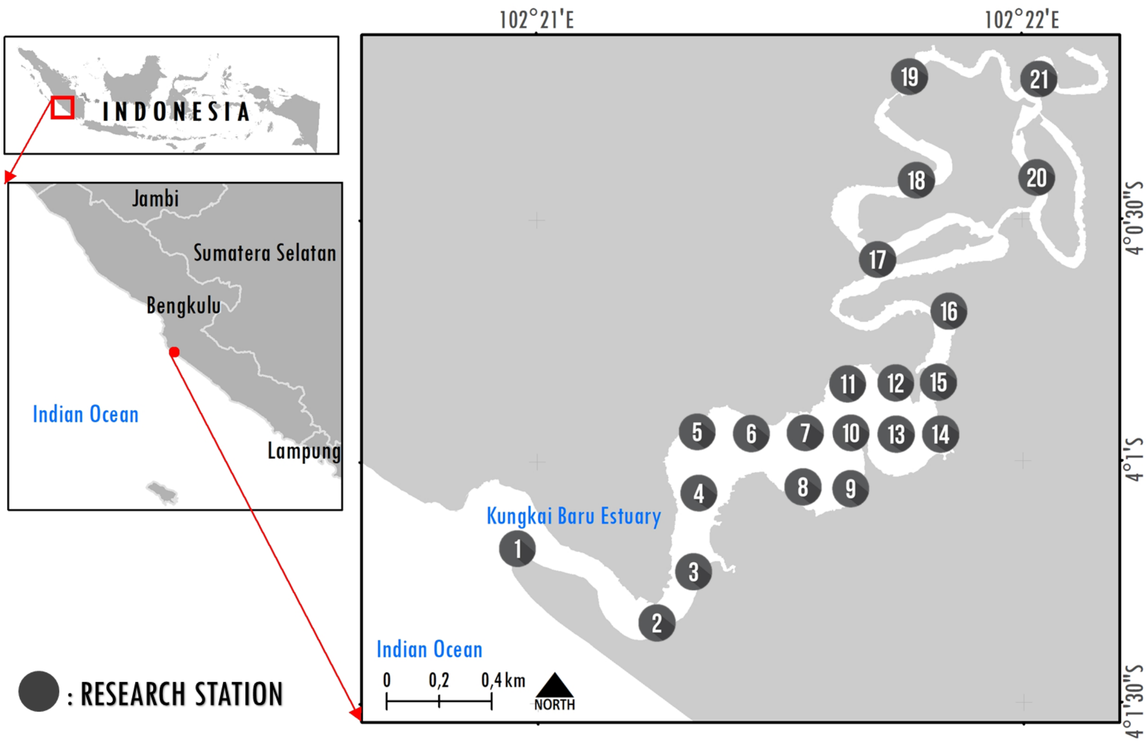

Figure 1. Research stations in the Kungkai Baru Estuary, Bengkulu, Indonesia.

Sampling stations and data collection. The research was conducted at 21 sampling stations distributed across 3 zones in the Kungkai Baru Estuary: the estuarine mouth (6 stations), mixing zone (9 stations), and upstream estuary (6 stations). Station selection was purposive, representing distinct ecological and hydrological conditions. Macrozoobenthos samples were collected using an Ekman grab, with three replicates per station. Substrate samples were sieved (1 mm mesh) to isolate organisms, sorted manually, preserved in 70% alcohol, and identified to species level using taxonomic guides. Environmental data (pH and salinity) were measured in situ using a calibrated digital pH meter and hand refractometer, respectively, with triplicate readings at each station. These parameters are critical for understanding macrozoobenthos distribution, as they reflect the estuary's chemical and hydrological dynamics, which influence benthic habitats and ecosystem health.

Diversity indices and community analysis. The ecological status of macrozoobenthos communities was assessed using diversity, evenness, and dominance indices to evaluate species distribution, community balance, and dominance patterns. These indices were calculated using the software PAST 4.16c to ensure precision and efficiency.

