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Hydrodynamic Control of Suspended Sediment Transport and Coastal Morphodynamics in Tropical Estuarine Systems Under Environmental Pressure: A Case Study of Balikpapan Bay

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Abstract

Balikpapan Bay has large and small river estuaries, including the Sepaku River, the Wain River, and the Riko River. The watershed of Balikpapan Bay has a fairly important and strategic role, including as a buffer for the sustainable function of the bay as a seaport for Balikpapan and a source of income for the surrounding community as well as the life of the bay's marine ecosystem.The purpose of this study was to determine the distribution pattern of Total Suspended Solid (TSS)s and changes in the morphology of Balikpapan Bay based on the tidal flow pattern model using the 3-dimensional Mohid model approach. Data collection was carried out on 3rd-20thSeptember 2024. The model used is a hydrodynamic model with bathymetry data and tidal data as the main drivers and secondary data, namely the constant Total Suspended Solid concentration as the input value in model processing. The distribution of very high Total Suspended Solid concentrations occurs at full moon tide until it reaches the mouth of Balikpapan Bay, the area with the highest sediment concentration, namely the Sepaku Bear River ranges from 200-250 $mg.L^{-1}$ and at the mouth of Balikpapan Bay it ranges from 50-100 $mg.L^{-1}$. Erosion occurs in the Jenebora area, part of the Kariangau area, and the eastern part of the bay, especially on the coast of Kemala Balikpapan. The observed pattern—elevated TSS during neap or spring-tide conditions and near the estuary mouth, tidal forcing and riverine inputs shape SSC distributions and estuarine turbidity maxima (ETM). Balikpapan Bay could develop an ETM in the vicinity of the river mouths or the estuarine channel mouth under similar forcing, with stronger sediment exchange during higher-energy tidal phases. The Balikpapan Bay results indicate a robust coupling between tidal flow, sediment transport, and estuarine morphodynamics, with significant implications for port operations, coastal resilience, and ecosystem health. High TSS in riverine plumes and erosion hotspots along the coast imply a dynamic sediment regime that will influence dredging needs, shoreline stability, and habitat conditions.

Keywords: *Suspended sediment transport, Coastal, Tropical, Estuarine, Pressure*

Introduction

Hydrodynamic conditions in coastal and estuarine environments play a critical role in shaping geomorphological processes, sediment transport, and ecological interactions. For instance, studies on low-crested porous breakwaters have demonstrated that wave transmission and reflection induce complex hydrodynamic processes, including wave breaking and overtopping, which significantly influence local sediment dynamics and habitat structure (Koutrouveli and Dimas, 2018; Saengsupavanich *et al*., 2022; Leone *et al*., 2023; Gent, 2024).

Additionally, the interplay of hydrodynamics and biogeochemical cycles is essential for understanding sediment transport in estuarine systems, as exemplified by the modeling of mud and sand transfers at macrotidal estuaries (Diaz *et al*., 2020; Xu *et al*., 2023; Li *et al*., 2025). The dynamics of these environments can also be affected by anthropogenic changes and climate factors, such as sea-level rise, which modifies tidal hydrodynamics and can drastically alter marsh evolution and sediment fluxes in coastal regions (Passeri *et al*., 2016; Guzman *et al*., 2020; Pannozzo *et al*., 2022; Maren *et al*., 2025). Furthermore, the influence of

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biogenic structures, such as bivalve reefs, enhances local hydrodynamics, promoting sediment stabilization and biodiversity within coastal ecosystems (Ysebaert *et al*., 2018; Pomeroy *et al*., 2021; Ogbuagu *et al*., 2022). These interactions highlight the necessity for a multidisciplinary approach to studying and managing the hydrodynamic conditions of these vital marine environments, as they are indispensable for biodiversity conservation and resource management (DuVal *et al*., 2021).

Coastal areas are characterized by complex physical and dynamic phenomena shaped by both natural processes and human activities. Notably, coastal hydrodynamics and sediment transport are critically influenced by factors such as wave energy, tidal variations, and morphological features. For example, the study by Noujas *et al*. reveals significant differences in hydrodynamics between high-energy and lower-energy coastal zones, emphasizing that contrasting wave regimes lead to diverse sediment mobility and beach morphology (Noujas *et al*., 2019). Additionally, coastal erosion, exacerbated by both natural and anthropogenic factors, poses substantial risks to these regions. Barillà *et al*. highlight the need for comprehensive assessment methodologies to evaluate coastal erosion hazards and vulnerabilities, stressing the complexity of managing sediment balance amidst human interventions (Barillà *et al*., 2021). Examining a specific seasonal inlet, K. *et al*. documented extreme erosion at Cua Dai Beach, attributing morphological changes to sediment supply disruptions and urban development (Do *et al*., 2019). Furthermore, the effect of tidal dynamics on longshore sediment transport, indicating that deeper understanding of such interactions is essential for effective shoreline management (Nnafie *et al*., 2025). These findings collectively underscore the importance of multidisciplinary approaches that integrate physical modeling, remote sensing, and ecological assessments to address the multifaceted challenges facing coastal systems.

The distribution of Total Suspended Solids (TSS) in aquatic environments is influenced by a myriad of physical factors, including hydrodynamic conditions, sedimentation processes, and environmental alterations. Notably, river hydrodynamics plays a critical role, as the flow velocity and turbulence dictate the resuspension of sediments and particulate matter. For instance, studies have shown that high flow velocities can lead to increased resuspension of sediments from riverbeds into the water column, which subsequently elevates TSS concentrations (Sahid and Zainab, 2024). Moreover, sedimentation dynamics are significantly affected by the transport of materials via river waters, where sedimentation processes can vary based on the sediment load carried by the flow, impacting TSS levels observed downstream (Sahid and Zainab, 2024; Venevsky *et al*., 2025).

Estuaries, as dynamic interfaces between riverine and marine environments, are significantly influenced by both natural processes and human interventions that drive morphological changes. Recent studies underscore that alterations to sediment fluxes at the estuary-sea interface are crucial for understanding these transformations. Grasso *et al*. emphasize that anthropogenic activities such as estuary deepening and narrowing can severely affect sediment dynamics, thereby threatening estuarine ecosystems and their associated services (Grasso *et al*., 2021). The impacts of such changes are seen in various estuaries worldwide; for example, the Sittang River estuary showcases how channel migration due to tidal flows and sediment transport can result in complex morphological alterations (Shimozono *et al*., 2019; Baar *et al*., 2022; Hsieh *et al*., 2022; Escauriaza and Williams, 2024). Moreover, both sea-level rise and reduced fluvial sediment supply are recognized as critical factors influencing the geomorphological responses of estuaries. Leuven *et al*. identified how different sizes of estuaries respond variably to these pressures, with larger estuaries being more susceptible to sediment starvation, leading to loss of intertidal areas (Leuven *et al*., 2019). The impact of climate and seasonal variations has also been illustrated in the Qiantang Estuary, where morphological changes driven by river discharge variations significantly affect tidal dynamics (Lefebvre *et al*., 2021; Xie and Wang, 2021; Cai *et al*., 2022; Jalón-Rojas *et al*., 2023; Li and Pan, 2024). Similarly, anthropogenic actions such as dredging and land reclamation significantly disrupt natural processes, exacerbating morphological changes in estuarine systems (Dai *et al*., 2016; Grasso *et al*., 2021; Schrijvershof *et al*., 2024). The emerging pattern from recent studies demonstrates that both natural hydrodynamic processes and human interventions interact complexly in shaping estuary morphology, which necessitates a comprehensive understanding for effective management and conservation (Grasso *et al*., 2021; Jung *et al*., 2021; Deb *et al*., 2022; Ni *et al*., 2022; Jenkins *et al*., 2023; Deng *et al*., 2025; Gerritsma *et al*., 2025; Zhou *et al*., 2025).

