

# Hydrodynamics and Sediment Transport Under River-Coastal Forcing in Malili Estuary

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## Abstract

*Malili Estuary experiences progressive channel shoaling driven by interactions among river discharge, tidal currents and wave forcing. As a navigation route serving Balantang Port and Malili Fish Landing Port (PPI Malili), understanding sediment dynamics is essential to maintain hydraulic capacity and navigability. This study analyses hydrodynamic characteristics and sediment transport under coupled river–tidal–wave forcing using a two-dimensional numerical model integrating hydrodynamic (HD), spectral wave (SW) and sediment transport modules (ST). Model validation shows good agreement with field observations, with MAPE values of 3% for water level, 9.4% for current velocity, and 16% for suspended sediment concentration.*

*Results indicate that sediment transport varies throughout the tidal cycle, with ebb and flood phases influencing redistribution along the estuarine channel. River discharge primarily controls current velocity, while wave-current interaction near the estuary mouth increases near-bed shear stress and sediment mobilization. Simulated bed level changes reveal gradual suspended-load accumulation of approximately  $\pm 0.02$  m, whereas bed load transport produces larger bed elevation changes from 0.2 - 0.3 m within three-month simulation period, confirming its dominant role in morphological evolution. These findings highlight the importance of integrated river-tidal-wave interactions in controlling channel shoaling and supporting sustainable navigation management.*

**Keywords**— Hydrodynamic modelling, Sediment transport, Wave-current interaction, River discharge, Channel Shoaling

## I. INTRODUCTION

Malili River, located in East Luwu Regency, South Sulawesi, Indonesia, serves as a vital navigation channel providing access to Balantang Port and the Malili Fish Landing Port (PPI Malili). In recent years, progressive channel shallowing has disrupted vessel movement, particularly during low tide conditions, potentially affecting port operations and local economic activities. Despite its strategic importance, quantitative assessments of hydrodynamic behaviour and sedimentation processes in Malili Estuary remain limited. As a dynamic estuarine system influenced by the interaction of river discharge, tidal currents, and wave forcing, Malili Estuary is governed by combined river–coastal processes that control circulation patterns and suspended sediment distribution. Similar hydrodynamic–sediment interactions have been demonstrated in previous estuarine modelling studies highlighting the relationship between flow dynamics and suspended sediment concentration (Hidayah, Maula & Wardhani 2023), while hydrodynamic simulations in macro-tidal estuaries have shown their fundamental role in sediment transport estimation (Dunn, Zigic, Burling & Lin 2015).

Recent developments in integrated current–wave–sediment modelling emphasize the importance of coupling physical processes within a unified numerical framework. The one-model one-mesh approach enables data exchange among hydrodynamic, wave, and sediment sub-models within the same time step, thereby improving the accuracy of process representation and numerical stability (Lai 2024). Comparable coupled wave–current modelling approaches incorporating variable grain size properties have also been applied to analyse sediment dynamics in estuarine and river-mouth environments (Wu, Zhao, Li & Zhang 2025). Furthermore, the role of river discharge in

controlling sediment dispersal toward coastal waters has been investigated using coupled modelling systems that account for tidal forcing, wave effects, settling velocity, and critical shear stress parameters (Zhang, Hu, Yu, Zhang & Gong 2025). In highly turbid estuaries, three-dimensional simulations reveal that seasonal variability and sand–mud interactions play a crucial role in the formation of the estuarine turbidity maximum (Do, Huybrechts, Jálon-Rojas, Tassi & Sottolichio 2025).

A systematic review of hydro-morphological modelling over the past decade highlights that integration of river and coastal forcing has become a central focus in modern estuarine modelling studies (Mora-Uribe, Caamaño-Avenidaño, Villagrán-Valenzuela, Roco-Videla & Alcayaga 2025). Additional regional studies confirm that tidal current patterns combined with wave transformation significantly influence sediment transport processes (Esti Himawan et al. 2025). Wave characteristic analysis (Mas'ud M, Suntoyo & Pratikto 2024) and two-dimensional coupled tidal–wave modelling (Talitha, W & Agassi 2024) further support the necessity of integrated approaches for representing coastal hydrodynamics. In the context of cohesive sediments, numerical coupling of hydrodynamics and sediment transport has proven effective in explaining suspended sediment concentration patterns in estuarine systems (Nguyen, Vu & Zhang 2021).

Although integrated current–wave–sediment modelling has advanced considerably, quantitative evaluation of sedimentation rates under combined river discharge, tidal currents, and wave forcing remains limited, particularly for navigation-critical tropical estuaries. In Malili Estuary, ongoing channel shallowing highlights the need for a coupled numerical assessment. Therefore, this study analyse hydrodynamic characteristics and sediment transport rates under fully coupled river–tidal–wave forcing to support sediment management strategies.

## II. RESEARCH METHOD

### Study Area

This research was conducted at Malili Estuary. The study area defined based on coverage of the bathymetric survey, extending from the river mouth to the upstream channel and including a shoaled section indicating sediment deposition. The detail location is shown in Figure 1.

