The current flow pattern and sedimentation rate in the Malili River Estuary, South Sulawesi, Indonesia

Mustono, Mahatma Lanuru, Amir Hamzah Muhiddin

Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar 90425, Indonesia. Corresponding author: M. Lanuru, mahatma.lanuru@unhas.ac.id

Abstract. Field work, and modeling study was conducted in the Malili River Estuary to understand the river estuary's current flow pattern and sedimentation rate. The field work was conducted at Malili River Estuary on 28 – 29 November 2021 and 20 – 25 July 2022. Water flow measurements were conducted downstream at the dredged area boundary (S4) for 17 hours using a Marotte HS current meter. The water flow pattern in the wider area was modeled using a 2D hydrodynamic model using the finite element method. Bathymetry measurements were carried out on 20 - 21 July 2022 using a GPS Mapsounder. The depth obtained in the field, after correcting against the mean sea level, was plotted into a digital map based on GPS position to create a depth contour map. Sediment traps made of PVC pipe with a diameter of 2.5 inches (6.35 cm) and a height of 30 cm were deployed at five sampling points to measure the sedimentation rate. The water flow measurement results show that the current's speed and direction varied with time in the 0.028 – 0.578 m/s in November 2021 and varied from 0.20 to 1.20 m/s in July 2022. The field measurements and the hydrodynamic model show that the current velocity at the Malili River estuary is higher at low tide than at high tide, especially in the confluence area of the Malili River with the Usu River. However, the vector direction remains seaward. The highest sedimentation rate occurred in the upstream area of the Malili River (S1), and the lowest sedimentation rate was found in the Ussu River (S2). These results indicate that the most extensive sediment transport came from the upstream area of the Malili River, and the smallest came from the Ussu River.
Key Words: modeling, sediment, tidal.

Introduction. Estuarine regions are heavily populated and well-developed areas. Rapid population growth and urbanization in these regions will continue and will significantly affect the environment and water quality. River water flow carries sediment and deposits as it enters estuaries, while saltwater intrusion into the river mouth will affect river and estuary ecology and environments. A better understanding of the hydrodynamics of estuaries is therefore essential in order to accurately monitor the environment (erosion, sediment transport, and sedimentation) and water quality in these regions (Dunn et al 2015; Guo 2022). The hydrodynamics and sediment dynamics of estuaries are affected by many factors, are very complicated, and require a unique approach combining theoretical analysis, field work and modeling studies.

The river estuary of Malili is one of the estuarine waters that flows directly into the sea waters of Bone Bay, Luwu Timur Regency, South Sulawesi, Indonesia (Lanuru & Yusuf 2018). The river estuary plays a vital role in the lives of the river and coastal communities in the East Luwu Regency (South Sulawesi) since the river estuary connects the river to the sea and serves as a transportation route. In addition, fishermen have long used the river estuary of Malili as a fishing ground.

The interaction between water flow from the river and tidal currents from the sea affects the hydrodynamic and sediment transport processes at the river estuary of Malili, just like in other river estuaries (Rifardi et al 2021; Antariksa et al 2020; Wibowo et al 2020; Oktaviani et al 2017; Kim et al 2006). Sedimentation in the river estuary is relatively high and large enough to cause siltation (Lanuru & Yusuf 2018). As a result, the ship's channel is sometimes blocked so that port managers carry out dredging in part of the estuary.

The accumulation of solid material in the river estuary can pollute the quality of the river and estuarine water and threaten the life of aquatic animals, plants, and humans. In addition, siltation can disrupt and can cause shipping lanes to be vulnerable and disrupt fishermen's fishing grounds. Finally, siltation in the riverbed and on the river's banks reduces the river's capacity, and hence water overflow (flood) will occur if the river can no longer hold water.

Therefore, it is necessary to study water flow (hydrodynamic) and sediment transport by analyzing the distribution of flow patterns and sedimentation rate in the Malili River Estuary to prevent siltation induced by natural processes or human interventions like dredging activities in the river estuary. This paper aims to report the study of the dynamics of the riverine and tidal flows and sedimentation rate in the Malili Rivers Estuary. A better understanding of the river estuary hydrodynamics and sediment dynamics will undoubtedly help solve siltation problems in the river estuary.