Sedimentation in Balikpapan Bay, East Kalimantan, presents a significant environmental challenge amid increasing anthropogenic activities driven by infrastructure development, particularly with the planned relocation of Indonesia's capital to the region. Research indicates that sediment dynamics are influenced by ecological factors and human activities, including land clearing and urban development. For instance, studies highlight alterations to local hydrodynamics due to sediment influx from deforested areas and construction activities associated with the capital relocation plans. These activities exacerbate sedimentation rates, leading to ecological ramifications such as the disruption of marine habitats, particularly affecting seagrasses and mangroves that play vital roles in carbon sequestration and coastal protection (Soeyanto and Arifiyana, 2018; Putri *et al*., 2021; Willard *et al*., 2022; Anwar *et al*., 2023; Nababan *et al*., 2023). The disruption of sediment balance can hinder the growth of critical coastal species, such as the seagrass *Enhalus acoroides*, which was notably dense in the area prior to significant alterations (Anwar *et al*., 2023; Nababan *et al*., 2023). Furthermore, an oil spill incident in March 2018, which released approximately 44,000 barrels of crude oil into Balikpapan Bay, illustrates the potential for ecological disaster caused by sedimentation and human interference, with studies suggesting a direct relationship between sediment transport mechanisms and the dispersal of contaminants (Soeyanto and Arifiyana, 2018; Muin *et al*., 2022; Juwari *et al*., 2024) . Hence, the interplay between natural sedimentation processes and anthropogenic factors necessitates continuous monitoring and adaptive management strategies to conserve the ecological integrity of Balikpapan Bay.

The purpose of this study was to determine the distribution pattern of TSSs and morphological changes based on tidal flow patterns during full moon and bandages in the waters of Balikpapan Bay using the 3-dimensional MOHID model approach.

Material and Method

This research was conducted in Balikpapan Bay with a longitude of 116.6 - 117 E and latitude of 1 - 1.5 S. The bathymetry in the study area (Figure 1) varies from 0 to 50 m. At the mouth of the Bay, the water depth ranges from 10 m to 50 m, and the inside of the bay between 0 m to 20 m. There is a channel more than 10 m deep in the middle of the bay that connects between the mouth and the inside of the bay. The channel formed not only facilitates transportation but also increases the discharge of seawater that enters the bay of Balikpapan. The red dot shows the location of the river discharge used as the model input, which is explained in detail in the section on field measurements. Time series points are sampled at Semayang Port as model validation points with sea-level observation, and there are 2-time series points at the mouth and in the Balikpapan bay to quantify the surface currents that are formed as shown in Figure 2. The open boundary of the model is the open sea area around the mouth of the Balikpapan Bay which is still influenced by the the Balikpapan Bay with the left and right boundaries of each 116.6 - 117 E, while the southern boundary is 1.5 S.

Field Measurement

The field measurement used for this research is hourly sea level monitoring from the Geospatial Information Agency (BIG) via the tides.big.go.id page during August 2019. This data is a direct measurement through a tide gauge located in the nearby Semayang Port. the mouth of the bay. This data is used as sea level validation against the simulated model results at the same time and interval. Measurement of the initial values of river discharge, temperature, salinity, and sediment concentration the upstream of the Wain River, the upstream of the Rikoriver, and the upstream of the Sepaku river was carried out on 3-20 September 2024 (Table 1).

River discharge measurement

River discharge measurements use the method developed by Shaw *et al.* (2010) using equation 1. In this method, river flow measurements are based on the basic equation in calculating the discharge (Q) (m^3 s^{-1}), namely the multiplication of current velocity (v) ($m.s^{-1}$) times the cross-sectional area (a) (m^2).

$$Q = v \times a \tag{1}$$

Increasing accuracy in measuring river discharge is done by dividing the river width into several parts of the same length (Figure 3). In each section, parameters are taken in the form of current velocity (v) ($m.s^{-1}$), depth (d) (m), and the width of the river cross-section (b) (m) measured. From these three parameters, equation 2 is obtained (Chen *et al*., 2022):

$$Q = v \times \frac{d_{i-1}+d_i}{2} \times (b_i + b_{i-1}) \tag{2}$$

Data of input model

The hydrodynamic model simulated in Balikpapan Bay using bathymetry, tides, salinity temperature, river discharge, and surface wind inputs. The bathymetry data were obtained from the Indonesian Navy's Center for Hydrography and Oceanography (Pushidrosal) which were then interpolated with a grid resolution of 1/100 degree. Surface winds are obtained from NOAA's Earth System Research Laboratory (ESRL) with a spatial resolution of 2.5 degrees and temporal every 6 hours (https: //www.esrl.noaa.gov.html). Tide data were obtained from the Finite Element Solution (FES) 2004 tidal model (Lyard *et al*., 2006), based on

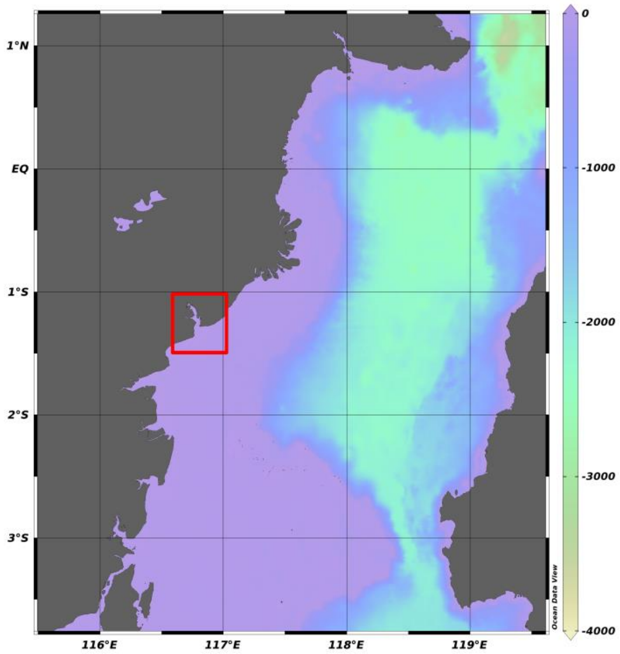

Figure 1. Map of the model area (marked with a red square)
(Source: Dishidros, 2005)