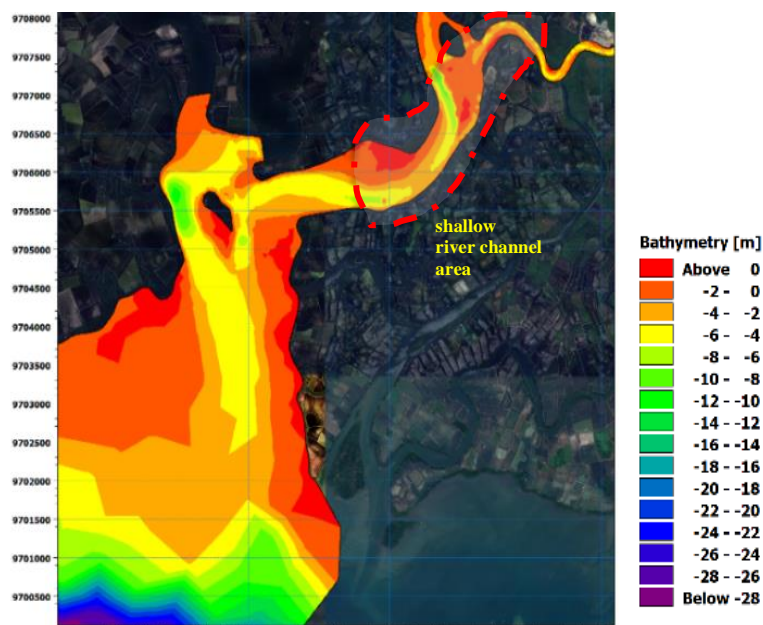


Figure 1. Location of the Study Area

### Data Collection

The data used in this study include primary and secondary datasets, as summarized in Table 1.

Table 1. Data Used

No.	Description	Type Data	Amount data	Data source
1	Topography-Bathymetry	Primary	-	Field Survey
2	Daily River Discharge	Primary	-	Field Survey & Data Analysis
3	Median Grain Size ( $d_{50}$ )	Primary	3 Sample	Field Sampling & Laboratory Analysis
4	Total Suspended Solids (TSS)	Primary	4 Sample	Field Sampling & Laboratory Analysis
5	Tides	Primary	15 Days	Field Survey
6	Current Data	Primary	Hourly Data	Field Survey
7	Wave Data	Secondary	365 Days	ERA-5 (Copernicus Climate Change Service 2024)

Primary data were collected through filed surveys, including topography-bathymetry, daily river discharge, tides (15 day-observations), hourly current measurements, and sediment characteristics include median grain size ( $d_{50}$ ) and total suspended solids (TSS) collected at three sampling points and analysed in laboratory. Secondary data include wave height ( $H_s$ ), period and direction obtained from ERA-5 for a one-year period (365 days). These datasets were used as model inputs and boundary conditions.

### Model Validation

The validation metric used in this study is the Mean Absolute Percentage Error (MAPE) as proposed by (Lewis 1982), the equation is expressed as follows:

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{actual-forecast}{actual} \right| \times 100 \quad (1)$$

Where  $n$  represents the total number of data points. The classification of MAPE accuracy levels for model validation is presented in Table 2.

Table 2. Typical MAPE Values in Modelling Validation

MAPE (%)	Forecasting Power
<10%	Highly accurate forecasting
10%-20%	Good forecasting
20%-50%	Reasonable forecasting
>50%	Weak and inaccurate forecasting

### Numerical Model Simulation

The hydrodynamic model was governed by the depth-averaged continuity and momentum equations for shallow water flow, as expressed in Equations 2.

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \quad (2)$$

The governing equations include advection, pressure gradients, bottom friction (Manning formulation), Coriolis force, radiation stress, and atmospheric pressure forcing. Here,  $p = uh$  and  $q = vh$  denote the flux densities in the  $x$ - and  $y$ -directions, respectively,  $h$  is the total water depth, and  $\zeta$  is the free surface elevation.

Wave characteristics (significant wave height, period and direction) were simulated using the Spectral Wave (SW) module, which solves the four-dimensional wave action balance equation as expressed in Equations 3.

$$\frac{\partial N}{\partial t} \nabla \cdot (c_g N) + \frac{\partial (c_g N)}{\partial \sigma} + \frac{\partial (c_g N)}{\partial \theta} = \frac{S}{\sigma} \quad (3)$$

Where  $N = E/\sigma$  wave action density,  $C_g$  is group velocity,  $C_\sigma$ , and  $C_\theta$  represent frequency and directional shifting due variations in depth and current, and  $S$  denotes the source terms including wind input, nonlinear interactions, and dissipation. Wave-current interaction was activated through the radiation stress mechanism, allowing wave-induced bed shear stress to be incorporated into the total bed shear stress.

Sediment transport computed using the Sand Transport (ST) module based on the total load formulation of Engelund and Hansen:

$$S_t = 0.05 \frac{C^2}{g} \theta^{5/2} \sqrt{(s-1)gd_{50}^3} \quad (4)$$

$$s = \frac{\rho_s}{\rho} \quad (5)$$

Where  $C$ , is the Chezy coefficient,  $g$  is gravity acceleration,  $\theta$  is Shield parameter,  $s$  is relative density, and  $d_{50}$  is the median grain diameter. The bed shear stress applied in the sediment transport calculation represents the combined effects of currents and waves. This integrated modelling approach was selected due to the dominance of non-cohesive sandy sediment and the combine influence of tidal currents and waves in estuarine study area

### III. RESULTS AND DISCUSSION

Water level fluctuations in Malili Estuary are primarily controlled by tidal forcing. tidal data were obtained from 30-day field measurements at Mangkas Point Terminal station. The model reproduces tidal amplitude and phase with very good agreement compared to observations. The comparison between measured and simulated water levels is shown in Figure 2.



Figure 2. Location of Tidal & Current Observation

Model Validation yields a MAPE of 3%, indicating highly accurate performance. The time series comparison between measured and modelled water levels presented in Figure 3.