The Shannon-Wiener diversity index (H'), proposed by Shannon & Weaver (1949), was used to measure species diversity by incorporating both species richness and relative abundance. This index was calculated using the following formula:

$$H' = - \sum (p_i \ln p_i)$$

Where:
H' - the diversity index;
p_i - the proportion of individuals belonging to species i ($p_i = n_i / N$);
n_i - the number of individuals of species i;
N - the total number of individuals in the sample.
Higher H' values indicate greater species diversity, reflecting a more complex and stable community structure.

To assess species distribution uniformity, Pielou's Evenness Index (E) was applied (Pielou 1966). This index quantifies how evenly individuals are distributed among species using the equation:

$$E = H' / \ln S$$

Where:
E - the evenness index;
H' - the Shannon-Wiener diversity index;
S - the total number of species observed.
Values of E closer to 1 indicate a more even species distribution, suggesting a balanced ecosystem.

The Simpson's Dominance Index (D) (Simpson 1949) was employed to determine the extent to which a single species dominates the community. The formula used is:

$$D = \sum (p_i^2)$$

Where:
D - the dominance index;
p_i - the proportion of individuals belonging to species i.
Higher D values indicate greater dominance by a few species, whereas lower values suggest a more evenly distributed community.

Spatial analysis and mapping. Spatial interpolation using the spline method was applied to generate maps of environmental parameters (pH and salinity), species diversity, and macrozoobenthos community structure. This approach was employed to identify spatial patterns and visualize seasonal differences within the Kungkai Baru

Estuary. The interpolation was conducted using ArcGIS software, enabling precise and smooth mapping of the data distribution across sampling stations. Such visualization enhances understanding of ecological dynamics and provides a basis for comparing conditions between the east and west seasons.

Statistical analysis. Correlation tests were conducted to examine the relationship between environmental parameters and macrozoobenthos community structure. The significance of differences was determined at $p<0.05$. Statistical analysis were performed using the PAST 4.16c software.

Results

Community structure and diversity. The abundance of macrozoobenthos is higher during the west season compared to the east season (Table 1). Gastropods are more abundant than macrozoobenthos groups, such as bivalves, crustaceans, and polychaetes. *Gabbia orcula* is the most abundant species in both seasons. *Campeloma* sp. and the bivalve *Unio* are more abundant during the west season, while *Erodonidae* sp. is found in more significant numbers during the east season. Species richness is higher in the west season than in the east season. Gastropods dominate, with a greater number of species than other groups. Crustaceans and polychaetes have the fewest species. Macrozoobenthos diversity is also higher in the west season, attributed to lower species dominance and higher evenness. In contrast, the east season exhibits lower diversity, largely due to greater species dominance and lower evenness.

Table 1

Macrozoobenthos community structure and diversity based on seasons, in the Kungkai Baru Estuary

Macrozoobenthos	*East season*	*West season*
Bivalves		
Anomalocardia squamosa	15	45
Atrina pectinata	0	45
Batissa violacea	0	2,697
Brachidontes setiger	521	2,726
Donax incarnatus	0	682
Eurytellina punicea	716	935
Maretrix maretrix	0	460
Mimachlamys sanguinea	15	30
Paphia textile	0	30
Ptridae sp.	0	149
Saccostrea cucculata	389	45
Tapes literatus	3,260	89
Unio bivalve	0	29,713
Erodonidae sp.	11,399	0
Eurytellina sp.	328	0
Neilonella sp.	193	0
Crustaceans		
Cirripedia sp.	580	802
Gastropods		
Brotia pagodula	0	30
Clithon diaderma	90	0
Clithon lentiginosum	0	45
Clithon mertoniana	0	771
Clithon oualaniense	75	0
Clithon sp.	30	0
Gabbia orcula	79,107	242,781
Gyraulus convexiusculus	0	30