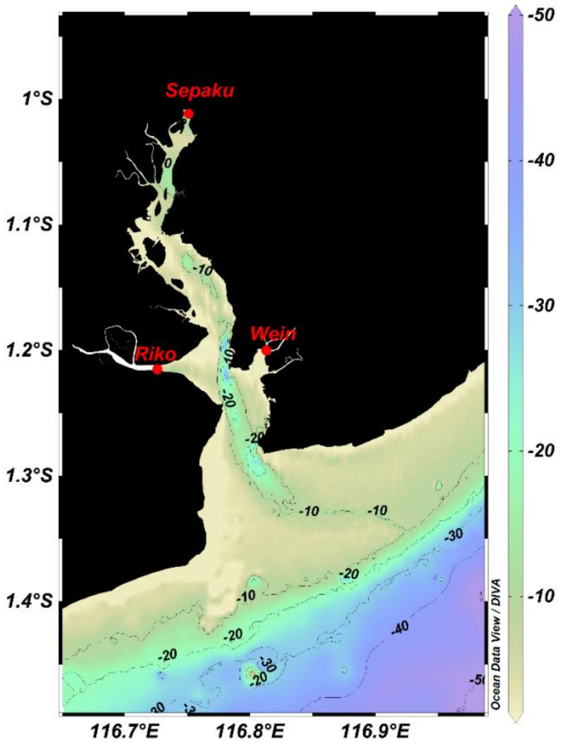

Figure 2. Domain of bathymetry model of Balikpapan Bay

hydrodynamic models assimilated by tidal devices and altimeter data (Topex / Poseidon and ERS-2). The FES 2004 model is obtained from AVISO (https://www.aviso.altimetry.fr) covering all global waters of each tidal component with a resolution of $1/8^0$, prediction data consisting of 14 components (Table 2). while wind data is obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) in the form of 3-hour wind data. River discharge data is the maximum value data from the monthly average in 2020, while the water depth data is obtained from Dishidros-AL. The dimension of the model uses a grid of 0.001x 0.001^0 d with a grid slope of 20^0. The model is run for 29 days starting from January 2020.

In developing the Balikpapan Bay model, the initial concentration of TSS in the waters is zero. Hence, the TSS that spreads in the seas is purely from the TSS input, a scenario from the river. The effect of wind in this study was calculated because the domain model at the open boundary is open water facing the Makassar Strait where the wind effect is strong enough to affect the currents formed in the mouth of the Balikpapan Bay.

The tides in Balikpapan Bay waters propagate from the Makassar Strait so that the tidal component is also similar to the propagation conditions that occur in the Makasssar Strait. The dominant component of the Balikpapan Bay waters is M2 (Lunar semidiurnal Tide).

Equation of model developed.

MOHID 2016 is used for hydrodynamic modeling and sedimentation concentration distribution. The model device used is MOHID STUDIO 2016 software (Cancino and Neves, 1999). Hydrodynamic modeling is modeled using the finite volume approach with vertical generic discretization with sigma vertical coordinate type. The model is built with the Navier-Stokes equation with the Boussinesq and hydrostatic approaches for the continuity, momentum equation 3-6.

Solution of Sediment transport can use the advection-diffusion flux equation, the form of the equation can be written (Cancino and Neves, 1999) (Eq 7-8).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{3}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=\frac{1}{\rho_0}\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\nu_H\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_H\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial u}{\partial z}\right) \tag{4}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=\frac{1}{\rho_0}\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\nu_H\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_H\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial v}{\partial z}\right) \tag{5}$$

$$\frac{\partial p}{\partial z}=-\rho.g \tag{6}$$

Where are u, v and ware velocities in direction *x*, *y*and z (m.s^{-1}); f is Coriolis parameter (rad.s^{-1}); ν_H and ν_t are coefficients turbulent viscosity horizontal and vertical (m^2.s^{-1}); pis pressure (Pa); ρ_0 is the reference density (Kg.m^{-3})

$$\frac{\partial A}{\partial t}+\frac{\partial (uA)}{\partial x}+\frac{\partial (vA)}{\partial x}+\frac{\partial\big((w+w_s)A\big)}{\partial z}=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial A}{\partial y}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial A}{\partial y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_z\frac{\partial A}{\partial z}\right) \tag{7}$$

$$\frac{\partial A}{\partial t}+\frac{\partial (uA)}{\partial x}+\frac{\partial (vA)}{\partial x}+\frac{\partial\big((w+w_s)A\big)}{\partial z}=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial A}{\partial y}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial A}{\partial y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_z\frac{\partial A}{\partial z}\right) \tag{8}$$

Where *A* is concentration of total suspended solid; *t* is time; *x, y* are horizontal coordinates, *z* is vertical coordinates; ε_x,ε_y, $\varepsilon_z$are the diffusion coefficient of the sediment mass; w_s is velocity of the falling sediment; *u, v, w* are velocity of the flow in the direction *x, y* and *z*.

Table 1. Field measurement data: river discharge, temperature, salinity, and sediment concentration

	Sepaku River	Riko River	Wain River
river discharge (m^3.s^{-1})	4000	400	75
Salinity (psu)	10	28	28
Temperature (◦C)	27	28	27
TSS (mg.L^{-1})	300	150	150

Table 2. Tidal Harmonic Components used in the model

No	Symbol	Amplitudo	Fase	Name of components
1	M2	0.540	-81.157	Principal lunar semidiurnal constituent
2	S2	0.449	-24.970	Principal solar semidiurnal constituent
3	K1	0.222	156.962	Lunar diurnal constituent
4	K2	0.135	-21.138	Lunisolar semidiurnal constituent
5	N2	0.071	-89.320	Larger lunar elliptic semidiurnal constituent
6	2N2	0.014	-97.470	Lunar elliptical semidiurnal second-order constituent
7	O1	0.162	133.363	Principal lunar diurnal
8	Q1	0.073	152.659	Larger lunar elliptic diurnal constituent
9	P1	0.038	123.115	Solar diurnal constituent
10	M4	0.000	0.000	Shallow water overtides of principal lunar constituent
11	Mf	0.013	12.193	Lunisolar fortnightly constituent
12	Mm	0.007	9.276	Lunar monthly constituent
13	Mtm	0.002	14.440	Long period termensual
14	MSqm	0.000	13.711	Long term constituent

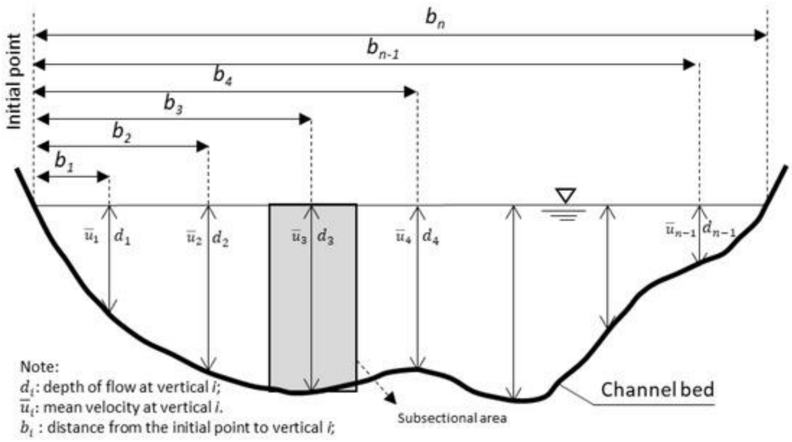

Figure 3. Mid-section method of computing cross-section area and stream discharge (Chen *et al*., 2022)