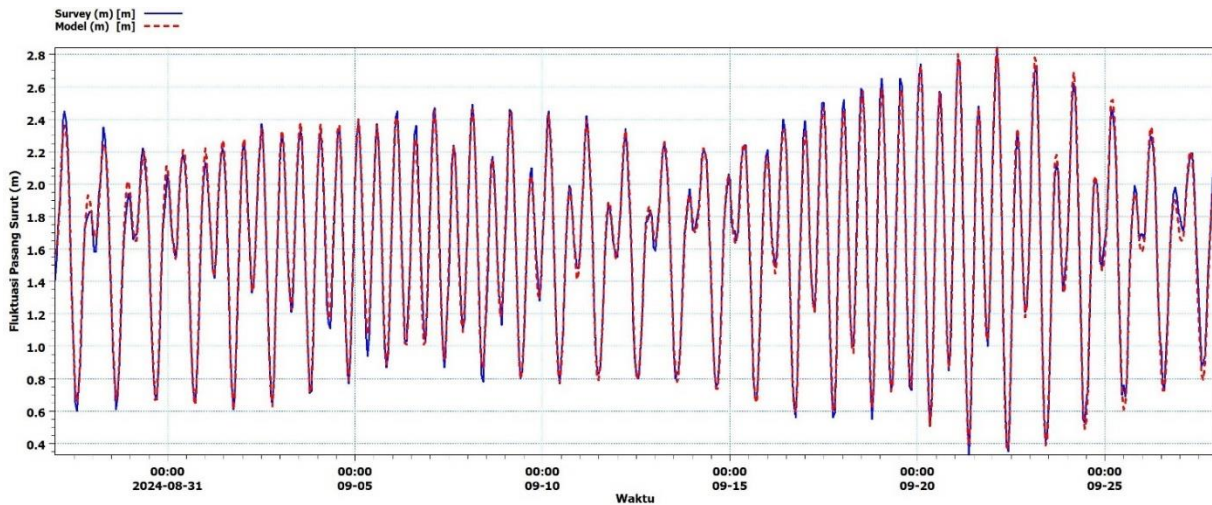


Figure 3. Tidal Validation between Model Simulation and Field Observation

The tidal oscillation, combined with river discharge, generates dynamic current patterns along the estuarine channel. Validation of simulated current velocities against field measurements results in a MAPE value of 9.4%, classified as good accuracy. The comparison of modelled and observed current velocities is shown in Figure 4.

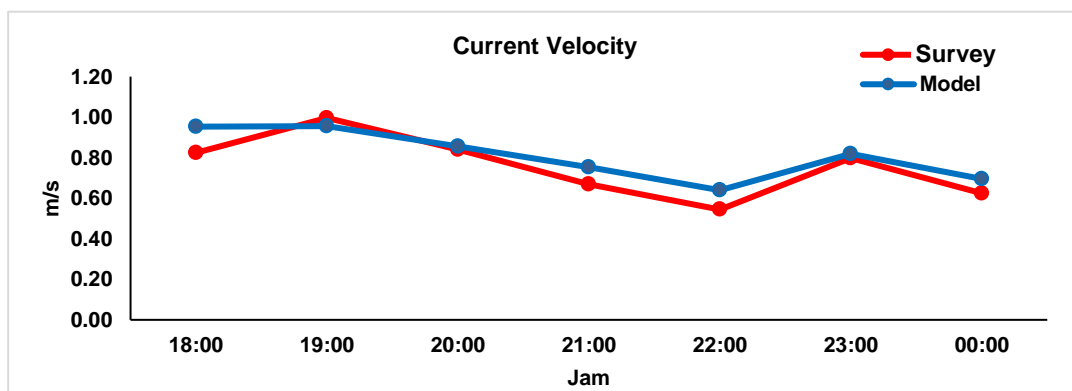


Figure 4. Current Velocity between Model and Measurement

In estuarine systems, tidal propagation interacts with river discharge, channel geometry, and bottom friction, which collectively control current magnitude and flow reversal patterns (ebb and flood) (Sorensen 2006). Tides may also generate strong reversing currents at estuary entrances, where ebb flow is further enhanced by river discharge and surface runoff. Under ebb conditions, current velocities are predominantly controlled by river discharge, reaching 0.30 - 0.75 m/s in the upstream section and 0.15 - 0.60 m/s near the estuary mouth. The spatial distribution of current velocity during ebb conditions is presented in Figure 5.