Material and Method

Description of the study sites. This study was conducted at Malili River Estuary, South Sulawesi, Indonesia. This river estuary is one of the estuarine waters that flow directly into the sea waters of Bone Bay. The river estuary's waterways are between 0.5 and 17 meters deep. The tide at the study site is mixed tide prevailing semidiurnal with a tidal range of 2.35 m. Silt to medium sand was the most common bed sediment at the river estuary. However, the bed sediment distribution reveals that the deposit tends to be finer from inland (upstream) to the river mouth (Lanuru & Yusuf 2018).

Field work. The field work was conducted at Malili River Estuary on 28 – 29 November 2021 and 21-25 July 2022 (Figure 1). Water flow measurements to determine the current speed and direction were carried out downstream at the dredged area boundary (S4) for 17 hours on 28 – 29 November 2021 using a Marotte HS current meter. Additional current flow measurement was conducted at the Ussu River (S2) in July 2022. The flow pattern in the wider area was modeled using a 2D hydrodynamic model using the finite element method.

Bathymetry measurements were carried out on 20 - 21 July 2022, using a GPS Mapsounder. The depth obtained in the field, after correcting against mean sea level (MSL), is plotted into a digital map based on GPS position to create a depth contour map. A sediment trap made of PVC pipe with a diameter of 2.5 inches (6.35 cm) and a height of 30 cm were deployed at five sampling points (S1, S2, S3, S4, and S5) for seven hours to measure the sedimentation rate. The sedimentation rate was calculated using the following formula and expressed in g/m^2/day units:

$$\mathbf{LS} = \frac{\mathbf{BS}}{\mathbf{Number\ of\ days\ x}\ \boldsymbol{\pi r^2}}$$

Where LS is the sedimentation rate (g/cm^2/day), BS is the dry weight of sediment (g), π is a constant (3.14), and r is the radius of the sediment trap circle (3.175 cm).