Erosion occurs when the ambient shear stress exceeds the erosion threshold. The eroded sediment flux is given by:

$$\frac{\partial M_E}{\partial t} = E\left(\frac{\tau}{\tau_E} - 1\right) \quad for\ \tau > \tau_E$$
$$\frac{\partial M_E}{\partial t} = 0 \quad for\ \tau < \tau_E \qquad (9)$$

Where τ is bottom shear stress; $\tau_E$is the critical sliding measure for erosion; E is erosion constituent (kg.m^{-2}.s^{-1}).\

Deposition is calculated as the result of the precipitation flux and the probability of the particles remaining at the bottom:

$$\frac{\partial M_D}{\partial t} = C_B(W_s)\left(1 - \frac{\tau}{\tau_D}\right) \quad for\ \tau > \tau_D$$
$$\frac{\partial M_D}{\partial t} = 0 \quad for\ \tau < \tau_D \qquad (10)$$

where$\tau_D$is a critical voltage for deposition.

Data analysis.

The current data were analyzed by performing a low pass filter to eliminate the influence of high-frequency wave ripples on the current. The filtered flow data were analyzed to separate tidal and residual flows using the Institute of Ocean Sciences (IOS) method (Foreman, 2004).

Results and Discussion

The tides of the model results are validated with the tide measurement results carried out by the Geospatial Information Agency (BIG) (Figure 4), showing that the tidal results of the model results and measurement results show a correlation of 0.99 or very good so that the model can be considered to represent environmental conditions in Balikpapan Bay. Although the amplitude result of the model result is lower than the measurement result, it has the same tidal wave phase.

Tidal current patterns

Surface current patterns during the displacement toward the low tidal conditions (ebb) and during the lowest elevation of tides. At the current pattern (Figure 5) at displacement toward the low tidal condition, it can be seen that the current leaves Balikpapan Bay with a speed reaching 0.02-0.04 m.s^{-1} in the narrowing part of the bay. The high velocity of currents leaving Balikpapan Bay apart from the tidal contribution is also by the mass of river water that comes out of the 3 river estuaries that are simulated in the model. The current pattern in Balikpapan Bay at the lowest tide condition shows that the maximum current velocity is 0.04 - 0.06 m s^{-1} leaving Balikpapan Bay. The speed increases to the maximum reflecting the narrowing flow from the direction of the Sepakuriver.

The pattern of current velocity toward the high tidal conditions (flood) (Figure 6a) shows the current movement pattern entering Balikpapan Bay from the high seas with an increase in current velocity when experiencing flow constriction in Balikpapan Bay. At low tide the current velocity ranges from 0.04 m.s^{-1}-0.06 m.s^{-1}. Meanwhile, at the highest tide, the current velocity ranges from 0.1 m.s^{-1} to 0.12 m.s^{-1}. The pattern of current velocity at the highest tide conditions (Figure 6b) shows that the inflow into the bay area with this small current velocity is caused by the contribution of the current from the river because the tidal current is in a stable condition from the movement of the water mass entering the bay which is then right when it will leave the bay following current patterns during the displacement toward the low tidal conditions.Stable condition is a condition where the tide reaches its highest point so that the current will shift from entering the bay to the outflow from the bay. From low tide towards high tide, the mass of water enters the waters of Balikpapan Bay which is narrower, and the water conditions are shallower so that the speed increases. On the other

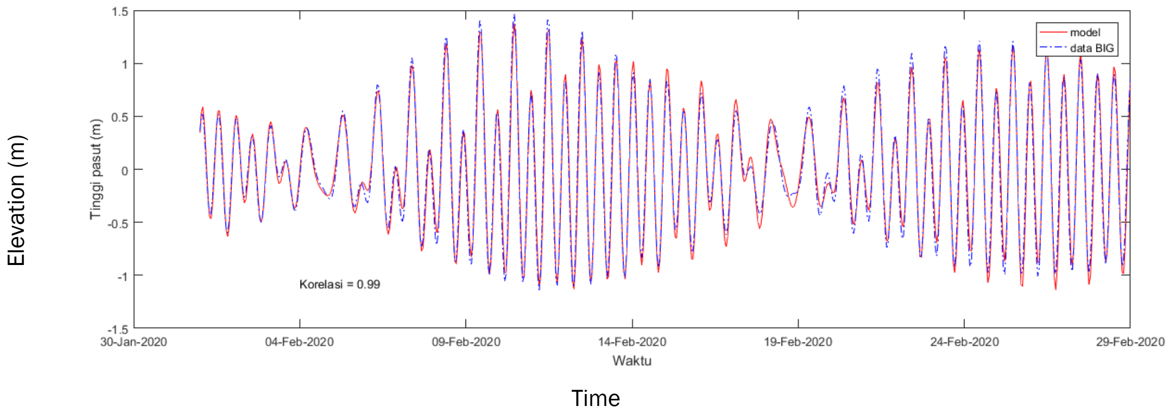

Figure 4. Tidal validation of model results and measurement results

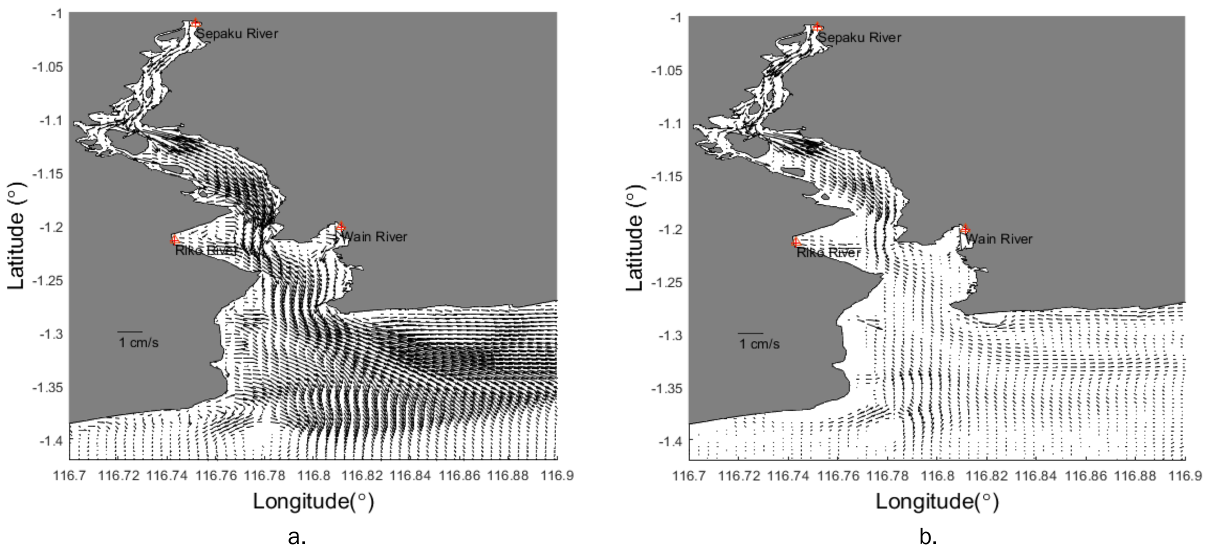

Figure 5. Surface current patterns during the displacement toward the low tidal conditions (ebb) (a) and during the lowest elevation of tides (b)