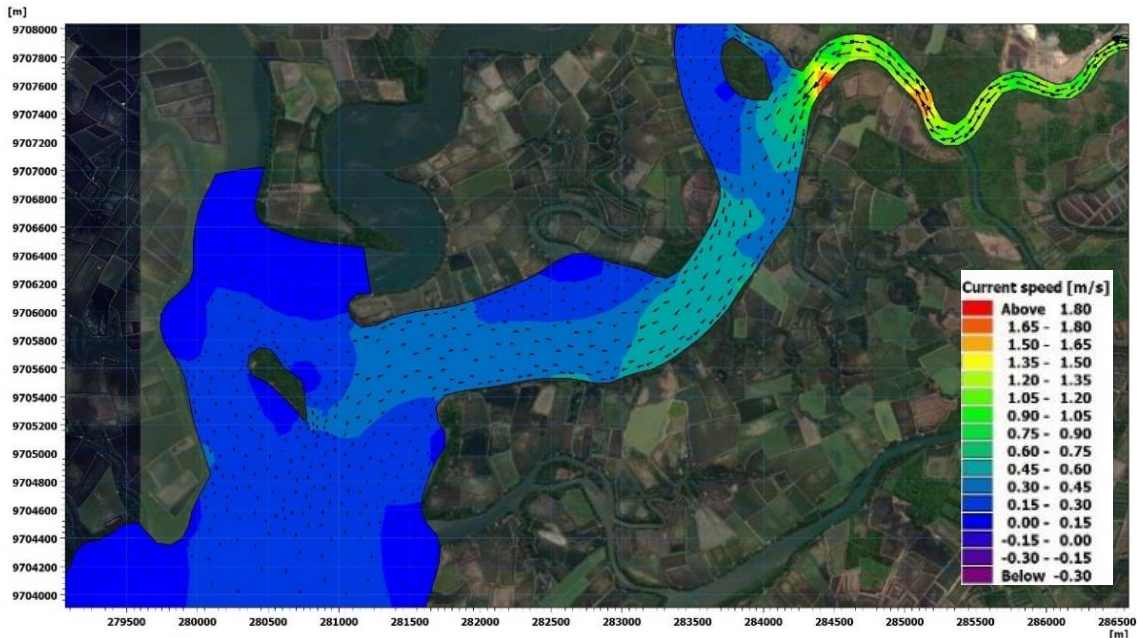


Figure 5. Current Velocity Distribution under Ebb Condition

During flood conditions, tidal influence reduces the current velocity near the estuary about 0.15 - 0.30 m/s, while upstream velocities remain relatively strong at 0.32 -0.75 m/s, indicating that river discharge still dominates the flow direction. The spatial distribution of current velocity under flood condition is shown in Figure 6.

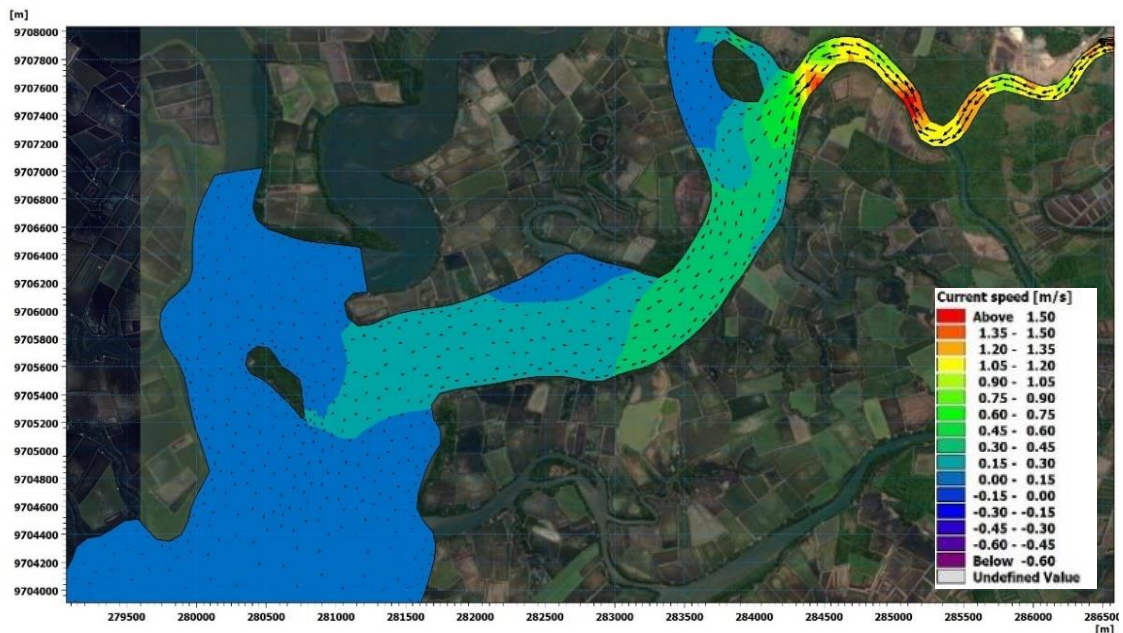


Figure 6. Current Velocity Distribution under Flood Condition

Tidal waves behave as shallow-water (long) waves and their propagation in estuaries is strongly influenced by basin geometry, depth variation, and bottom friction, which may modify tidal range and current patterns (Dean & Dalrymple 1991). Wave transformation further modifies hydrodynamic conditions near the estuary mouth. The model uses a 25-year return period wave input ( $H_s = 0.59$  m;  $T = 5.19$  s) from the dominant southern direction. The wave propagation pattern under high tide condition as shown in Figure 7, while low tide condition is presented in Figure 8.

