# Numerical Simulation of Hydrodynamic and Sediment Transport in the Madura Strait

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***Abstract*— Surabaya serves as a coastal and economic center in East Java, where rapid coastal development around the Madura Strait has intensified sedimentation and shoreline change. Understanding hydrodynamic behavior and sediment transport is crucial for sustainable coastal management. This study applies a three-dimensional Delft3D numerical model to simulate hydrodynamics and sediment transport in the Madura Strait. The model accounts for tides, waves, wind, river discharge, temperature, salinity, and sediment properties to capture seasonal variations in circulation and sediment dynamics. Model validation using tidal and current observations shows acceptable accuracy based on RMSE and MAE values. Results indicate that tidal forcing predominantly controls current circulation, showing bidirectional flow with a phase lag between flood and ebb tides, leading to net sediment transport toward the Pamurbaya convergence zone. Significant wave heights (0.1–0.5 m) exhibit seasonal variation, increasing during the East Monsoon and the Second Transitional Season due to easterly winds. Sediment transport simulations show minor morphological changes (–0.02 to +0.02 m/year) but active redistribution, particularly near Pamurbaya. These findings highlight the dominant role of tidal dynamics and the need for adaptive, morphodynamic-based coastal management to ensure the long-term stability of the eastern Surabaya coastline.**

*Keywords*—*Hydrodynamic, Sediment Transport, Madura Strait, Pamurbaya, Numerical Modeling*

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## I. INTRODUCTION

Surabaya is part of the National Strategic Area (KSN) known as GERBANGKERTOSUSILA (GKS), which plays an important role as a national center of economic and maritime activities, as stipulated in Presidential Regulation of the Republic of Indonesia No. 66 of 2022 concerning the Spatial Plan for the Gresik, Bangkalan, Mojokerto, Surabaya, Sidoarjo, and Lamongan Metropolitan Area. The development strategy of this region includes the designation of coastal areas for industrial purposes and the enhancement of port logistics functions to support economic growth in Java Island. Japan International Cooperation Agency (JICA) also emphasized that the development of the GKS area, including Surabaya, is part of a long-term plan to strengthen Tanjung Perak Port as a national gateway.

Nevertheless, this regional development faces significant challenges, particularly concerning the complex environmental conditions of the coastal zone. One of the major issues is sedimentation and coastal erosion, which have become increasingly severe in the Madura Strait (Figure 1.). The Madura Strait serves as an essential transportation corridor and a hub of maritime economic activities in East Java [3]. These conditions not only cause ecological impacts but also have the potential to disrupt economic activities and the implementation of coastal infrastructure development directly.

Madura Strait also plays a crucial role in regulating hydrodynamic exchanges between the Java Sea and the Surabaya coastal system [4]. Consequently, sediment transport processes occurring within the strait may influence sedimentation and erosion patterns along the Pamurbaya coast, which represents the eastern coastal zone of Surabaya [5]. This spatial linkage highlights the importance of understanding the physical connectivity between the strait and the adjacent coastal environment, particularly in the context of ongoing and planned coastal development activities.

One of the large-scale development projects planned around the Madura Strait is the Surabaya Waterfront Land (SWL) Reclamation, which has been designated as part of the National Strategic Projects (PSN) based on the Coordinating Minister for Economic Affairs Regulation No. 6 of 2024, concerning the Fifth Amendment to Regulation No. 7 of 2021 on the List of National Strategic Projects. The project aims to accelerate economic growth in East Java Province. The proposed reclamation site is located along the eastern coast of Surabaya (Pamurbaya), where environmental challenges such as sedimentation and coastal erosion could significantly affect the success and sustainability of the project.

The Pamurbaya region is characterized by a highly dynamic coastal environment, influenced by both natural processes and anthropogenic activities such as port expansion [3], land reclamation [7], and river discharge [8]. Given its strategic location adjacent to the Madura Strait, any alteration in hydrodynamic and sediment transport regimes in the strait could have direct implications for sediment deposition and shoreline evolution in Pamurbaya. Hence, evaluating these

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interactions is essential for anticipating potential environmental consequences and supporting evidence-based coastal management.

To address these challenges, an in-depth analysis is required as part of coastal zone management efforts, particularly by examining the oceanographic conditions of the area. Such an oceanographic study serves as a fundamental step toward understanding the characteristics of the waters comprehensively, especially in the context of sediment dynamics that influence coastal morphological changes. This is because hydrodynamic conditions in coastal waters play a crucial role in the process of sediment transport [9]. The sediment transport process subsequently affects coastal morphology and contributes to beach morphodynamics [10], which ultimately determines the success and sustainability of coastal development.

Various approaches have been employed to investigate sediment transport and coastal morphodynamics, including empirical, analytical, and numerical methods. Empirical and analytical approaches are often limited by simplifying assumptions and spatial constraints, making them less suitable for regions with complex hydrodynamic behavior [11] such as the Madura Strait. In contrast, numerical modeling, particularly using Delft3D provides the ability to simulate coupled hydrodynamic and sediment transport processes under realistic boundary conditions, allowing for a more comprehensive assessment of spatial and temporal variations [12]. Therefore, the Delft3D model is adopted in this study to represent the dynamic characteristics of the Madura Strait and its influence on the Pamurbaya coastal area.

Therefore, a more detailed analysis through numerical modeling is necessary to obtain a comprehensive understanding of the oceanographic conditions in the Madura Strait. However, studies that comprehensively analyze the patterns of hydrodynamics and sediment transport in this region remain limited, particularly in identifying seasonal variations that influence local water dynamics.