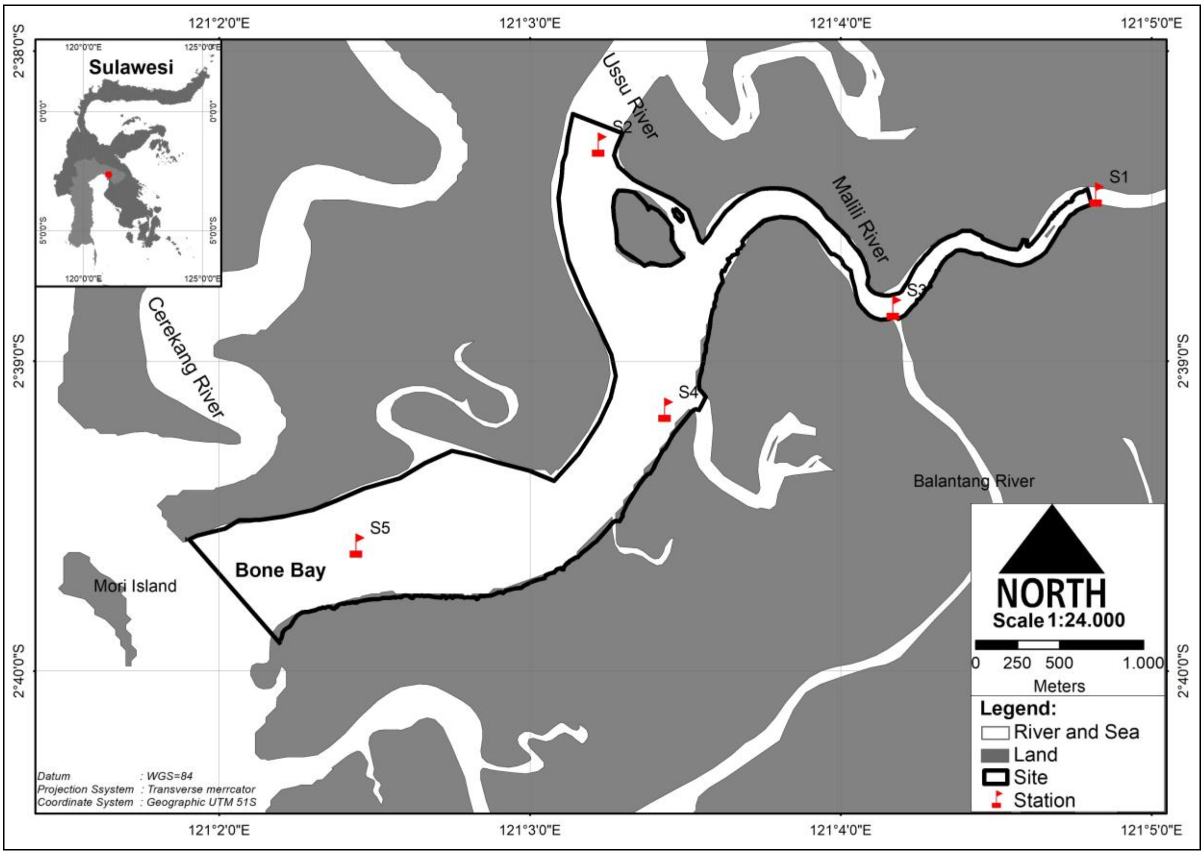

Figure 1. Map of the study site and sampling points at the Malili River Estuary (map generated using QGIS 3.30 's-Hertogenbosch).

Modeling of current flow pattern. The flow pattern (hydrodynamic) modeling was carried out using a flow model (FM) module of the MIKE 21 student version software. The flow model (FM) of MIKE 21 is a two-dimensional depth-averaged finite element hydrodynamic numerical model (DHI 2017). The model of the flow pattern is simulated by entering the bathymetry data, shoreline data, tide data, and river water discharge at the study location, i.e., 631 m^3/s for Malili River and 318 m^3/s for Ussu River. The developed 2-D depth-averaged finite element hydrodynamic model was verified using measured field data by calculating the RMS (Root Mean Square Error) value using the following formula (Ismanto et al 2017):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_m - x_e)^2}{n}}$$

Where RMSE is root mean square error value, x_m is field measured data; x_e is model data and n is the number of data.

Results

Bathymetry. Riverbed depths vary from less than 1 m to 12 m (Figure 2). For example, the water depth in the sampling point of S1 (upstream Malili River) was 1 to 5 m, while the water depth in the downstream area (Sampling point S5) varied from 3 to 6 m. Ussu River (sampling point S2) was slightly deeper than Malili River, with water depth varying from 1 to 10 m.