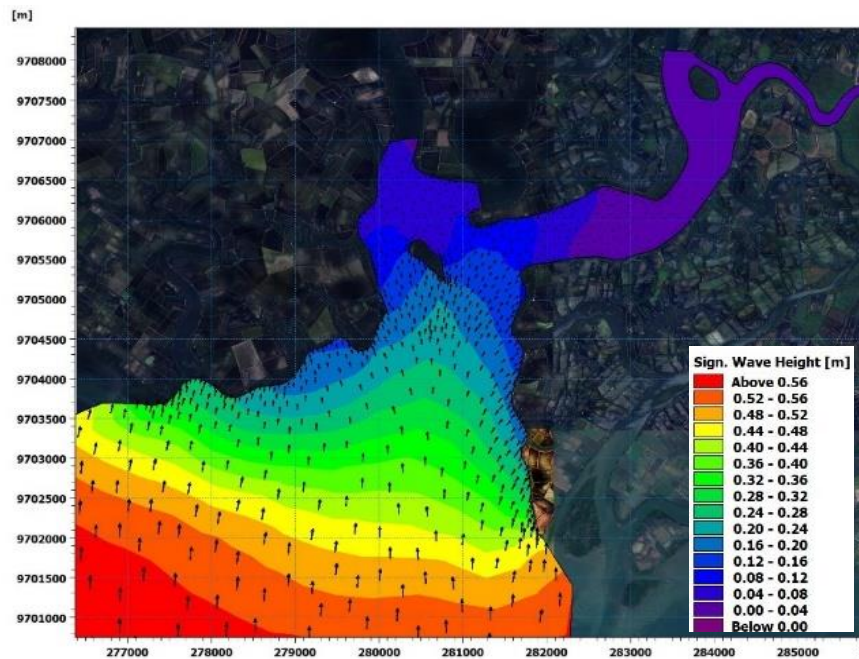


Figure 7. Wave Propagation from Southern Direction under High Tide Condition

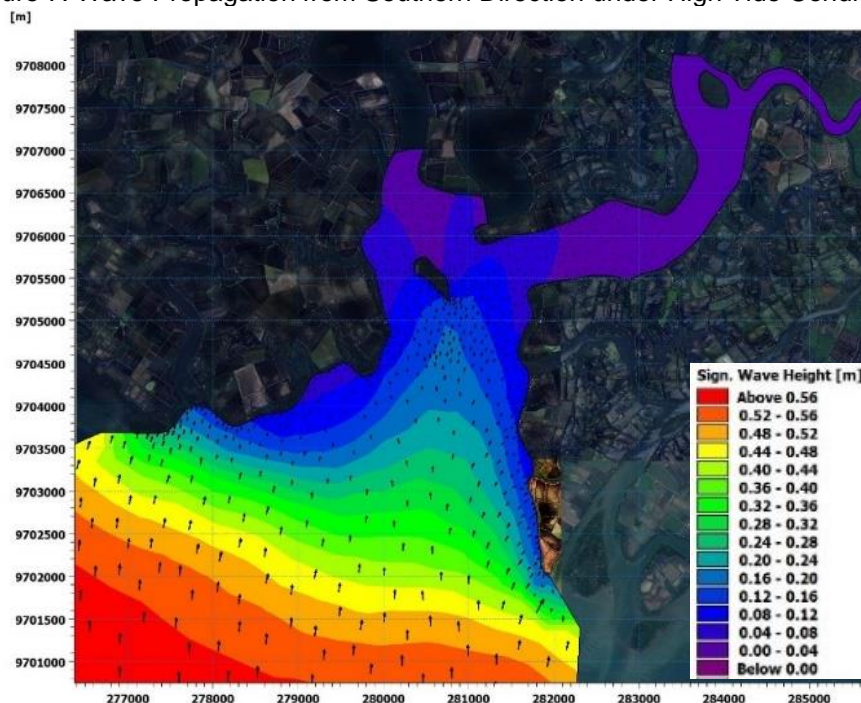


Figure 8. Wave Propagation from Southern Direction under Low Tide Condition

Although wave energy decreases significantly inside the river channel, wave-current interaction near the estuary mouth increases near-bed shear stress and supports sediment mobilization. During high tide, wave reach the estuary mouth with height of 0.24 – 0.28 m then propagate into the river channel decreasing to 0.00 – 0.04 m within the inner river area. Under low tide conditions, wave height at the estuary mouth range between 0.16 – 0.20 m and similarly decay to 0.00 – 0.04 m inside the river. Overall, the interaction between tidal oscillation, river discharge, and wave transformation represents the primary hydrodynamic mechanism controlling sediment redistribution and channel shoaling in the study area.

In addition to hydrodynamic and wave transformation processes, sediment dynamics further explain the observed channel shoaling in the study area. The estuary receives sediment supply from two primary river systems, namely the Malili River and the Ussu River, which contribute to suspended and bed load transport under existing natural condition. The spatial distributin of Total Suspended Solids (TSS) is presented in Figure 9.