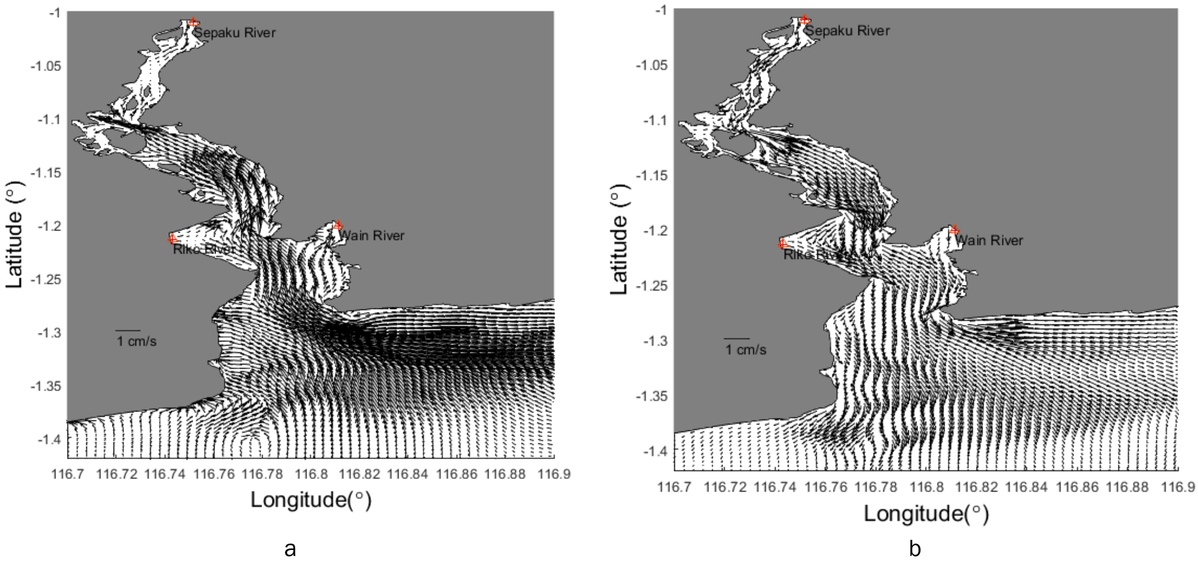

Figure 6. Tidal current patterns during the displacement toward the high tidal conditions (flood) (a) and during the highest elevation of tides (b)

hand, the mass of water at low tide leaves the bay towards the open sea, so the current speed is not as strong as when it comes to high tide.

Distribution of Total Suspended Solid (TSS)

The model was simulated for 29 days in February 2020. The model was run for 29 days due to the condition of the bay-shaped waters. The main driving factor was tides, with the simulation for 29 days having passed the tidal cycle twice, and the distribution of TSS no longer experienced any additional area after 29 days. TSS distribution was sampled at 5, 10, 20, and 29 days. The difference in simulation time is displayed because, at the beginning of the simulation, the change in the distribution area took place quickly. After all, it was still in a narrow river body, while when it entered open water, the difference in the exposed site was not significant, so the time of the image samples was extended. From the simulation model results, the data output results in the form of sediment concentration at the Balikpapan Bay location. During the 30-day simulation, the distribution of sediment concentrations was seen from the upstream of the Sepaku and Riko rivers to the center of Balikpapan Bay. On the fifth day, the TSS concentration in Balikpapan Bay had spread above 50 mg.L^{-1} which increased along with the direction of the flow towards the mouth of the Sepaku River with a TSS concentration of 300 mg.L^{-1} at the mouth of the Sepaku River. The maximum value of sediment concentration in the upper reaches of the Sepaku river during neap tide conditions is 300 mg.L^{-1}, while the minimum value is offshore, which is only 2 mg.L^{-1}. During spring tide conditions, the maximum value is still upstream of the Sepakuriver, which is 300 mg.L^{-1}, while the minimum value is located offshore which is only 2 mg.L^{-1}.

The value of sediment concentration is strongly influenced by the amount of salinity at the study site, where the upstream of the Sepakuriver has the lowest salinity value, which is only 0.1 ppt, while the highest salinity value is offshore 32 ppt.The concentration and range of TSS distribution in the sea is influenced by the size of a river discharge, the concentration of TSS from the river, diffusion coefficient, and ocean currents will move the water mass and TSS when the TSS transport reaches the sea. The source of sedimentation comes from river discharge which has low salinity, so that in the upstream of the river with low salinity, the sediment concentration is high, but after entering a high-salinity water body the sediment has spread towards the sea so that the sediment concentration has decreased. Modeling with river water input is a mass of water with low salinity so that the higher the runoff of river water carrying sediment will cause large amounts of low salinity to enter such waters with a sediment concentration because the mass of river water is the scenario as a sediment carrier, the concentration of TSS also increases with increase in river discharge (Liu *et al*., 2022).

At the neap tide (0-5 day), TSS concentrations are still accumulating in the bay area and have not yet reached the bay mouth due to their low dispersion (Figure 7a). At this time the tide and the low tide reach a minimum height compared to other days or it is usually called the low tide and low tide. The value of TSS concentration spreads only around the observation point of the Sepaku River area, which ranges from 200 - 250 mg.L^{-1}, and the mouths of the Riko and Wain Rivers, which range from 100-150 mg.L^{-1}. The distribution pattern of the TSS spreads upstream of the Sepaku and Wain Rivers following the current pattern that occurs at high neap tides with tidal currents reaching 0.04 m s^{-1} - 0.06 m s^{-1}, while at low tide the bandages move to the direction of the sea (Balikpapan Bay) with a current speed of about 0.02 m.s^{-1} - 0.04 m.s^{-1}.