Although several previous studies have investigated hydrodynamic or sediment transport processes in the Madura Strait, most of them were focused on localized regions such as river mouths [13] or port approaches [3], [14] and did not evaluate the integrated relationship between the overall strait and the Pamurbaya coastal system. Consequently, the spatial linkage and its implications for coastal management and reclamation planning remain insufficiently explored.

This study aims to analyze the hydrodynamic patterns and sediment transport processes in the Madura Strait using a numerical modeling approach as an initial step toward a deeper understanding of the area's physical characteristics. The results of this study are expected to provide valuable insights into the influence of hydrodynamics on sediment transport and coastal morphodynamics in the Madura Strait and to serve as a scientific basis for developing more targeted and sustainable coastal management policies.

The findings obtained from this research are also expected to form a fundamental basis for subsequent quantitative assessments of sediment fluxes and sediment budget analysis in the Madura Strait, which are essential for evaluating long-term morphological evolution and coastal response to natural and anthropogenic forcing.

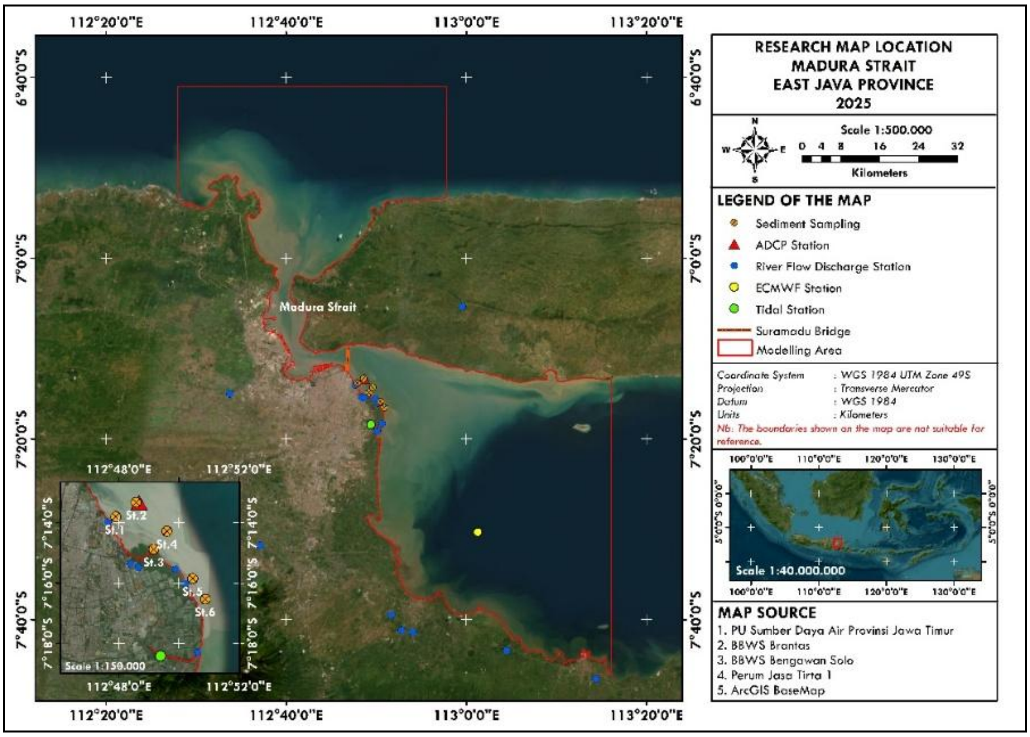

**Figure 1**. Research Location

## II. METHOD

### *A. Governing Equations*

Delft3D is a numerical modeling software capable of simulating coastal and marine environments in a computational framework. The Delft3D model calculates hydrodynamics using the two- or three-dimensional continuity and momentum equations based on depth-averaged assumptions [12]. The continuity equation is expressed as follows, Equation (1):

$$\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left((d+\zeta)U\sqrt{G_{\eta\eta}}\right)}{\partial \xi} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left((d+\zeta)V\sqrt{G_{\xi\xi}}\right)}{\partial \eta} = (d+\zeta)Q \quad (1)$$

where U and V are the depth-averaged velocity components, ζ is the water elevation, *d* is the water depth, *G* represents the grid transformation coefficient, and *Q* denotes the source or sink per unit area. The momentum equations are formulated as follows, Equation (2):

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + \upsilon\frac{\partial U}{\partial y} + \frac{w}{h}\frac{\partial U}{\partial \sigma} - fV = -\frac{1}{\rho_0}P_x + F_x + M_x + \frac{1}{h^2}\frac{\partial}{\partial \sigma}\left(\upsilon_V\frac{\partial u}{\partial \sigma}\right) + M_\xi,$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + \upsilon\frac{\partial V}{\partial y} + \frac{w}{h}\frac{\partial V}{\partial \sigma} - fU = -\frac{1}{\rho_0}P_y + F_y + M_y + \frac{1}{h^2}\frac{\partial}{\partial \sigma}\left(\upsilon_V\frac{\partial u}{\partial \sigma}\right) + M_\eta. \quad (2)$$

where, P represents the pressure gradient, F the Reynolds stress, and M external forces such as waves or river discharge (as sources or sinks). The term $v_v$ denotes the vertical eddy viscosity.

For the wave model, the SWAN (Simulating Waves Nearshore) approach is applied. The SWAN model is based on the spectral action balance equation, which accounts for all wave directions and frequencies [15]. The governing equation of the SWAN model is presented in Equation (3).

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}c_x N + \frac{\partial}{\partial y}c_y N + \frac{\partial}{\partial \sigma}c_\sigma N + \frac{\partial}{\partial \theta}c_\theta N = \frac{S}{\sigma} \quad (3)$$

where N is the wave action density, c denotes the propagation velocity in physical, frequency, and directional space, and S represents the source term (generation, dissipation, and nonlinear interactions).