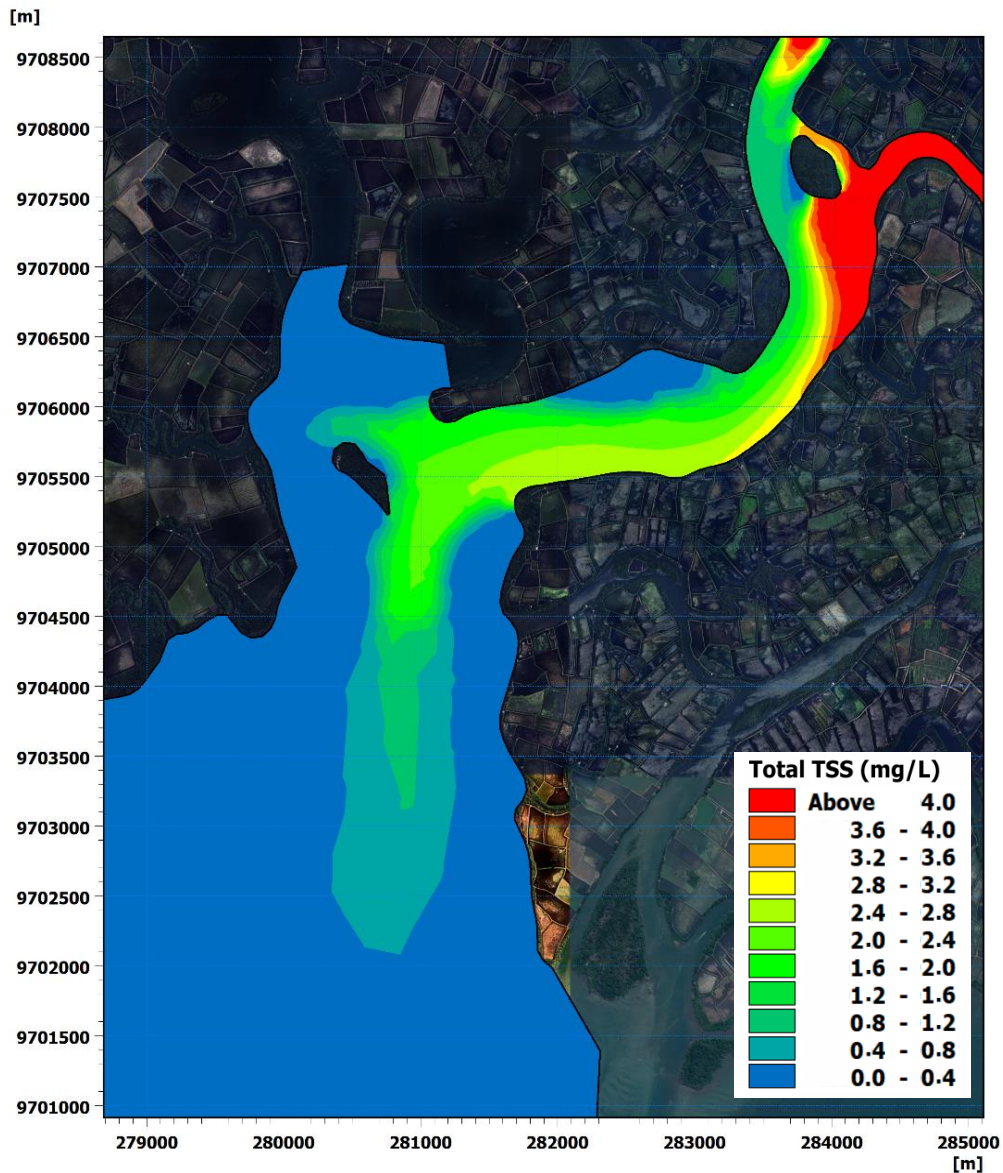


Figure 9. Spatial Distribution of Suspended Sediment (TSS)

The results indicate that higher TSS concentrations originate from the Malili River ( $>4.0$  mg/L) and gradually decrease toward the estuary mouth to approximately 1.6–2.0 mg/L. In contrast, the Ussu River shows relatively lower concentrations ( $>2.4$  mg/L), with similar downstream attenuation. This pattern suggests that the Malili River acts as the dominant contributor of suspended sediment within the estuarine system.

To evaluate model performance, a comparison between simulated and observed TSS values was conducted at several monitoring points. The sampling locations are shown in Figure 10.

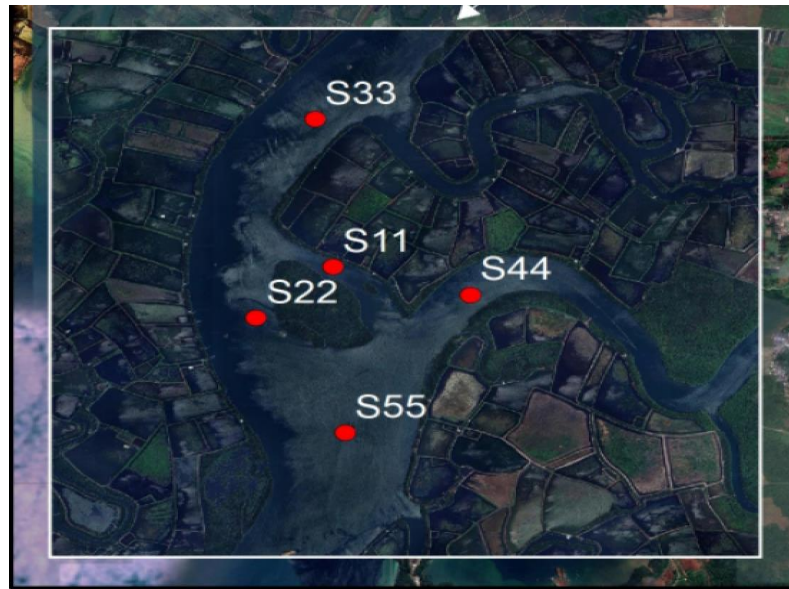


Figure 10. TSS Sampling Locations

The quantitative comparison is summarized in Table 3.

Table 3. Comparison Between Modelled and Observed TSS

Titik	Kordinat (UTM)		TSS (mg/L)	
	Easting	Northing	Survei	Model
S11	283939.21	9707900.75	7.3	4.4
S22	283639.93	9707645.3	2.3	1.6
S33	283870.09	9708641.03	2.0	2.0
S44	284473.91	9707760.27	3.7	3.6
S55	283986.86	9707068.28	3.0	3.2
<b>MAPE</b>			<b>16%</b>	

The Validation results show a MAPE of 16%, indicating good accuracy between model results and field measurements. The graphical comparison between simulated and measured concentration is presented in Figure 11.