Macrozoobenthos	East season	West season
Natica collaria	0	30
Natica lineata	0	30
Neripteron auriculata	45	30
Neritina iris	0	30
Polineces tumidus	0	15
Pomacea canaliculata	0	15
Radix rubiginosa	0	30
Stenomelania clavus	0	30
Stenomelania hastula	45	0
Stenomelania plicaria	164	0
Stenomelania sp.	134	978
Tarebia granifera	0	3,215
Tarebia lineata	0	30
Terebralia sulcata	3,428	2,223
Thiara rufis	0	75
Thiara scabra	0	134
Tylomelania sp.	2,732	15
Vittina turrita	0	15
Campeloma sp.	15	56,490
Clypeomorus sp.	0	904
Parvanachis sp.	0	386
Pirenella sp.	2,259	104
Polychaetes		
Alitta viren	0	15
Chironomus sp.	0	1,381
Capucinus sp.	0	430
Bivalves Abundances (ind m^{-2})	16,836	37,646
Crustaceans Abundances (ind m^{-2})	580	802
Gastropods Abundances (ind m^{-2})	88,124	308,436
Polychaetes Abundances (ind m^{-2})	0	1,826
Total Abundances (ind m^{-2})	105,540	348,710
Bivalves species richness	9	13
Crustaceans species richness	1	1
Gastropods species richness	12	25
Polychaetes species richness	0	3
Total species richness	22	42
Dominance index	0.58	0.52
Diversity index	1.03	1.07
Evenness index	0.13	0.07

Spatial distribution maps. Figures 2, 3 and 4 illustrate the differences in the spatial distribution of environmental conditions and macrozoobenthos diversity. Generally, salinity during the east season (12–25 ppt) is higher than during the west season (5–10.5 ppt). The highest salinity in the east season is observed in the downstream area of the Kungkai Baru Estuary. In contrast, salinity in the west season tends to be more uniform across the estuary.

In contrast, pH levels are generally lower during the east season (7.89–8.89) compared to the west season (8.33–9.50). The average pH during the east season (8.38) is also lower than that of the west season. The upstream area of the Kungkai Baru Estuary exhibits more stable pH levels than the downstream area. These findings highlight distinct seasonal variations in salinity and pH within the Kungkai Baru Estuary.

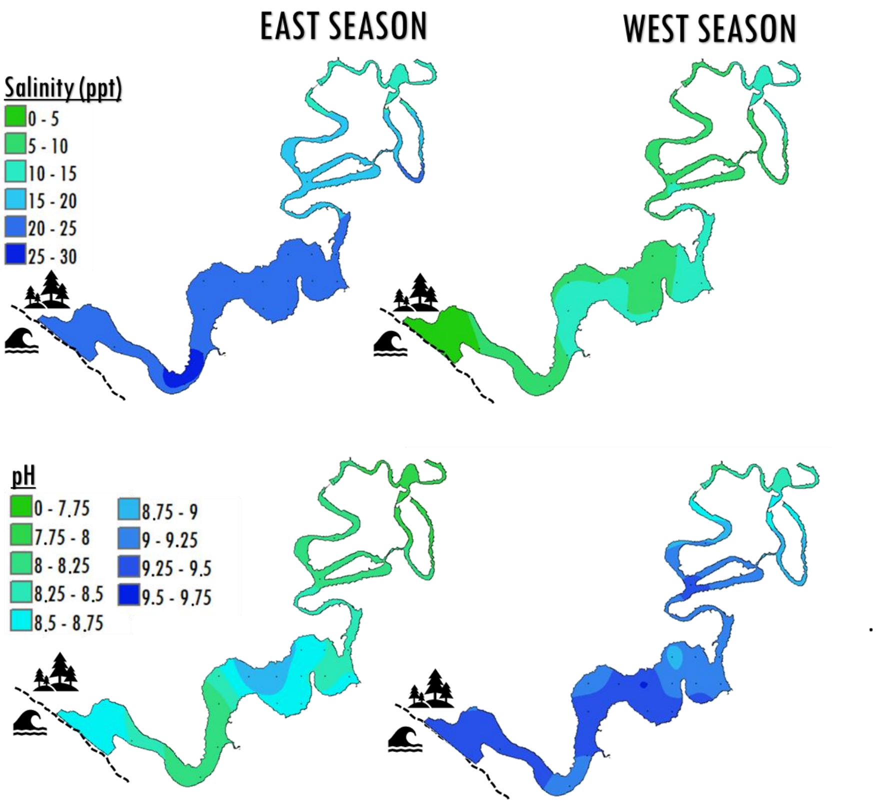

Figure 2. Spatial distribution maps of pH and salinity.