The sediment transport model in Delft3D applies several empirical formulations, such as Engelund & Hansen (1972), [17], [18], [19], and [20]. These formulations account for the combined influence of currents and waves on the sediment transport process. The governing equation is presented in Equation (4)

$$\frac{\partial z}{\partial t} = \frac{z(1+a-e^z)}{e^z(z-1)+1}\frac{1}{U_0}\frac{\partial U_0}{\partial t} + \frac{30K}{k}\frac{\sqrt{K^2U_0^2\left|z^2U^2{}_{f0}\right|2K_zU_{f0}U_0\cos\gamma}}{e^z(z-1)+1} \quad (4)$$

where K is the von Kármán constant, t is time (s), z represents the boundary layer thickness (m), $U_0$ is the near-bed wave orbital velocity (m/s), $U_{f0}$ is the shear velocity within the wave boundary layer (m/s), γ is the angle between current and wave (°), and k is the bed roughness (m).

### *B. Model Setup*

#### *1.) Boundary Conditions and Computational Grid*

The model domain in this study covers an area of approximately 4,222 km², encompassing the Madura Strait. The boundary conditions were defined using three open boundaries located on the northern, western, and eastern sides of the domain, while the remaining sides were assigned as land boundaries. The main focus area of this research lies within the Madura Strait and the Pamurbaya region. The total length of the model domain, measured from the northern inlet to the southeastern part of the strait, is about 128 km.

This study employs a nested modeling approach, in which the boundary conditions for the smaller-scale (nested or fine) grid are derived from the simulation results of a larger-scale (overall or coarse) grid model. This approach provides a significant advantage by reducing computational load, thereby improving the efficiency of the numerical simulation. In this research, the data transferred from the overall grid to the nested grid include tidal elevation, wave parameters, river discharge, temperature, salinity, and sediment concentration. The applied boundary configuration and grid design of the model are illustrated in Figure 2.

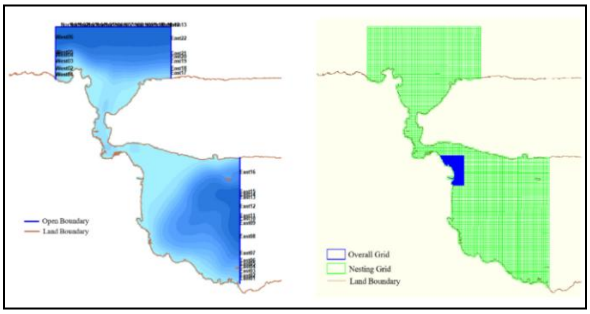


**Figure 2.** Boundary Condition and Meshing Grid

#### *2.) Model Parameters*

In the numerical modeling stage, determining the input parameters is a critical process, as they represent the field conditions in a realistic manner. Several previous studies have emphasized that calibration and validation of specific parameters are crucial aspects in both hydrodynamic and sediment transport models. In this study, the model setup includes several key parameters, such as salinity of 32.61 ppt and water temperature of 29.22°C, representing the average hydro-oceanographic conditions in the Madura Strait. The gravitational acceleration used was 9.81 m/s², with water and air densities of 1025 kg/m³ and 1 kg/m³, respectively. Bottom roughness was defined using the Manning uniform formula with a coefficient of 0.024.

For sediment characteristics, the model applied both cohesive and non-cohesive fractions, with dry bed densities of 900 kg/m$^3$ and 1600 kg/m$^3$, and volumetric concentrations of 0.205 kg/m$^3$ for cohesive sediment and 0.001 kg/m$^3$ for non cohesive sediment. The specified sediment density was 2650 kg/m$^3$, with a reference density for hindered settling of 1600 kg/m$^3$ and a median grain size ($D_{50}$) of 40 µm. The morphological scale factor was set to 1, with a spin-up interval of 1440 minutes before morphological changes were activated to ensure model stability and equilibrium prior to sediment transport simulation.

### *C. Model Validation*

The model results were subsequently validated by comparing the model outputs with field observation data. This process was conducted to evaluate the accuracy and reliability of the numerical model. When the modeled results show good agreement with the observed data, the model can be considered valid and suitable for further prediction or analytical purposes.

In this study, the validation of the model performance was conducted using the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) methods, as expressed in Equations (5) and (6). The RMSE value

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_i')^2}{n}} \quad (5)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x}_i) \quad (6)$$

Where, Xi denote the observed or measured values, $X_i'$ the predicted or simulated values from the model, and $n$ the total number of data points. In the RMSE and MAE calculation, smaller values approaching zero indicate a higher level of model accuracy relative to the observed data. The classification of RMSE and MAE value ranges used for model performance evaluation is presented in Table 1 [21], [23].

TABLE 1.
RANGE OF RMSE AND MAE VALUES

| RMSE and MAE Range | Description |
|---|---|
| 0,00 – 0,299 | Low Error Level |
| 0,30 – 0,599 | Moderate Error Level |
| 0,60 – 0,899 | High Error Level |
| > 0,9 | Very High Error Level |

TABLE 2.
OBSERVED TIDAL CONSTITUENTS

| | S0 | M2 | S2 | N2 | K1 | O1 | M4 | MS4 | K2 | P1 |
|---|---|---|---|---|---|---|---|---|---|---|
| A (m) | 1.768 | 0.528 | 0.279 | 0.117 | 0.424 | 0.291 | 0.028 | 0.033 | 0.075 | 0.093 |
| g° | 0 | 131 | 311 | 4 | 305 | 65 | 290 | 194 | 311 | 395 |

## III. Results and Discussion

### *A. Tidal Characteristics and Validation*

Based on the results of the Admiralty method analysis, the tidal type at the Wonokromo Station is classified as Mixed Mainly Semidiurnal, with a Formzahl (F) value of 0.89, as indicated by the tidal constituents presented in Table 2. The validation results between the observed tidal data and the simulated model, which have been referenced to the Mean Sea Level (MSL), are shown in Figure 3. According to the graph, the values of HHWL, LLWL, MHWL, and MLWL at Wonokromo Station are 1.548 m, –1.182 m, 0.649 m and -0.545 m, respectively.