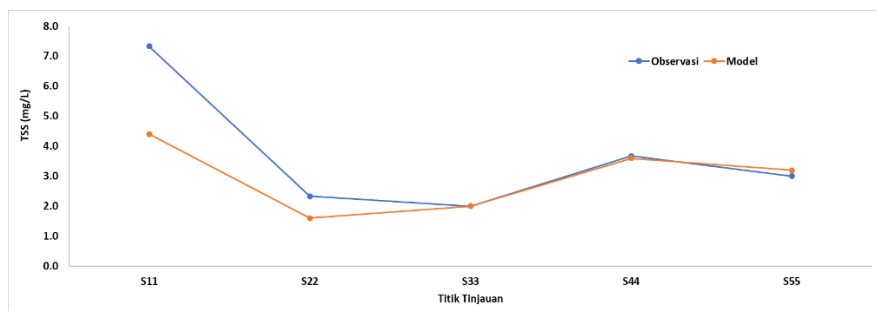


Figure 11. Comparison of Modelled and Measured TSS Values

Further analysis was performed to asses bed level changes resulting from sediment transport processes. The simulated bed level change due to suspended load over a one-month period is shown in Figure 12.

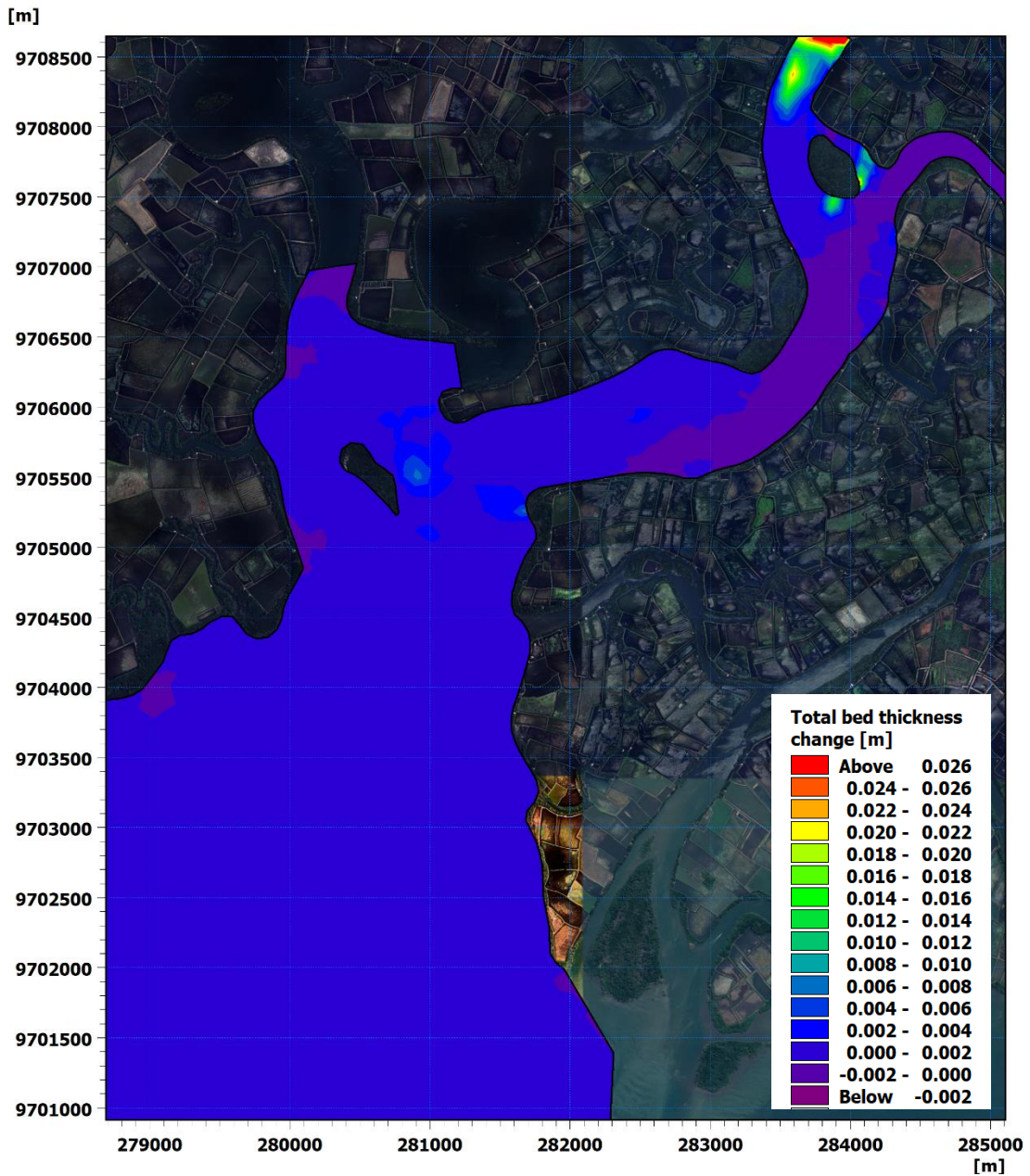


Figure 12. Bed Level Change Due to Suspended Load

The results indicate sediment accumulation of approximately  $\pm 0.02$  m (2 cm), reflecting gradual deposition from suspended sediment transport. In contrast, bed level change due to bed load transport is presented in Figure 13.