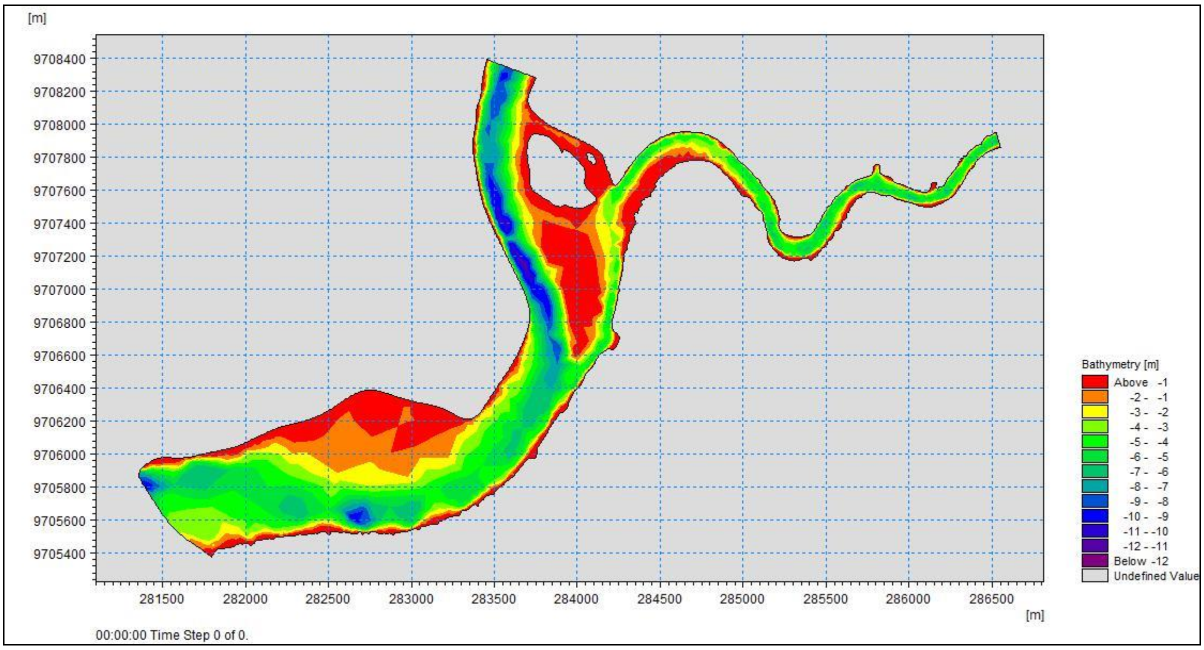

Figure 2. Bathymetry of the study site (figure generated using MIKE 21).

Measured flow speed and direction. The flow speed varies with time, fluctuating between 0.028 – 0.578 m/s in November 2021 at the dredged area of Malili River (S4). Two dominant flow patterns are observed in the study site, namely south and southwest flow directions. When the water is receding (low tide), the highest flow speed reaches 0.578 m/s in November 2021, with the dominant current direction to the southwest due to the influence of river discharge flowing towards the river estuary downstream (Figure 3 and Figure 4). Meanwhile, when the water reaches high tide, the highest speed reaches 0.238 m/s with the dominant current direction to the northeast.

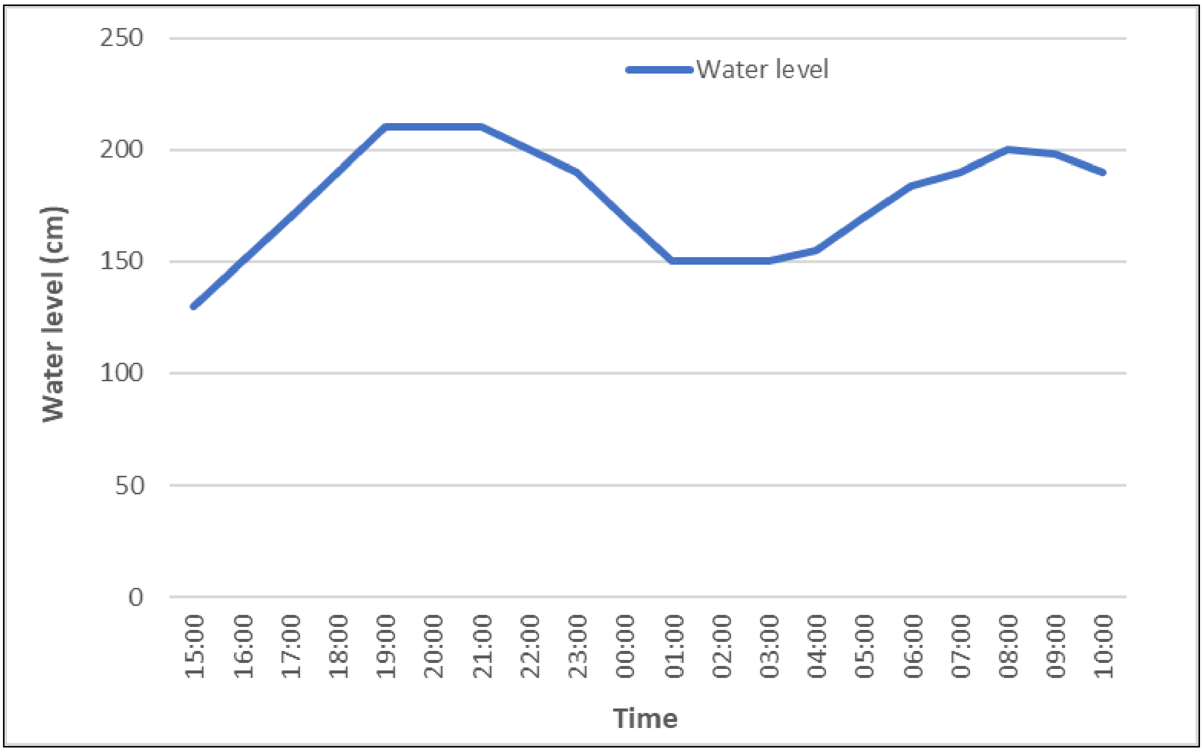

Figure 3. Water level fluctuation at the study site on 28 – 29 November 2021.