The spatial distribution of macrozoobenthos at the Kungkai Baru Estuary demonstrated significant seasonal variations (Figure 3 and Figure 4). Species richness was highest during the east season, particularly at station 15, and generally concentrated between stations 6 and 15. In contrast, species richness was high only at certain locations, such as stations 2, 6, and 16, during the west season. The downstream area exhibited lower species richness compared to the upstream region.

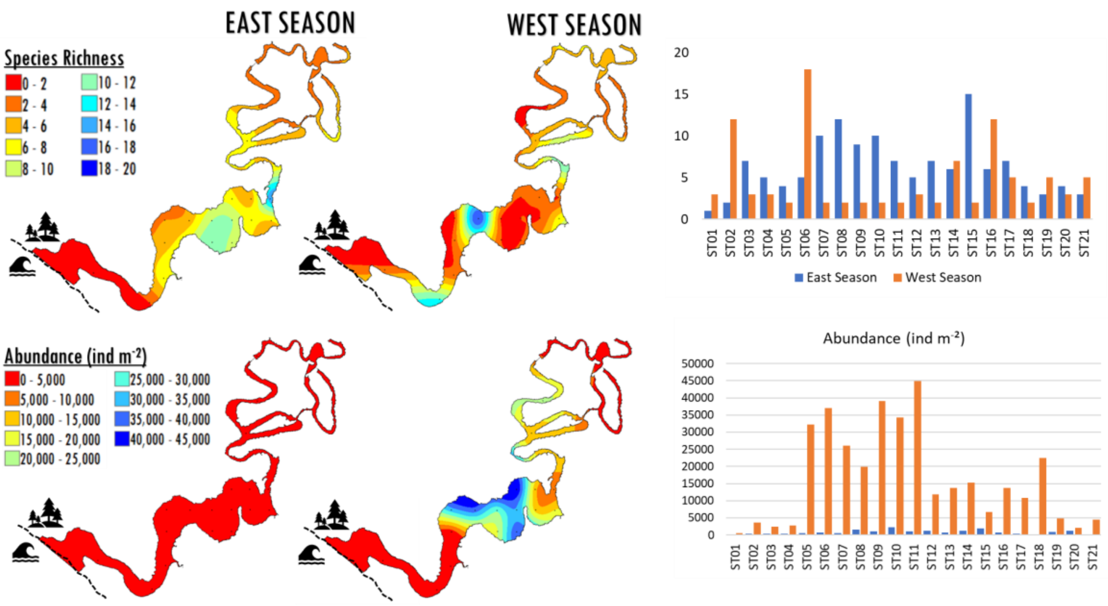

Figure 3. Spatial distribution maps of macrozoobenthos richness and abundance.