The accuracy assessment using the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) methods indicates that the model exhibits a low level of error, with RMSE and MAE values of 0.221 m and 0.177 m, respectively. The simulated tidal patterns generally show good agreement with the observed data, reflecting the model's reliability in reproducing the tidal characteristics in the study area represents the average magnitude of the error in a given dataset, while the MAE value indicates the mean absolute difference without considering the direction of the error. Therefore, RMSE is generally used to assess the accuracy of model simulations against observations [21], whereas MAE provides a more appropriate representation of uniformly distributed errors [22], [23].

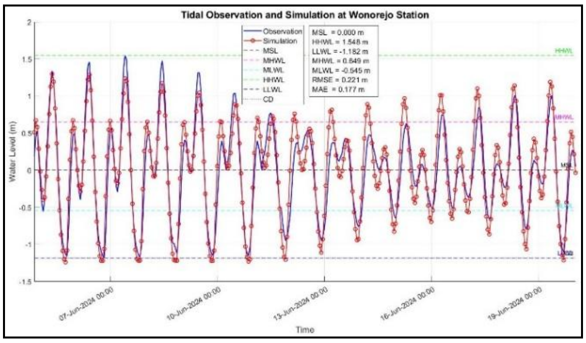

**Figure 3.** Tidal Validation Observed and Simulation

### *B. Current Dynamics and Validation*

The current patterns, Figure 4, generated from the simulation produced RMSE and MAE values of 0.232 m/s and 0.192 m/s, respectively, indicating that the validation results fall into the low error level category. Although the differences between the modeled and observed data appear relatively high, the overall current patterns and trends remain reasonably consistent.

The noticeable bias or significant discrepancies compared to field measurements are likely due to the model not accounting for incidental current-generating factors, such as currents induced by ship movements and port operational activities.

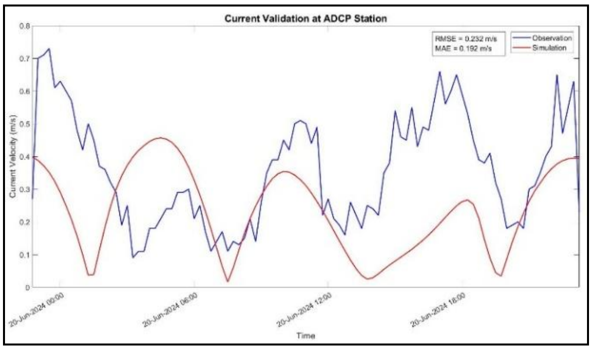

**Figure 4.** Current Validation Observed and Simulation

Based on the comparison between current velocity and tidal elevation data at the ADCP station, Figure 5, in general, the average current pattern follows the variation of the tidal elevation. However, at certain periods, the current velocity appears to lag the tidal elevation, indicating a tidal phase delay between flood and ebb tides. This phenomenon commonly occurs in tidal currents within shallow waters, where the current response to changes in water level is delayed due to the influence of seabed morphology [24] and bottom friction [25]. Overall, this pattern suggests that the currents in the Madura Strait are predominantly driven by tidal processes [26], [27], [28], with the maximum current velocity generally occurring during the transition phase between flood and ebb tides.

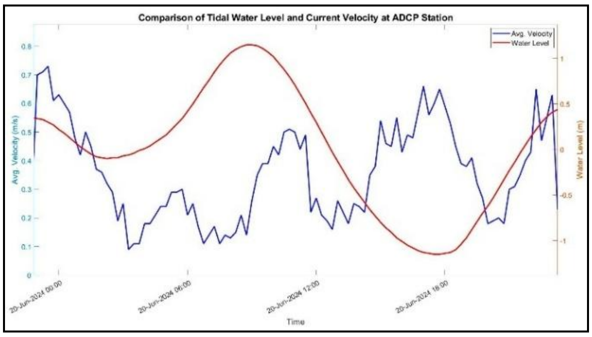

**Figure 5**. Comparison of Tidal Water Level and Current Velocity at ADCP Station

Based on the comparison between the ADCP observation data and the simulation results (Figure 6), the fluctuation pattern of current velocity shows a similar trend, indicating that tidal dynamics play a dominant role in driving current movement at the ADCP station. In general, the u-component of the current is more dominant than the v-component, suggesting that the main direction of water mass transport at the station is aligned along the east–west orientation. This condition indicates that the current system in the coastal area is primarily controlled by bidirectional tidal oscillations, with flow reversals occurring parallel to the shoreline.

Given the dominance of the u-component, which flows along the coastline, it can be assumed that sediment transport in this area also occurs primarily in the alongshore direction, following the main tidal flow. During the flood phase, the current tends to move westward, while during the ebb phase, it reverses eastward, resulting in periodic advection and resuspension of sediments. Although the current direction is bidirectional, differences in intensity between flood and ebb phases may generate a net transport toward one dominant direction [29], [30], [31]. In the long term, this difference in intensity, influenced by the tidal lag phenomenon, may affect the patterns of sedimentation and erosion within the study area. [32]. Therefore, tidal currents play a key role in sediment transport and distribution processes in this coastal region, particularly in maintaining the dynamics of suspension and redistribution of sediment along the shoreline [33], [34].