During the spring tide (5-10 day), the TSS concentration has reached a wider area to reach the outer area of Balikpapan Bay (Figure 7b), this is because the high tidal energy of the strong spring tide increases the TSS distribution in the waters of Balikpapan Bay. At this time the high tide and low tide are very high compared to other days or it is usually called the big tide and ebb. The distribution of TSS concentrations has reached the mouth of the Balikpapan Bay in the range of 50-100 mg.L^{-1}. It can also be seen that the distribution of TSS concentrations in the Sepaku River is spreading towards the mouth of Balikpapan Bay. This is due to the movement of water masses entering these rivers (tidal currents) reaching 0.1 m.s^{-1} - 0.12 m.s^{-1}. At low tide (spring), the distribution of TSSs moves towards the sea (Balikpapan Bay), with current speeds reaching 0.04 m.s^{-1} - 0.06 m.s^{-1}. On days 20 and 29, there was a combination of spring tide and neap tide

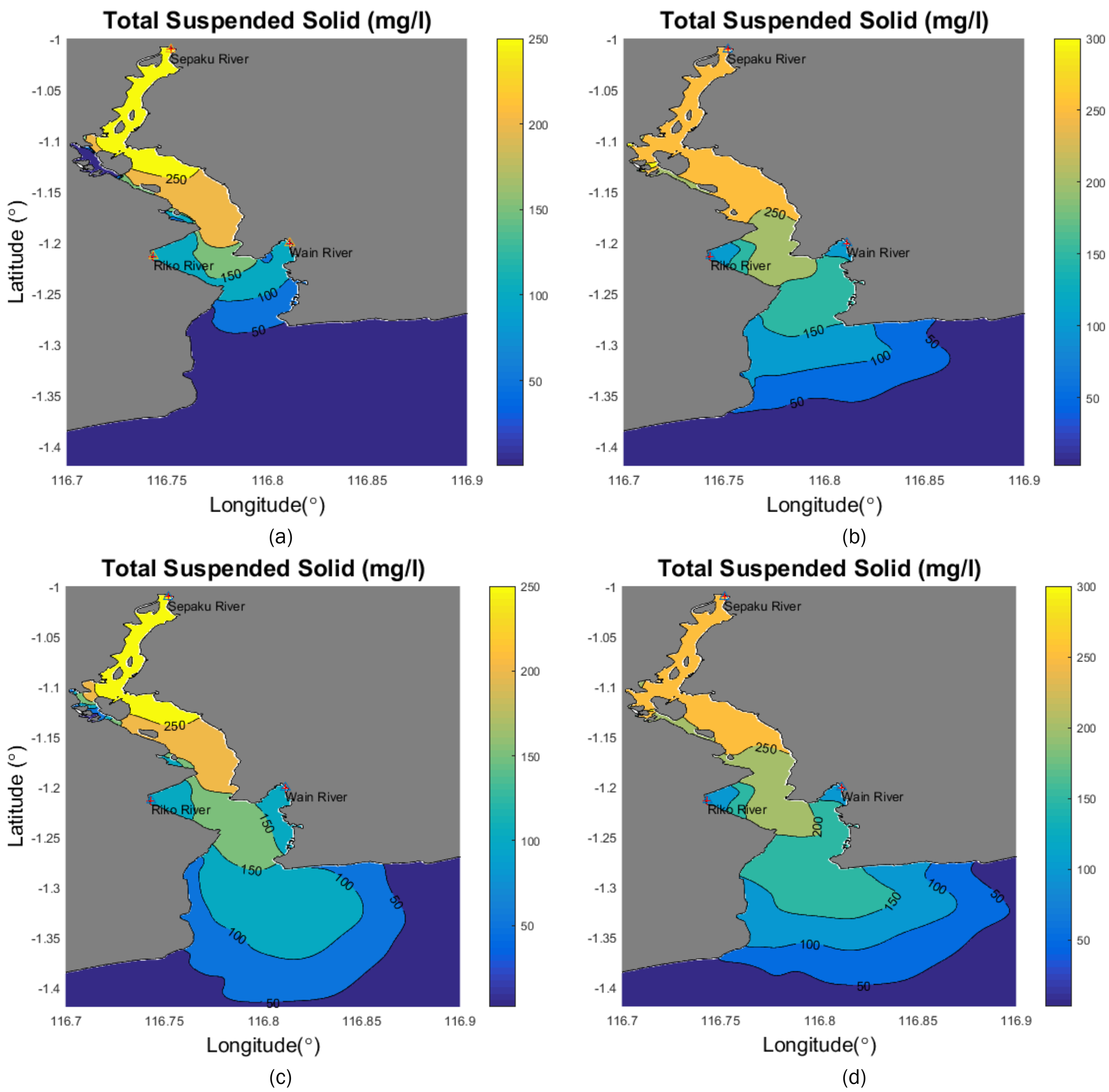

Figure 7. Distribution of TSS at day-5 (a), at day -10 (b), at day -20 (c), and at day-29 (d)

where the TSS concentration continuously spread out to the saturation point.

The highest sediment concentration is in the upstream area of the Sepaku river (near mouth of the Sepaku River), this is due to the high sediment carried by the river which is the source of sediment in the model, the sediment concentration is based on the results of measurements at that location. River discharge is more dominant in the estuary area of the Sepaku River because the value of the river discharge is greater than the tidal current, when there is a tide in the Spring Tide condition, the current movement cannot reach the mouth of the Sepaku River because it is blocked by river discharge, resulting in a buildup of sediment in the area near mouth of the Sepaku River.

Abrasion

The interaction between TSS and current velocity will result in erosion and sedimentation rates; if the TSS concentration is high and the current velocity decreases, it will increase the sedimentation rate; on the other hand, if the TSS concentration is low and the current velocity increases it will cause

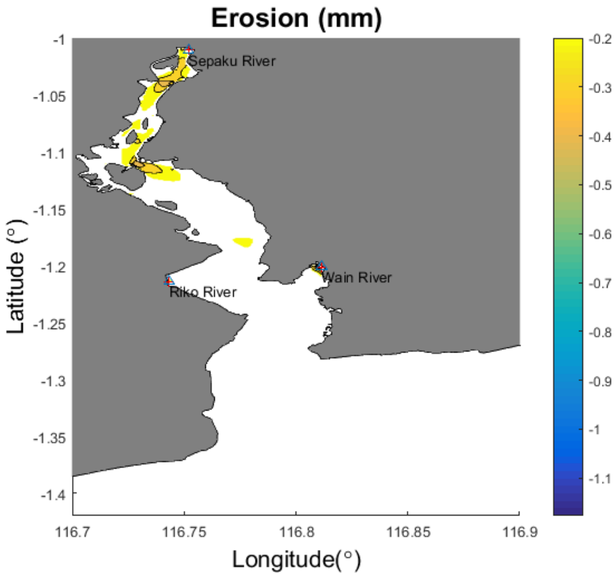

Figure 8. Erosion rate during the simulation period

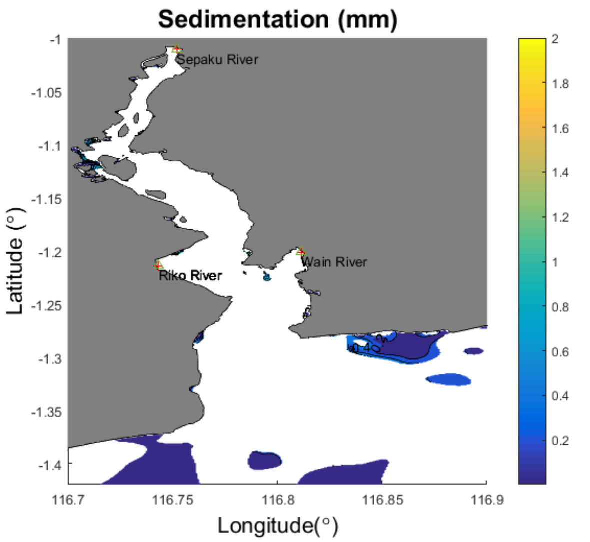

Figure 9. Sedimentation rate during the simulation period

high erosion rates. The rate of bottom erosion by currents is described as erosion, as shown in Figure 8.