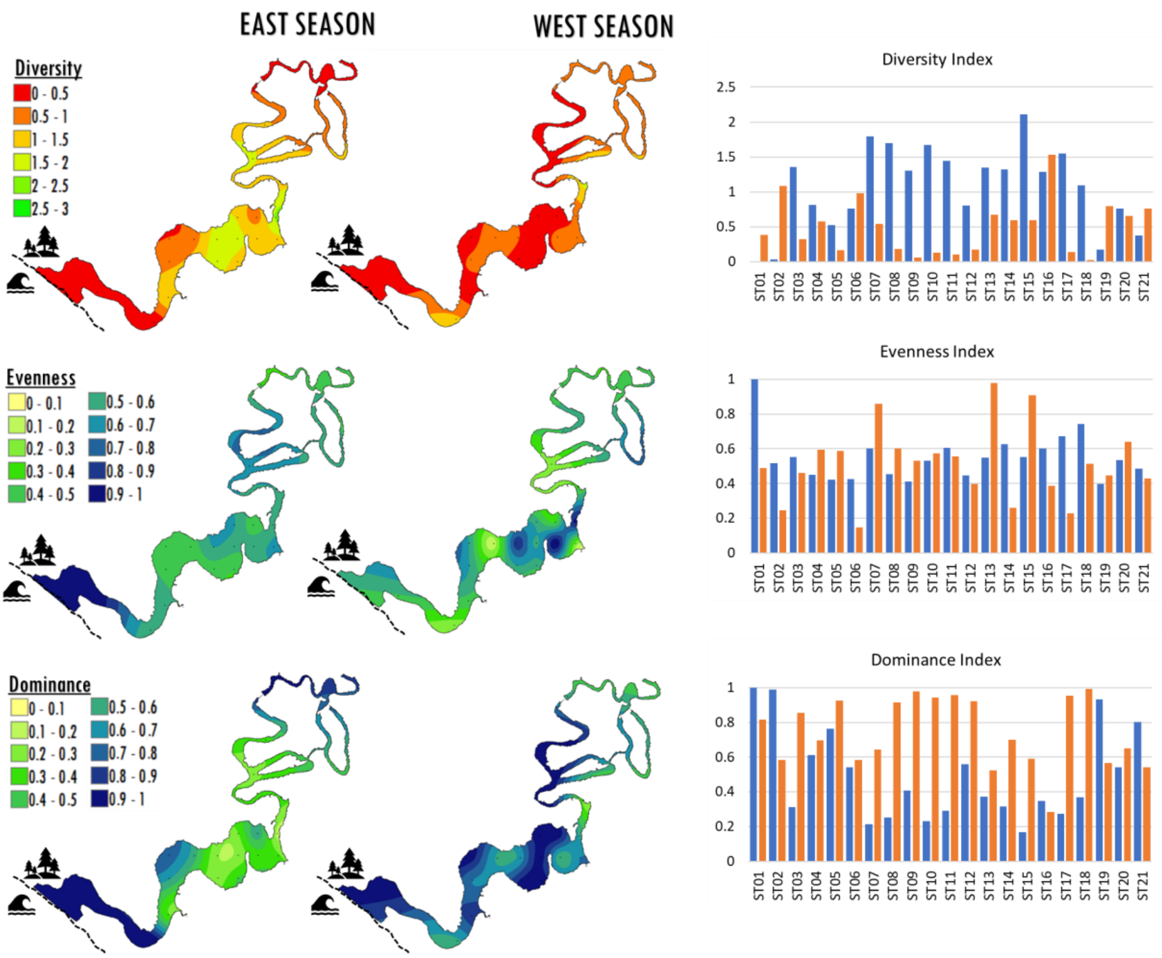

Figure 4. Spatial distribution maps of macrozoobenthos diversity, evenness and dominance.

Macrozoobenthos abundance was higher in the west season, with the highest values observed between stations 5 and 11, while the downstream area consistently showed lower abundance. Diversity indices (H') peaked at station 15 during the east season, with the lowest diversity in the downstream region. These findings indicate distinct seasonal and spatial patterns in the macrozoobenthos community structure at the Kungkai Baru Estuary.

Environmental correlations. The correlation analysis (Figure 5) between macrozoobenthos and environmental parameters showed a positive correlation (0.55) between benthos abundance and pH ($p<0.05$). Salinity exhibited a negative correlation (-0.40) with macrozoobenthos abundance ($p<0.05$). This indicates that an increase in salinity, commonly observed during the east season, leads to a decrease in macrozoobenthos abundance.

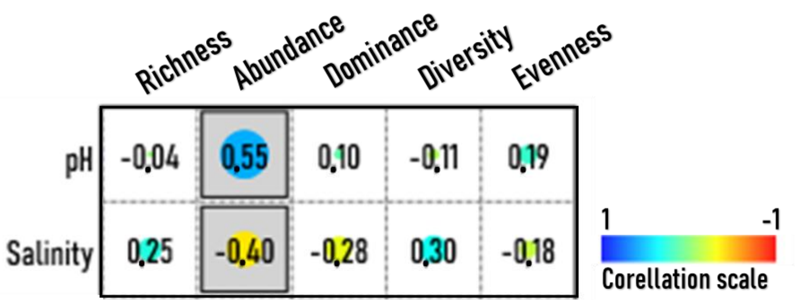

Figure 5. Correlation test.