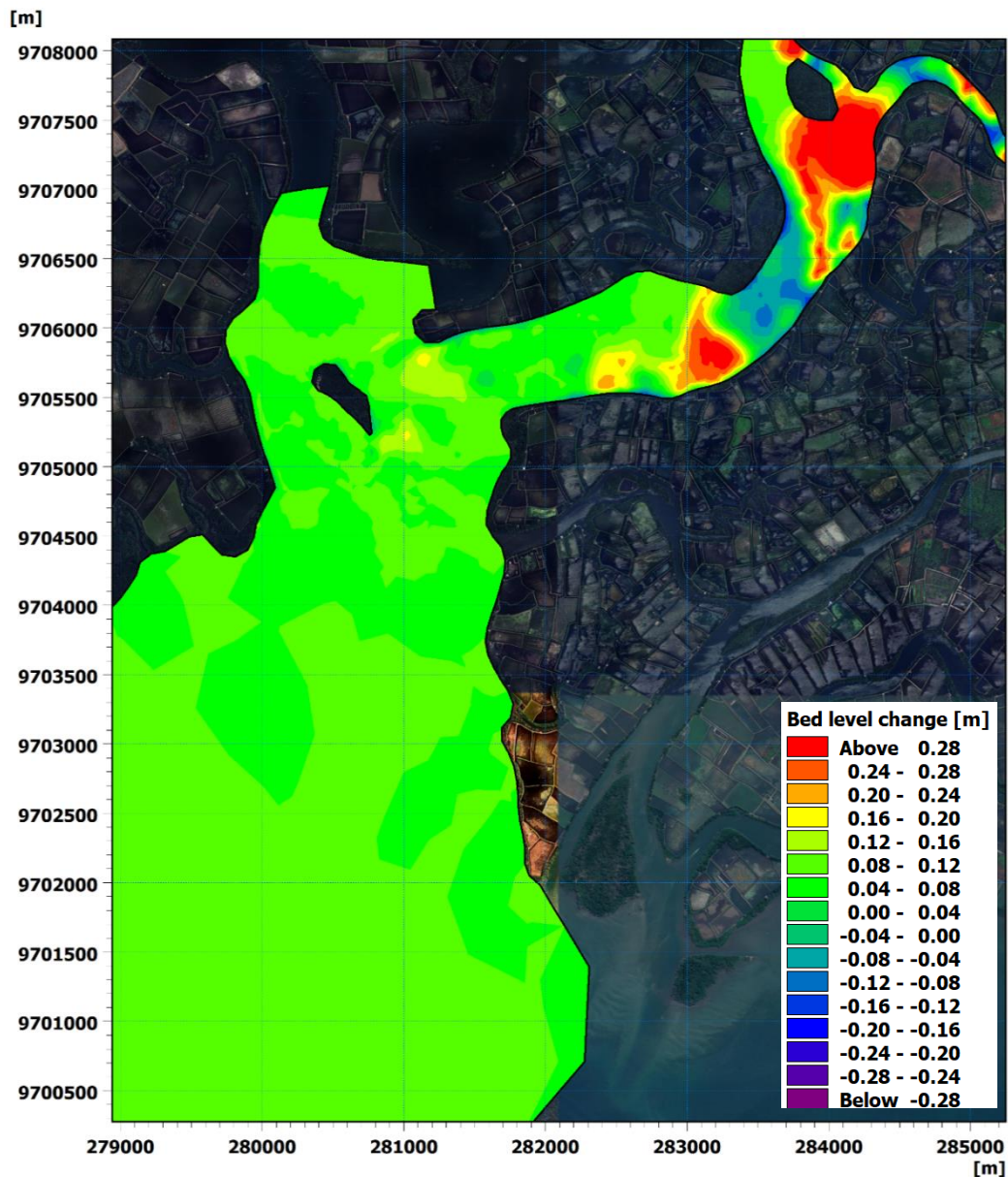


Figure 13. Bed Level Change Due to Bed Load Transport

The simulation shows bed elevation variations ranging from 0.2 – 0.3 m within three-month, which is significantly greater than the accumulation caused by suspended load. This indicates that bed load transport plays a dominant role in controlling morphological evolution in the study area. The higher flow velocities, particularly in the Malili River, increase bed shear stress beyond the critical threshold of motion, resulting in substantial bed adjustment.

Overall, while suspended sediment contributes to gradual accumulation, bed load transport represents the primary mechanism driving channel shoaling under existing hydrodynamic conditions.

Based on the integrated analysis, the hydrodynamic and sediment transport processes play a significant role in controlling channel shoaling in the Malili Estuary under existing conditions. Tidal fluctuations influence flow direction and sediment redistribution, while river discharge controls current velocity and sediment mobilization. Wave transformation near the estuary mouth contributes to sediment resuspension, although its influence decreases inside the river channel.

The simulation results indicate that suspended load transport contributes to gradual sediment accumulation; however, bed load transport produces more significant bed level changes within the same period. This finding suggests that bed load transport is the dominant factor influencing morphological changes in the study area. Therefore, the interaction between river discharge, tidal dynamics, and wave effects must be considered comprehensively in understanding sedimentation patterns and channel evolution in the Malili Estuary.

#### **IV CONCLUSION**

This study confirms that hydrodynamic processes in the Malili Estuary are governed by the combined influence of river discharge, tidal oscillation, and wave transformation. River discharge predominantly controls current velocity, especially during ebb conditions, while tidal dynamics regulate flow reversal and sediment redistribution near the estuary mouth. Wave action enhances near-bed shear stress in the coastal–estuarine transition zone but has limited influence further upstream.

The simulation results demonstrate that bed load transport generates more substantial bed level changes than suspended load within the same period, indicating that bed load is the primary mechanism driving channel shoaling under existing natural conditions. Therefore, the research objective to quantitatively assess hydrodynamic characteristics and sediment transport under coupled river–coastal forcing has been successfully achieved.

These findings provide a scientific basis for sediment management and navigation planning in the Malili Estuary. Further investigation is recommended to simulate post-dredging conditions in order to evaluate hydrodynamic adjustment, sediment redistribution, and potential long-term morphological response following channel deepening activities.

#### **ACKNOWLEDGMENT**

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