The simulated Balikpapan Bay erosion ranging from 0.2 to 1.1 mm with peak erosion in narrow gaps underscores a morphodynamic regime in which locally intensified currents, turbulence, and shear stress drive selective sediment removal and bedform adjustment, with narrow channels acting as focused erosion hot spots that can propagate shoreline retreat and alter bay-wide circulation over time. This finding aligns with broader hydrodynamic–sediment dynamics literature, which shows that increases in current velocity and associated turbulence amplify bed shear stress and enable preferential scour in constricted sub-basins, thereby accelerating erosion when wave–current interactions elevate near-bed stresses (e.g., M2-dominated tides and spring-neap cycles) (Fauzah *et al*., 2021). The results reinforce the precaution that even modest average erosion rates can translate into pronounced morphological change where geometry concentrates flow, consistent with studies demonstrating strong sensitivity of sediment transport and bed level evolution to tidal and wind-forced circulation patterns in Balikpapan Bay and similar microtidal embayments (Fauzah *et al*., 2021; Hermansyah *et al*., 2020). Practically, this implies that port and harbor protection plans for Balikpapan should prioritize monitoring and management of narrow-channel morphologies, implement sediment budgets that account for turbulence-enhanced scour during spring tides, and consider adaptive dredging or channel relinking strategies to prevent feedbacks that worsen scour and sedimentation imbalances as currents intensify under changing climatic and anthropogenic forcing (Fauzah *et al*., 2021; Finotello *et al*., 2023; Wen *et al*., 2022). Notably, the literature indicates potential regime shifts in tidal flats and shallow bays when wave-dominated processes interact with evolving sediment supply, suggesting the Balikpapan case could foreshadow broader morphodynamic transitions if current patterns persist or intensify (Finotello *et al*., 2023; Zhu *et al*., 2025). In sum, the Balikpapan Bay case highlights the critical need for integrated, high-resolution hydrodynamic–morphodynamic modeling and targeted coastal engineering interventions to manage erosion hot spots, sustain sediment budgets, and preserve port stability in a dynamic, turbulence-driven coastal system (Fauzah *et al*., 2021; Finotello *et al*., 2023; Hermansyah *et al*., 2020; Pelawi *et al*., 2021).

Sedimentation

The sedimentation rate describes silting up the waters due to the addition of material to the bottom of the waters. The sedimentation process impacts changes in the geometry of the waters and can have a destructive impact on shipping lanes. The sedimentation rate in the model domain mostly occurs in areas outside Balikpapan Bay (Figure 9).

This sedimentation is formed by the flow of sediment from rivers entering the ocean, which then weakens the current energy so that the TSS experience sedimentation at the bottom of the waters. The Balikpapan Bay sedimentation pattern described—driven by riverine sediment discharge that attenuates local current energy and promotes bottom sedimentation, with the northern, more protected sectors acting as sediment-trapping zones where flow decelerates—fits within a broader, globally observed context in which riverine plumes and local hydrodynamics control suspended-sediment dynamics and turbidity maxima in estuarine-coastal systems, thereby shaping salinity structure, light climate, and habitat suitability (e.g., mangroves, seagrasses, and fisheries) in both the nearshore and port areas.

Numerical and observational studies across twenty-first-century cases consistently show that estuarine turbidity maxima (ETMs) and bottom sedimentation arise where river discharge interacts with tidal and residual currents, leading to attenuated velocity, enhanced residence time, and accumulation of suspended sediments that can persist for days to weeks under seasonal forcing. The reported sedimentation rate of 0.2–2 mm during the simulation period aligns with observed ranges in other estuarine systems where episodic high-discharge events or seasonally driven changes in river–ocean coupling yield measurable bed-level changes and shifts in turbidity structure, with implications for channel morphology, dredging needs, and water-quality management in Balikpapan Bay's northern, more sheltered sub-regions. Moreover, the spatial pattern of sediment deposition in protected bay sectors parallels findings from similar microtidal to mesotidal settings where low-energy zones act as sinks for fine sediments, influencing nutrient cycling, light attenuation, and ecosystem productivity within and adjacent to Balikpapan Bay (Seo *et al*., 2024; Wu *et al*., 2024). Where nuancing exists, some studies emphasize that lateral exchange with the open sea or coastal seiches can modulate ETM strength and sediment residence times, potentially altering deposition patterns compared with purely river-dominated scenarios, a nuance relevant for Balikpapan Bay given its semi-enclosed geometry and branching flows (Noya and Manuputty, 2023; Seo *et al*., 2024). In sum, the Balikpapan Bay case demonstrates how river-derived sediment inputs, when coupled with local hydrodynamics, can produce bottom sedimentation in protected zones, a process that bears broad implications for sediment budgets, navigation, port operations, and coastal ecosystem health in tropical estuarine systems (Xiao *et al*., 2023).

Morphology Changes in Balikpapan Bay

The morphology changes of Balikpapan Bay is a combination of erosion and sedimentation processes in Balikpapan Bay with negative values indicating erosion and sedimentation showing positive values (Figure 10). For 30 days, there was a deposition of 4 mm along the Sepaku River and 3 mm along the Riko River. Meanwhile, erosion is still off the east coast, which is 68 mm, with a bottom shear stress value of 16 *dyne cm*$^{-2}$. In areas close to the port, namely the Wain River, experiencing silting around 0.03 to exceed 0.1 m.yr^{-1}, besides that some areas close to the river also experience high silting, which is more than 0.1 m.yr-1 with silting the maximum is 0.53 m.yr-1 and the average siltation is 0.0048 m.yr-1. Apart from silting, several areas of the river are experiencing deepening, namely the areas close to the estuary of the Wainriver, the Jenebora area, and parts of the Kemala beach area. Changes in depth in the waters are caused by deposition and erosion processes that occur in these waters.