Discussion

Interpretation of seasonal changes. The study revealed distinct seasonal patterns in macrozoobenthos communities within the Kungkai Baru Estuary, driven by variations in environmental parameters such as salinity and pH. Statistical analyses highlighted a positive correlation between macrozoobenthos abundance and pH, while salinity negatively correlated with abundance. These findings align with prior studies, which indicate that higher salinity levels can reduce macrozoobenthos diversity and abundance due to species' sensitivity to salinity fluctuations (Wijnhoven & Hummel 2011; Coelho et al 2022). Conversely, neutral to alkaline pH levels during the west season created favourable conditions for macrozoobenthos proliferation. During the west season, the estuary's open condition facilitates more significant freshwater inflow, reducing salinity levels and fostering an environment conducive to higher diversity and abundance. In contrast, the east season is characterized by the estuary's closure due to sediment accumulation, leading to reduced freshwater inflow and elevated salinity levels, particularly in downstream areas. These observations mirror findings in similar estuarine systems, where reduced freshwater discharge and increased evaporation during closed seasons result in higher salinity and altered sediment composition, significantly impacting macrozoobenthos communities (Ortega-Cisneros & Scharler 2015; Chazanah et al 2017).

Spatial patterns. Spatial analysis revealed significant variability in macrozoobenthos diversity across the Kungkai Baru Estuary, driven by habitat characteristics and environmental gradients. Downstream areas consistently exhibited lower diversity than upstream regions, particularly during the east season. This pattern is attributed to higher salinity levels and limited habitat heterogeneity in downstream areas during estuary closure. Salinity, a well-documented stressor, reduces the ability of many macrozoobenthos species to thrive under such conditions (Coelho et al 2022). Conversely, upstream regions, characterized by more stable pH levels and significant sediment heterogeneity, supported higher macrozoobenthos diversity. Organic-rich sediments present in upstream areas during the west season enhanced food availability, promoting greater macrozoobenthos abundance and diversity (Nakano et al 2022). Additionally, proximity to freshwater inflows buffered against extreme salinity fluctuations, providing a more stable environment for diverse macrozoobenthos communities.

Environmental influences. The roles of salinity and pH in shaping macrozoobenthos communities are significant. pH levels directly affect physiological processes, with acidic conditions generally reducing diversity and abundance (Mimier et al 2017). The study confirmed this trend, as higher macrozoobenthos abundance was observed during the west season when pH levels were more neutral to alkaline (8.33–9.50). These findings are consistent with patterns observed in other estuaries, such as the Godavari Estuary, where lower pH values during high freshwater discharge phases negatively impacted macrozoobenthos populations (Sarma et al 2011). This finding agrees with Muskananfola et al (2020), which states that macrobenthos abundance varies seasonally, with total individual abundance being higher in March (wet season).

Salinity, another critical factor, creates physiological challenges that influence species distribution. During the east season, elevated salinity levels (12–25 ppt) were negatively correlated with macrozoobenthos abundance (-0.40, $p<0.05$), reflecting findings from global studies that highlight the negative impact of high salinity on estuarine biodiversity (Novichkova et al 2023). Salinity gradients also favour salt-tolerant species, which can dominate during high salinity periods, reducing overall diversity and altering ecological roles (Hemraj et al 2017). These dynamics emphasize the importance of salinity management in conserving estuarine ecosystems. The interplay between salinity and pH presents a complex scenario in which both factors act synergistically or antagonistically to influence macrozoobenthos communities. During the west season, alkaline pH and lower salinity provided optimal conditions for increased diversity and abundance. Conversely, elevated salinity and reduced pH during the east season disrupted community structures, resulting in lower diversity indices (H') and dominance by salt-tolerant species. These patterns are consistent with observations from estuarine systems such as the Pearl Estuary, where salinity and pH jointly shape the resilience and functionality of macrozoobenthos populations (Liu et al 2014; Simpson et al 2022). These findings underscore the need for integrated monitoring and management of pH and salinity to sustain estuarine biodiversity.