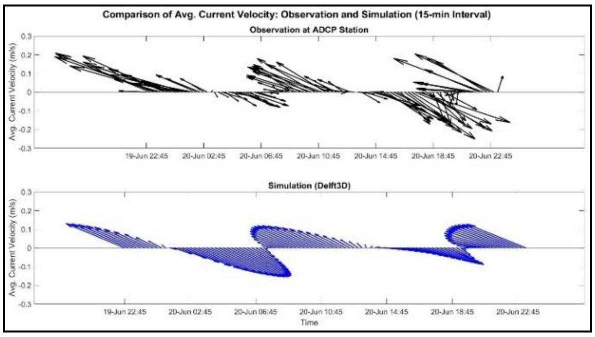

**Figure 6**. Comparison of Avg. Current Velocity Components (U and V) Observation and Simulation

Based on Figure 7, the spatial current pattern indicates that the circulation in the Madura Strait is dominated by two primary flow systems: one originating from the northern waters (Java Sea) and the other from the southern part of the strait. During the flood tide condition, these two water masses move toward each other and converge in the Pamurbaya region (Kenjeran, Wonokromo, and adjacent areas), forming a convergence zone characterized by relatively low current velocities. Conversely, during the ebb tide, the flow reverses direction, with water masses from Pamurbaya moving outward toward the Java Sea in the north and the southern Madura Strait. This bidirectional pattern suggests that the current system in the Madura Strait is predominantly driven by tidal dynamics, with the convergence around Pamurbaya potentially acting as a sediment deposition area due to the reduction in current energy at the meeting zone of the two water masses [35].

The spatial and seasonal analysis of current velocity indicates that the potential for sediment transport is at its maximum during the West Monsoon and Second Transitional Season. During these periods, the current velocity increases significantly within the narrow sections of the strait (where morphological constriction occurs) [36], which enhances the capacity for sediment mobilization and transport [37].

In addition to seasonal variability, the tidal phase analysis reveals that the current energy during the flood phase is consistently higher than during the ebb phase [38]. Since the capacity of currents to transport sediment is highly sensitive to variations in flow velocity [39], this energy imbalance indicates the presence of a net sediment transport directed toward the flood condition, particularly during the West Monsoon and the Second Transitional Season. Consequently, sediments mobilized during the flood phase tend to accumulate within convergence zones such as Pamurbaya [40].

Therefore, the combined influence of seasonal variations and tidal dynamics acts as the dominant controlling mechanism in the sediment transport and distribution processes along the Pamurbaya. These findings are consistent with the general characteristics of semi-enclosed, tide-dominated coastal systems, where stronger flood currents typically promote sediment accumulation within nearshore convergence zones [30], [41].

*C. Wave Characteristics*

Based on the time series data of significant wave height (Hsig) in the Pamurbaya area, located along the eastern coast of Surabaya, Figure 8, the fluctuations in Hsig exhibit a clear seasonal pattern throughout the year. The annual Hsig values range between 0.1 and 0.5 meters, with a notable increase observed during the East Monsoon and the Second Transitional Season. This increase correlates with the dominance of winds blowing from the east, northwest, and northeast directions, as shown in Figure 9. Such a pattern reflects the alternating monsoonal wind system between the prevailing east monsoon and the weakening influence of westerly winds, which dynamically affect wave generation and propagation [42].

Spatially, Figure 10, the distribution of Hsig displays a pattern consistent with the temporal (time series) analysis, where the highest wave heights occur in the northern part of the Madura Strait, directly facing the Java Sea. The wave amplitude gradually decreases southward toward Pamurbaya because of refraction, shoaling, and energy dissipation in the shallow coastal zone [43]. This condition indicates that the Pamurbaya area functions as a sheltered zone with low wave energy [44]. Consequently, sediment transport and deposition processes in this region are influenced by the interaction between dominant tidal currents [45] and low-energy waves propagating from the north [46].