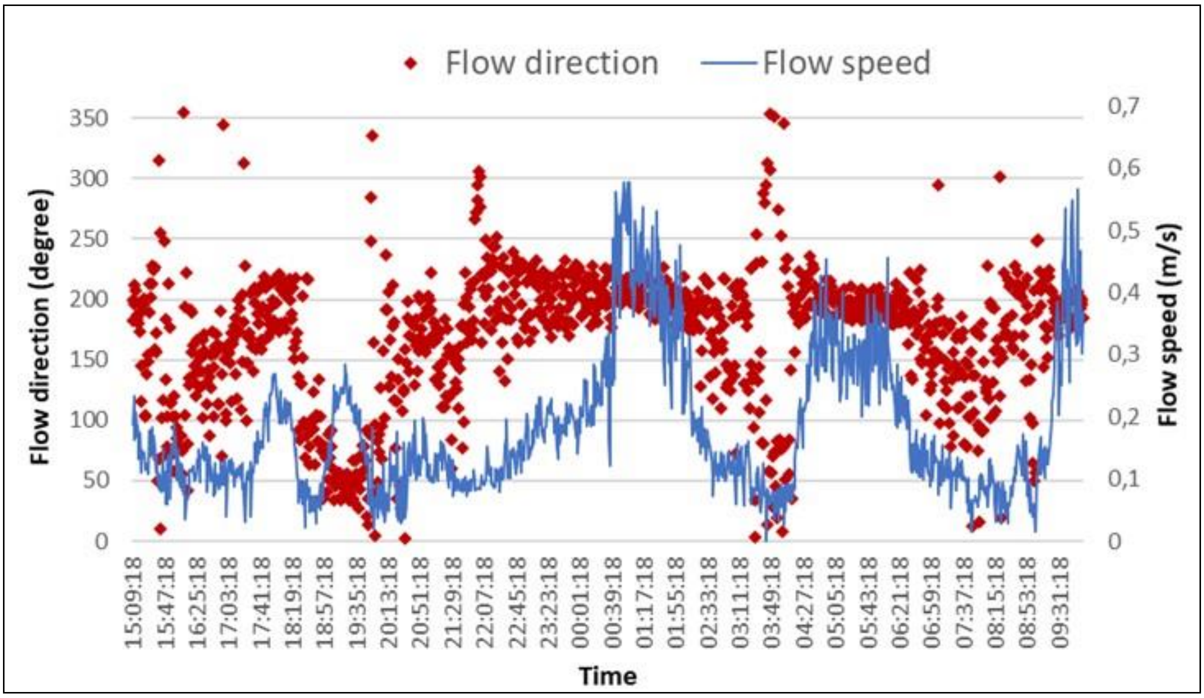

Figure 4. Flow speed and direction at the sampling point S4 on 28 – 29 November 2021.

In a similar condition to November 2021, the flow velocity also varies with time in July 2022, which fluctuates from 0.20 to 1.20 m/s with the dominant flow direction to the southwest at the sampling point S1. Lower current velocities were observed in the Ussu River (S2), where the velocity varied from 0.02 to 0.30 m/s (Figure 5).