Ecological and conservation implications. The findings from the Kungkai Baru Estuary highlight the ecological impacts of seasonal closures on macrozoobenthos communities. During the east season, reduced freshwater inflow and elevated salinity lead to lower diversity and dominance of salt-tolerant species, while the open conditions of the west season support higher biodiversity and community balance. Management strategies should mitigate extreme salinity and pH fluctuations to enhance ecosystem resilience. For example, controlled freshwater releases during the east season could buffer salinity spikes and support a broader range of species, a practice supported by findings from similar estuaries (Coelho et al 2022).

Climate change and human activities pose additional challenges to estuarine ecosystems. Increasing hydrological extremes may exacerbate salinity and pH fluctuations, further stressing macrozoobenthos communities. Adaptive strategies, such as riparian buffer preservation and sediment management, are essential to stabilize estuarine habitats. Additionally, the role of macrozoobenthos as bioindicators underscores their importance in providing early warnings of ecosystem stress, enabling timely management interventions (Novais et al 2015). Human-induced impacts, including agricultural runoff and urbanization, alter freshwater inflows and nutrient dynamics, compounding biodiversity loss. To address these challenges, management efforts should focus on reducing nutrient loading, limiting pollution, and establishing protected zones during sensitive periods such as the east season. These measures will safeguard critical habitats, promote species recovery, and enhance ecological resilience. Integrating these strategies into estuarine management can better conserve biodiversity and sustain vital ecosystem services in the face of ongoing environmental changes.

Conclusions. This study highlights the significant influence of seasonal and spatial variations on macrozoobenthos communities in the Kungkai Baru Estuary, driven by salinity and pH fluctuations. During the west season, lower salinity (5–10.5 ppt) and alkaline pH levels (8.33–9.50) supported higher diversity and abundance, while the east season’s elevated salinity (12–25 ppt) and reduced pH (7.89–8.89) led to lower diversity and dominance of salt-tolerant species. These patterns underscore the critical impact of estuary closures on macrozoobenthos community structure. Spatially, upstream areas, characterized by stable pH and organic-rich sediments, supported greater diversity and abundance, particularly during the west season. In contrast, downstream areas experienced reduced diversity due to higher salinity and lower habitat heterogeneity during the east season. Statistical analysis confirmed a positive correlation between abundance and pH (0.55, $p<0.05$) and a negative correlation with salinity (-0.40, $p<0.05$), emphasizing the role of these parameters in shaping macrozoobenthos dynamics. The findings highlight the importance of managing salinity and pH to support biodiversity in estuarine ecosystems. Strategies like controlled freshwater releases during the east season could buffer salinity spikes and maintain ecological balance. Furthermore, macrozoobenthos are effective bioindicators, offering critical insights into ecosystem health. Future research should expand on this study by incorporating additional variables, such as nutrient dynamics and long-term monitoring, to capture the cumulative impacts of climate change and human activities. By applying these findings, policymakers and conservationists can better protect estuarine biodiversity and sustain critical ecosystem services in tropical estuaries. This research contributes to a deeper understanding of estuarine ecology, supporting science-based conservation efforts.

Acknowledgements. The authors sincerely thank the Faculty of Agriculture, University of Bengkulu, for providing laboratory facilities and equipment. Special thanks to the field team for their invaluable assistance during sampling and data collection in the Kungkai Baru Estuary. The authors also acknowledge the support from local authorities and communities for facilitating access to the study area.

Conflict of interest. The authors declare no conflict of interest.

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Received: 09 December 2024. Accepted: 28 February 2025. Published online: 16 March 2025.
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How to cite this article:
Nofridiansyah E., Hartoko A., Muskananfola M. R., Helmi M., Adi W., 2025 Mapping the impact of seasonal estuary closure on macrozoobenthos community structure and diversity in the Kungkai Baru Estuary. AACL Bioflux 18(2):611-621.