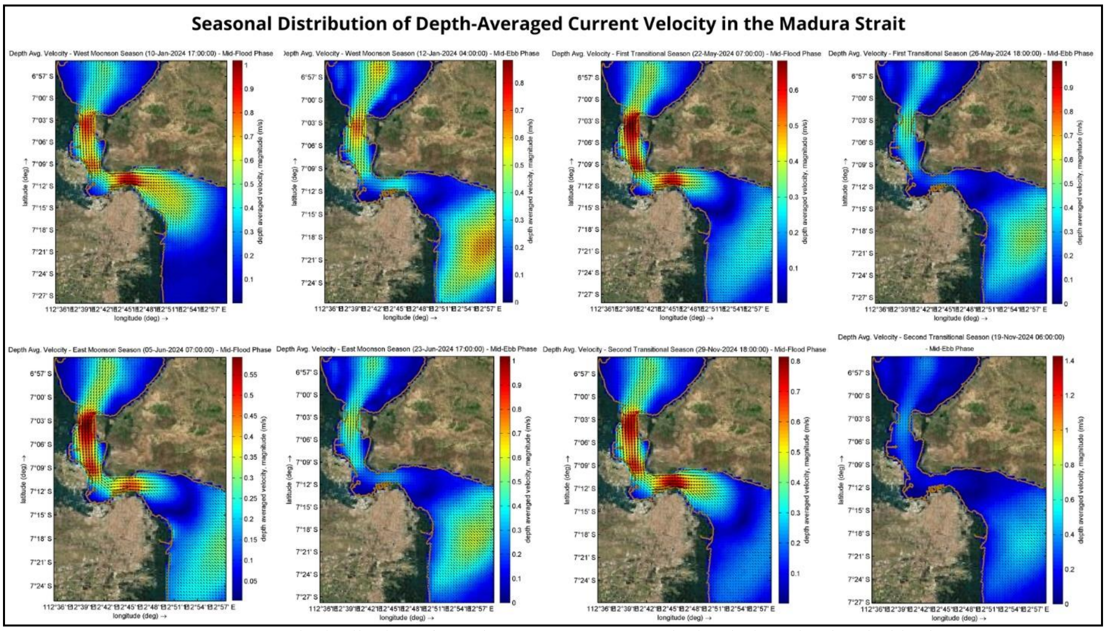


**Figure 7.** Seasonal Distribution of Depth Average Current Velocity during Flood and Ebb Phase

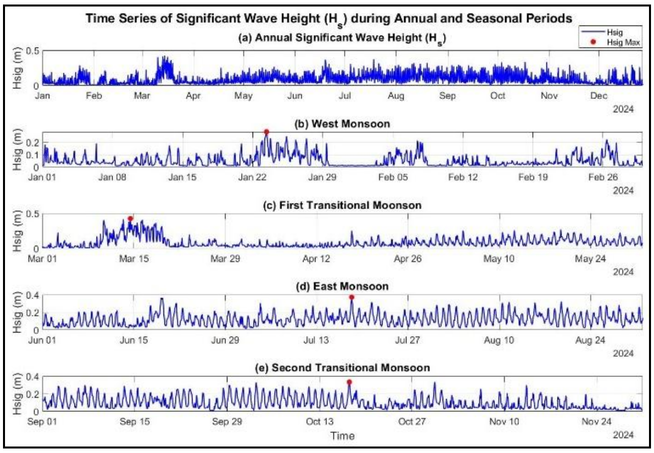


**Figure 8.** Time Series of Significant Wave Height during Annual and Seasonal Periods

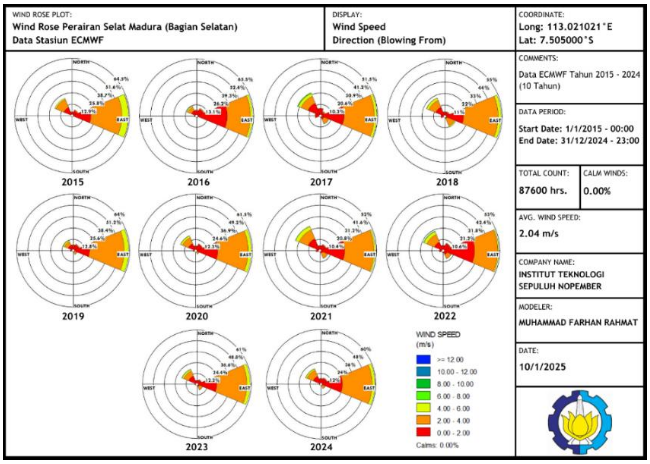


**Figure 9**. Wind Speed from 2015 to 2024 at the Southern Madura Strait Station

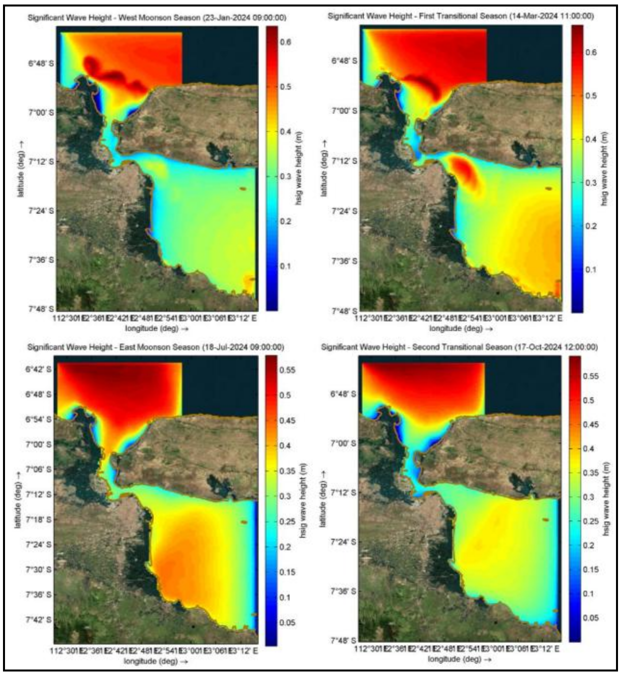


**Figure 10.** Seasonal Distribution of Significant Wave Height

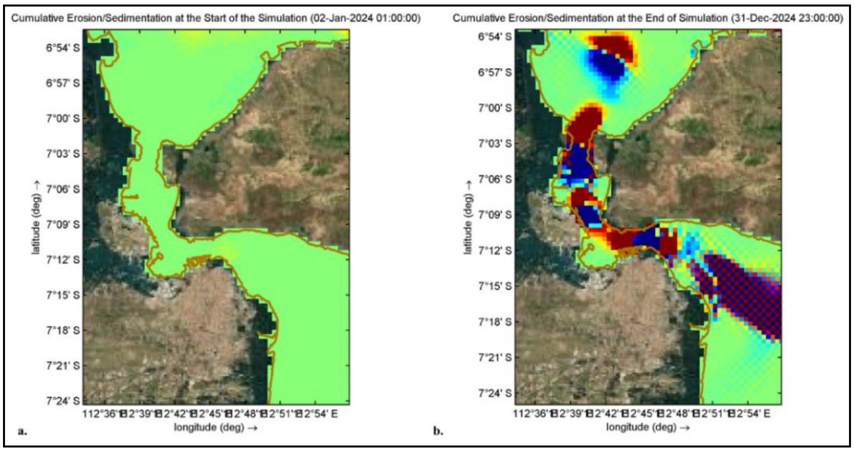


**Figure 11**. Cumulative Erosion and Sedimentation at the Start and End of Simulation

Furthermore, the hydrodynamic regime in the Java Sea and the Madura Strait is primarily governed by locally generated wind waves with short periods and low energy [44]. These waves contribute less to the overall energy balance compared to long-period swells that typically develop in open-ocean environments. In this region, semi-diurnal tidal currents exert stronger control over surface and near-bottom circulation, thereby diminishing the relative influence of wave forcing. The predominance of shallow coastal morphology also promotes enhanced bottom friction and rapid dissipation of wave energy, limiting its impact on nearshore sediment transport processes [47], [48].