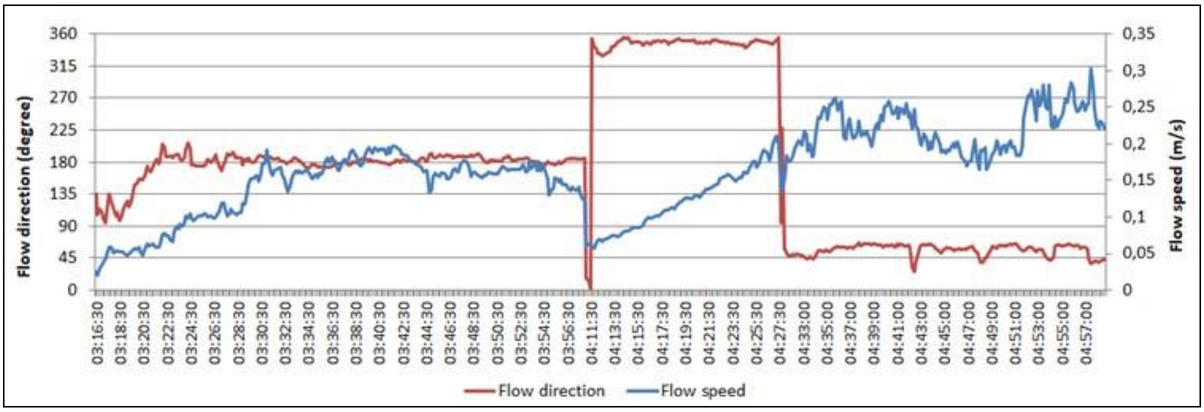

Figure 5. Flow speed and direction at the sampling point S2 (Ussu River) on July 2022.

Water flow model. The model of flow pattern during high tide, shift high tide to low tide, low tide, and shift low tide to high tide at the study site is presented in Figure 6. The model results show that the upper part of the Malili River (sampling point S1) location has the highest current velocity in each tidal condition. The velocity ranges from 1.80 – 1.95 m/s and moves predominantly from the northeast. On the other hand, the current velocity at the mouth of the Ussu River (sampling point S2) is relatively low (±0.15 m/s) both during high and low tide conditions, which predominantly move southward. The model results are relatively the same as current measurements in the field, where the results of field measurements show large current velocities in the upper reaches of the Malili River (S1) and small current velocities at the mouth of the Ussu River.