The high rate of sedimentation in the waters is caused by the low velocity of the current, so that the TSS tends to start settling towards the bottom of the water (An *et al*., 2025; Haun *et al*., 2025; Markova and Khanh, 2023; Zheng *et al*., 2024). The sedimentation rate in Balikpapan Bay has a high value in areas close to river estuaries as well as areas

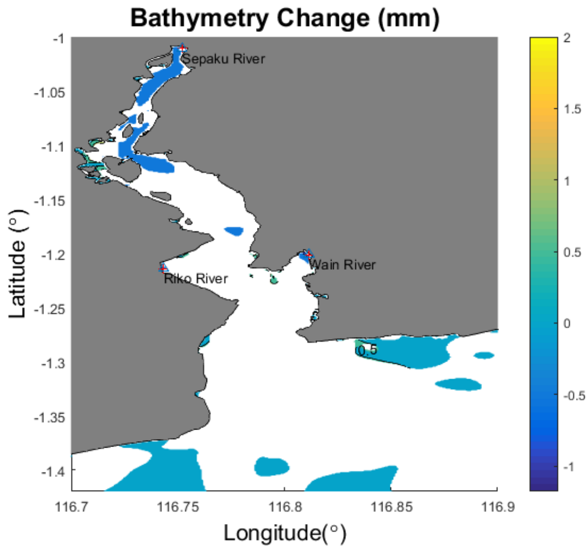

Figure 10. The morphology changes of Balikpapan Bayduring the simulation period

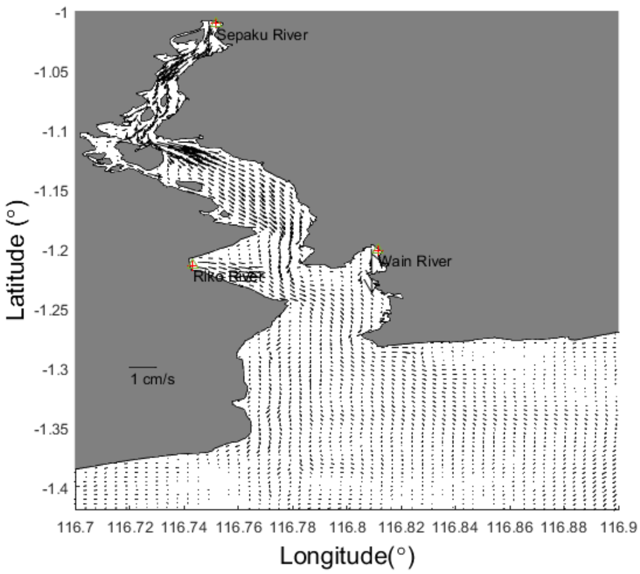

Figure 11. Residual current velocity in the Balikpapan Bay

with high TSS concentrations in the bottom layer of waters such as canals in the western part of the bay and waters that have canals which are the passage of ship traffic. In areas that have high TSS concentrations near the water bed, will have a high sedimentation rate (Eckland *et al*., 2025; Sauter *et al*., 2025).

Compared to other areas that have geographic conditions, similar anthropogenic activity and high sediment input from rivers such as Jakarta Bay which reaches 3.9071 kg.m^{-2}.day^{-1} (Aprilia and Pratomo, 2018) and Saint John Harbor in Canada which reaches 0, 9667 kg.m^{-2}.day^{-1} (Leys and Mulligan, 2011), the sedimentation rate in Balikpapan Bay is relatively low. In other areas that have similar geographic conditions but lower anthropogenic activity and sediment input from rivers, they have lower sedimentation rates than rivers such as the Wedung River which reaches 0.031 kg.m^{-2}.day^{-1} (Erfiko *et al*., 2023) and Pemangkat waters that reach 0.11 kg.m^{-2}.day^{-1} (Maharta *et al*., 2018). Based on the comparison of the sedimentation rate in several areas to environmental conditions, it shows that the sediment input from the river and anthropogenic activity greatly affects the rate of sedimentation that occurs in these waters.

Residual current velocity

Residual current is one type of current that plays a vital role in the movement of materials in water, including moving TSS in the waters. In general, the residual flow in Balikpapan Bay moves outward (Figure 11), leaving the residue eddy bay forming at the mouth of the bay which has the potential to trap material or pollutants. The observed residual circulation in Balikpapan Bay, characterized by a net outward surface flow with an accompanying residual onshore/ bottom-directed component that forms a residue eddy at the bay mouth, has important implications for material transport, sediment dynamics, and pollutant fate in anthropogenically impacted tropical estuaries. Contemporary studies reaffirm that residual or gravitational circulation sets the backbone of estuarine exchange, governing the net flux of water, heat, salts, sediments, and biotic propagules between riverine/estuarine zones and nearshore seas, with tidal and wind forcing modulating the strength and structure of this exchange (Kranenburg *et al*., 2023). In systems with river-dominated or stratified conditions, residual currents can entrain and trap contaminants or particulates in the estuarine/near-mouth region, potentially forming retention zones or localized eddies that concentrate pollutants or silt, while at other times promoting outward flushing that transports material seaward, depending on seasonal river discharge, stratification, and tidal phase (Hoguane *et al*., 2021).

The empirical description of a bay-mouth residue eddy in Balikpapan aligns with observed two-layer residual circulation patterns in tropical estuaries where surface outflow coexists with bottom-ward or landward flow, generating complex cross-sectional exchange and potential trapping at the margins or at the inlet throat (Li *et al*., 2024). Moreover, the presence of such a residence zone has direct management relevance for sedimentation, nutrient cycling, and pollutant risk assessment in Balikpapan Bay, especially given rapid coastal development, oil-related activities, and episodic contamination events; understanding the residual-driven transport and eddy formation informs forecasting of sediment transport, contaminant plumes, and larval dispersal, and supports targeted mitigation and monitoring strategies in similar estuarine systems under climate-driven changes in discharge and sea level (Hoguane *et al*., 2021; Kim and Suh, 2021; Kranenburg *et al*., 2023; Sande *et al*., 2021). Notably, while the residual pattern described here is coherent with the classical estuarine circulation framework, some references emphasize that the relative importance of gravitational residuals versus wind- or tide-driven variability can shift with seasonal forcing and basin geometry, suggesting the need for site-specific, time-resolved modeling to capture potential reversals or amplification of the eddy at the bay mouth under different hydrodynamic regimes (Kranenburg *et al*., 2023; Li *et al*., 2024).

Conclusions

Based on the research results, the results of sediment movement are influenced by tidal currents and river discharge currents. The sediment distribution pattern at high tide (spingand neap tide) moves upstream of the river while at low tide it moves towards the sea, namely the waters of Balikpapan Bay. The concentration of TSS during the tide and tide of the full moon spreads to reach the mouth of the Balikpapan Bay, which ranges from 50-100 mg..L^{-1}. With tidal flow velocity 0.1 m.s^{-1} - 0.12 m.s^{-1}. Meanwhile, during the tidal conditions, the TSS concentration was still accumulating in the bay area and had not yet reached the mouth of the bay due to its low distribution, the TSS concentration values spread only around the observation points of the Sepaku River area ranging from 200-250 mg.L^{-1} and the mouth of the Riko River Sungai Wain which ranges from 100-150 mg.L^{-1}, the tidal flow velocity is 0.02 m.s^{-1} - 0.04 m.s^{-1}. Sedimentation occurs upstream of the Sepaku river; this location is correlated with high TSS levels and weak current velocities, where the maximum value in one month is 4 mm. Meanwhile, the Rico River has a deposit of 4 mm. Erosion occurred in Balikpapan Bay, namely the Jenebora area, parts of the Kariangau area, and the eastern part of the bay, especially on the Kemala coast of Balikpapan; high current velocity played a dominant role in the erosion process in the area with a maximum value of 72 mm.

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