Conversely, during the West Monsoon, wave energy decreases significantly because the westerly wind direction is not aligned with the orientation of the Madura Strait, causing the incoming waves to dissipate before reaching the coastal area. Overall, the wave dynamics in the Madura Strait are governed by seasonal variability driven by annual monsoonal wind patterns, with easterly winds acting as the primary generator of waves propagating toward the eastern coastal waters of Surabaya.

### *D. Sediment Transport Pattern*

Sediment transport modeling in the Madura Strait was carried out using two types of sediment: non-cohesive (sand) and cohesive (mud or clay/TSS), which were determined based on laboratory analyses of collected sediment samples and subsequently used as input parameters in the Delft3D model. The simulation covered a one-year period, from 1 January 2024 to 31 December 2024, to evaluate the morphological changes induced by sediment transport processes driven by the prevailing hydrodynamics in the study area.

The simulation results, Figure 11, reveal that during the one-year period, morphological changes occurred across four key areas the mouth of the Madura Strait, the central strait, the vicinity of Tanjung Perak Port, and the Pamurbaya coastal zone. These changes are characterized by alternating erosion and sedimentation patterns, with cumulative bed-level variations ranging between –0.02 and +0.02 m. Although the overall morphological change is relatively minor, localized zones of erosion and deposition remain dynamically active throughout the domain.

Spatially, erosion tends to occur in the central and northern entrance of the strait, corresponding to areas with high current energy generated by tidal flows during the flood phase from both the northern and southern boundaries. In contrast, sedimentation is concentrated in shallow coastal zones such as Pamurbaya, where weak tidal currents favor the gradual deposition of cohesive (fine-grained) materials [49]. In addition to tidal forcing, the spatial sediment distribution is also influenced by the low-energy wave regime within the Madura Strait, particularly in the sheltered Pamurbaya region. The combination of weak wave energy and dominant tidal-driven currents promote enhanced deposition of fine sediments in this area [50].

To better illustrate these morphological changes, Figure 12 presents four cross-sectional transects selected for further analysis, with the simulated bed-elevation variations along each transect shown in Figures 13–16. The results indicate that the most pronounced morphological changes occur in the Pamurbaya area, marked by an increase in bed elevation due to sediment accumulation. Although the annual rate of change is relatively small (±0.02 m), continuous accumulation over time may contribute to estuarine [51] and port siltation [34], potentially altering local circulation patterns [52] and affecting benthic habitats [53]. These findings emphasize that the interaction between tidal dynamics, current velocity, wave conditions, and sediment characteristics acts as the principal control on the spatial distribution of erosion and sedimentation within the Madura Strait.

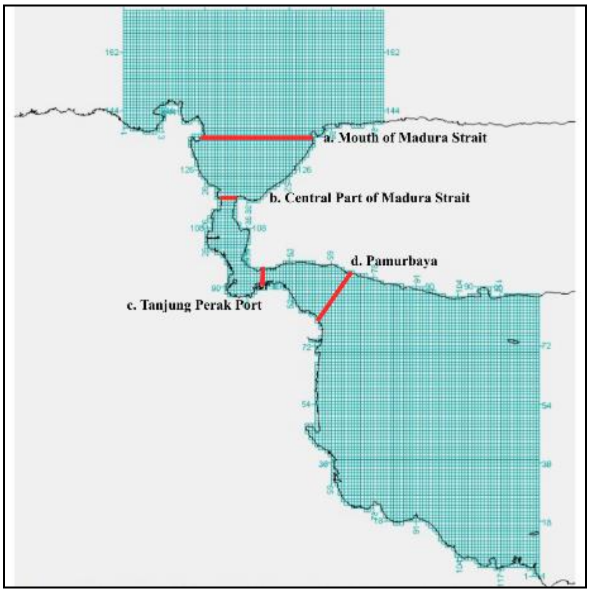


**Figure 12.** Cross Section at Madura Strait

## IV. CONCLUSION

This study focuses on analyzing the hydrodynamic characteristics and sediment transport processes in the Madura Strait and their implications for the eastern coastal area of Surabaya (Pamurbaya) through three-dimensional numerical modeling. The results indicate that current dynamics in the Madura Strait are predominantly driven by tidal forcing, exhibiting a bidirectional tidal flow pattern with a noticeable phase lag between flood and ebb tides. The difference in current intensity between these two tidal phases generates a net sediment transport in a particular direction, contributing to the formation of a convergence zone and the accumulation of sediments within the Pamurbaya region.

The wave dynamics in the Madura Strait display a distinct seasonal pattern, with significant wave heights (Hsig) ranging from 0.1 to 0.5 m and increasing notably during the East Monsoon and the Second Transitional Season due to the dominance of easterly winds. However, overall wave energy in the Pamurbaya area remains relatively low because of coastal morphological shielding and energy dissipation in the shallow nearshore waters. Consequently, sedimentation processes in this region are primarily influenced by tidal currents rather than wave action.