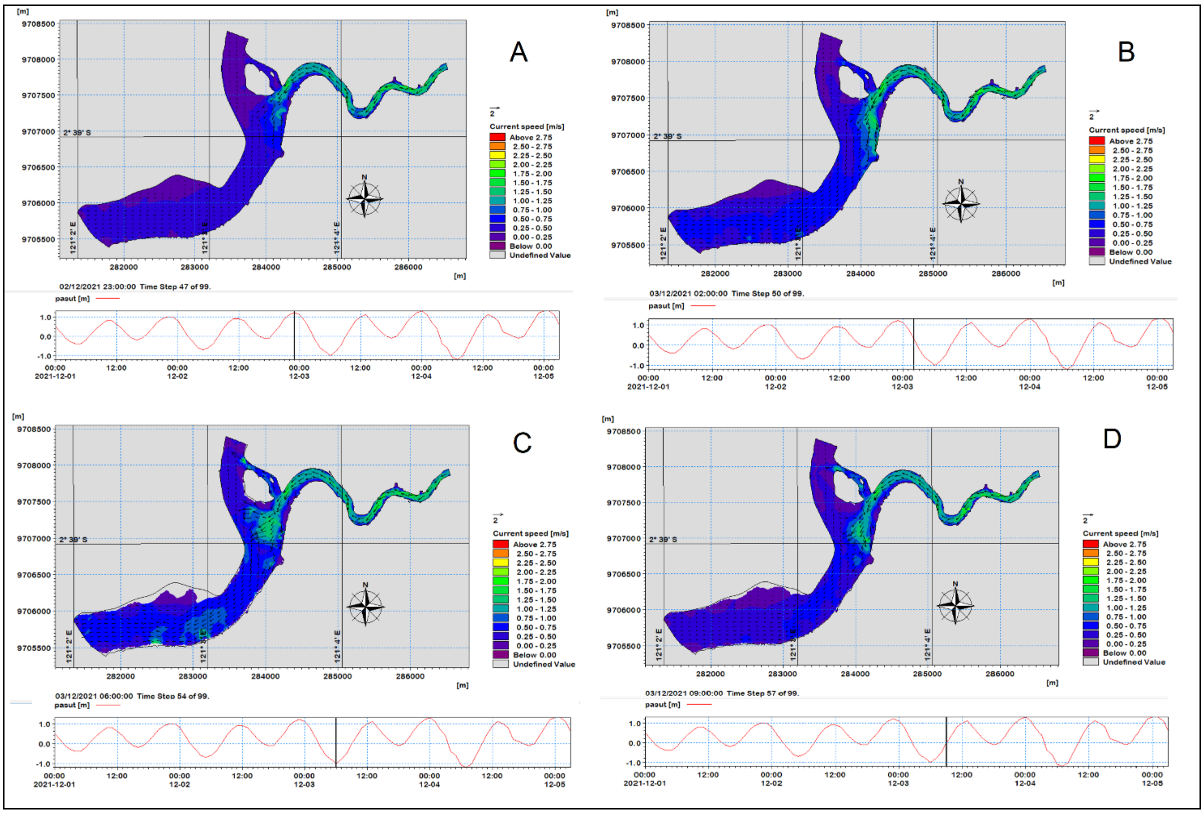

Figure 6. The model of flow pattern during high tide (A), high tide to low tide (B), low tide (C), and low tide to high tide (D) at the study site (figure generated using MIKE 21).

Sedimentation rate. The sedimentation rate at the five sampling points (S1, S2, S3, S4, and S5) are presented in Figure 7. The study site's sedimentation rate varied from 4.96 to 37.52 g/cm^2/day. The highest sedimentation rate occurred in the upstream area of the Malili River, namely the sampling point of S1, and the lowest sedimentation rate was found in the Ussu River (S2). These results indicate that the most extensive sediment transport came from the upstream area of the Malili River, and the smallest came from the Ussu River.

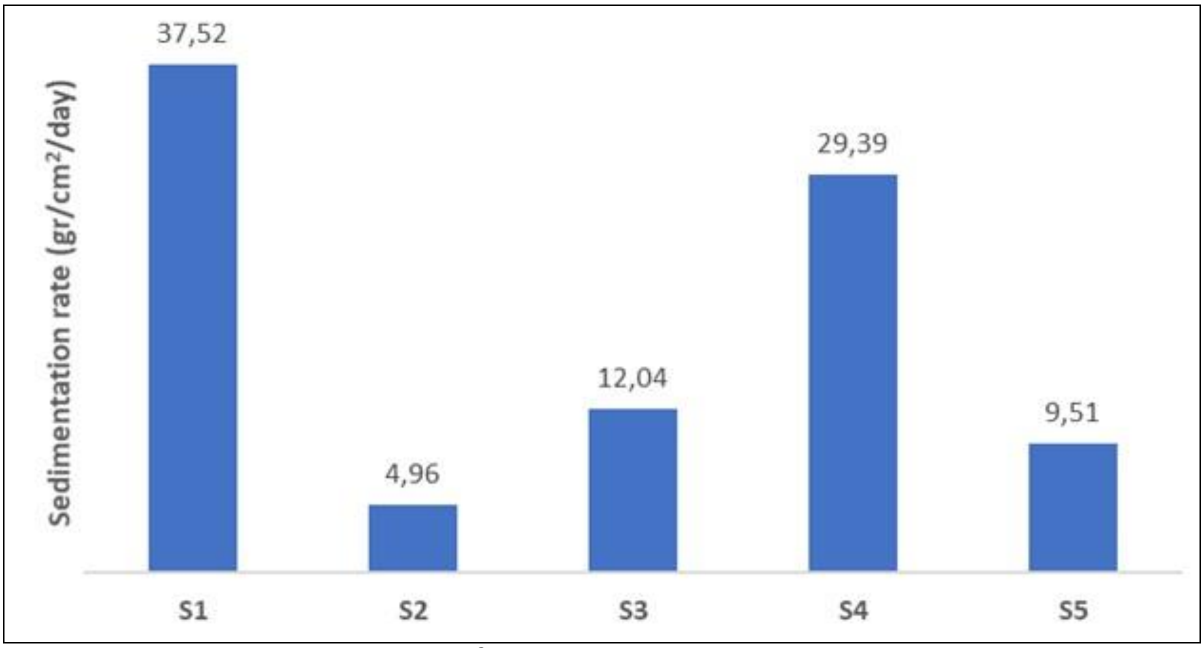

Figure 7. Sedimentation rate (gr/m^2/day) at five sampling points (S1, S2, S3, S4, and S5).