The sediment transport simulation results reveal relatively minor morphological changes (–0.02 to +0.02 m per year), though spatially active across key zones such as the mouth and central part of the Madura Strait, the Tanjung Perak Port area, and the Pamurbaya coastline. Repeated fine-sediment accumulation within the Pamurbaya convergence zone may lead to long-term estuarine and port siltation, potentially affecting local circulation patterns and shoreline stability.

These findings hold significant relevance for the ongoing and planned coastal development along eastern Surabaya, particularly the Surabaya Waterfront Land (SWL) project in Pamurbaya. Considering the area's low wave energy yet high sedimentation potential, adaptive and morphodynamic-based coastal management strategies are required. Furthermore, a comprehensive sediment budget analysis is recommended to evaluate the balance between sediment supply, transport, and deposition within the region. Such an approach would provide a scientific foundation for developing effective sediment management and periodic monitoring strategies to ensure long term sustainability of coastal morphology and infrastructure functions in the future.

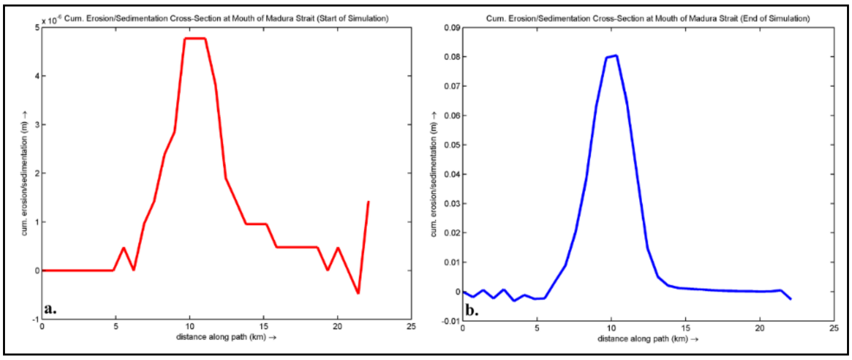


**Figure 13.** Cumulative Erosion and Sedimentation Cross Section at Mouth of Madura Strait

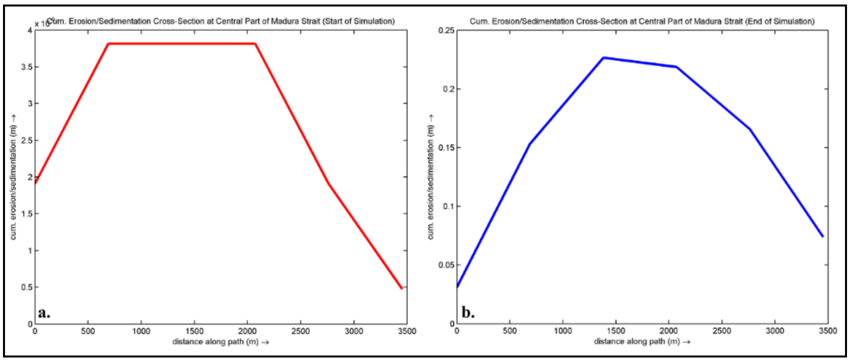


**Figure 14.** Cumulative Erosion and Sedimentation Cross Section at Central Part of Madura Strait

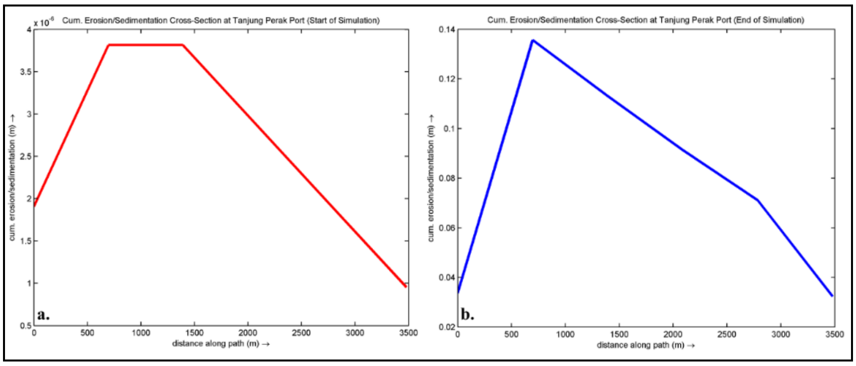


**Figure 15.** Cumulative Erosion and Sedimentation Cross Section at Tanjung Perak Port

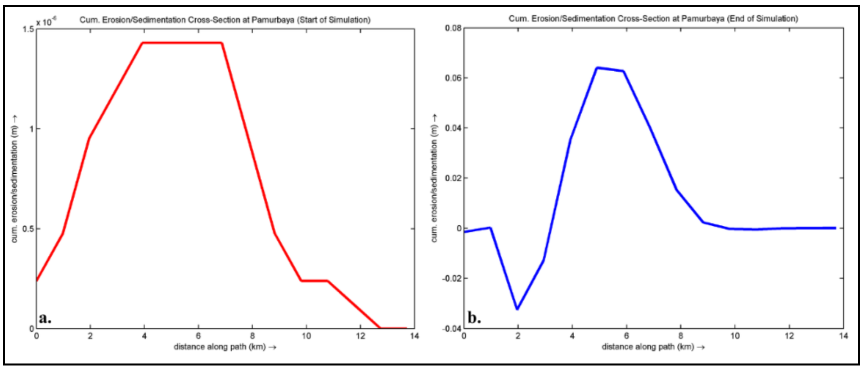


**Figure 16.** Cumulative Erosion and Sedimentation Cross Section at Pamurbaya

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