Discussion. It is observed in this study that the effect of river discharge dominates the downstream direction current flow in the Malili River channel. However, at the downstream area of the river estuary close to the river mouth, the current flow is influenced by tides, and the river discharge becomes less dominant. Setyani (2020), who studied sediment transport in the Estuary of Weriagar River, Bintuni Bay (West Papua), reported a similar phenomenon. Setyani (2020) found that the current in the river channel always flows downstream to the estuary. However, the current flows depend more on the tidal condition (flooding or ebbing) outside the river channel or at the estuary.

The hydrodynamic model results for high tide scenarios (Figure 6A) and low tide (Figure 6C) show differences in current velocity at high and low tide, especially in the confluence area of the Malili River and the Ussu River. At high tide, the current speed is slower than at low tide in the confluence area of the Malili and Ussu Rivers. The current speed in the confluence area of the river varies from 0.3 – 0.9 m/s at high tide, and the speed is higher at low tide, which is 0.9 to 1.5 m/s. The current field measurements confirmed the lower velocities during high tide than low tide shown in the model, which measured current velocities were lower during high tide than low tide.

These hydrodynamic model results indicate that during high tide, the tidal currents moving from the sea towards the river slow down the flow of river waters in the confluence area of the Malili River with the Ussu River (station S4). Surya et al (2019) also reported that the current speed was slightly higher at low tide than at high tide in Jakarta Bay due to the influence of river discharge entering Jakarta Bay. One of the implications of slowing currents at high tide in the confluence area of the Malili and Ussu rivers in this study is the occurrence of sediment deposition in the area which will eventually cause siltation in the confluence area of the two rivers.

The model results for the speed and direction of the currents at a shift from high tide to low tide condition (Figure 6B) and shift from low tide to high tide conditions (Figure 6D) show that the current velocity at both conditions is not significantly different. The model simulation results also show that the current velocity increases at low tide and slows down during high tide, but the vector direction remains seaward. The consistency of this net current direction indicates that the study site has a dominant river discharge flow.

The sedimentation rate that we obtained in this study falls within the range of sedimentation rates in the Karangsong River (Indramayu Regency) reported by Adrianto (2017) but slightly higher than in the Musi River Estuary (South Sumatra) reported by Sulistiyani et al (2019). The sedimentation rate in the Musi River Estuary ranges from 0.0071 to 0.0384 g/cm^2/day, with an average sedimentation rate of 0.0224 g/cm^2/day.

The sedimentation rate in the river estuary is influenced by several factors, including season, oceanographic conditions, and topography. For example, this study was conducted during the rainy season when the sediment load due to erosion from the soil entering the river was relatively higher than in the dry season. In contrast, Sulistiyani et al (2019) conducted their study in the Musi River during the dry season. So, differences in sampling time or season can explain why the sedimentation rate is relatively higher at the Malili River Estuary than at the Musi River Estuary.

In addition to season, oceanographic conditions like waves influence sedimentation in the river estuary. During storms, waves and swell at the entrances to estuaries can stir up large amounts of sediment, which can then be moved into the estuary by the incoming tide (Bell et al 2000). Another factor that influences sedimentation in the river estuary is the topography of the river estuary since the topography plays an essential role in impacting soil erosion intensity and, hence, sedimentation in the river estuary (Zhang et al 2015).

Conclusions. The field measurements and the hydrodynamic model show that the current velocity at the Malili River estuary is higher at low tide than at high tide, especially in the confluence area of the Malili River with the Ussu River. However, the vector direction remains seaward. Tidal currents moving from the sea to the river slow the flow of river waters in the confluence area of the Malili River and the Ussu River. The consistency of the current direction towards the sea indicates that the research location has a dominant river discharge flow. The highest sedimentation rate occurred in the upstream area of the Malili River (S1), and the lowest sedimentation rate was found in the Ussu River (S2). These results indicate that the most extensive sediment transport came from the upstream area of the Malili River, and the smallest came from the Ussu River.

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Conflict of interest. The authors declare that there is no conflict of interest.

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Authors:
Mustono, Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar 90425, Indonesia, e-mail: mustono11@gmail.com
Mahatma Lanuru, Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar 90425, Indonesia, e-mail: mahatma.lanuru@unhas.ac.id
Amir Hamzah Muhiddin, Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar 90425, Indonesia, e-mail: amirhm@unhas.ac.id

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