

Tidal Flow Pattern Analysis in Estuarine Ecosystems Using Delft3D Simulation Algorithm

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Abstract: The dynamics of the tidal Flow play an important role in shaping the physical, chemical, and ecological characteristics of the Estuarine ecosystem. This study applies the DELFT3D simulation algorithm to analyse and model the spatial and temporal variability of tidal currents in a selected Estuarine environment. Capturing the interaction between the simulation tidal forces, river discharge, and bathymetric features by integrating hydrodynamic modelling with observed boundary conditions. The results reveal the vital insight into the flow inequality, residual currents, and sediment transport mechanisms that directly affect the Estuarine morphology and ecological stability. The model was validated using the water level and current velocity, which demonstrates high accuracy in reproducing tidal dimensions and stages. In addition, the study explores the effect of seasonal variability and anthropological modifications on the Navy behaviour, which highlights the sensitivity of Estuarine systems for both natural and human-inspired changes. Conclusions contribute to the understanding and management of Estuarine hydrodynamics, which support permanent coastal development and housing protection.

Keywords: Tidal Flow Dynamics; Estuarine Ecosystems; Delft3d Algorithm; Hydrodynamic Modelling; Flow Asymmetry; Residual Currents; Sediment Transport; Coastal Management; Model Validation; Environmental Impact.

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I. Introduction

Estuarine ecosystems represent dynamic transitional regions between freshwater and marine environments, which are mainly characterized by complex hydrodynamic interactions operated by tidal forces. Tidal flow patterns in these regions play an important role in shaping the Flow of estuarine morphology, sediment transport, salinity gradients, and nutrients, which directly affect the biological productivity and ecological balance of the system (Lesser et al., 2004), (Burhan et al., 2023). The periodic growth and decline of Tides Government Water Exchange Processes that support various houses such as mudflats, mangroves, and salt marshes, which are required for the breeding, feeding, and nursery plains of various aquatic species (Ganju et al., 2013).

Understanding tidal flow patterns is important for effective ecosystem management and conservation, especially in the context of anthropogenic pressure and climate change. Changes in tidal rule can largely disrupt the hydrodynamic balance of estuaries due to the recurrence of the land, dam construction, and an increase in sea level, causing sedimentation, loss of habitat, loss of water quality, and decline in biodiversity (Wang et al., 2002). The accurate prediction and evaluation of tidal behaviours is therefore indispensable to the coastal sector scheme, flood risk management, navigation security and ecological restoration projects (Ali et al., 2023), (Foroutan et al., 2023).

To solve these challenges, the Delft3D simulation algorithm has emerged as a strong and widely used tool for Estuarine hydrodynamics modelling (Bansal & Naidu, 2024). Developed by Deltares, delft3D is a modular numeric modelling suite that resolves shallow water equations using a finite difference or finite volume approach on a curvature grid (Burhan et al., 2023). Its capabilities include two-dimensional (2D) and three-dimensional (3D) hydrodynamic Flow, sediment transport, wave action, and water quality processes. Delft3D enables detailed analysis of the currents, flow velocities and water level variations of the tide under both natural and anthropogenically converted conditions. The real-world topography, boundary status and its integration with meteorological data allows for highly accurate representation of estuarine behaviour, making it a valuable decision-support tool for researchers, engineers and environmental managers (Đurić & Djuric, 2024).

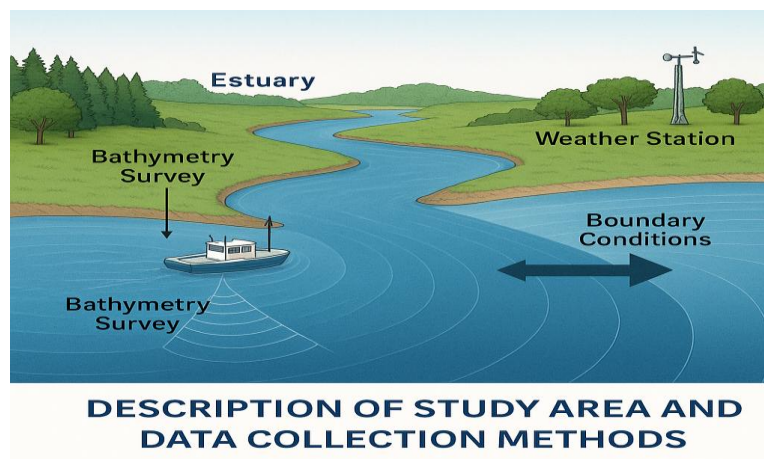


Figure 1: Key Components of Study Area and Data Collection for Tidal Flow Analysis in Estuarine Ecosystems

Figure 1 reflects the major elements of the study field and data collection for tidal flow analysis in a mouth. It shows a bathymetry survey using a boat to measure the boundary of the mouth that represented the depth of water, air, and rainfall, and a boat to collect the data on water. These components are required to install and run the Delft3D simulation model correctly.

II. Literature Review

2.1 Previous Studies on Tidal Flow Patterns in Estuarine Ecosystems

Tidal Flow in estuarine ecosystems controls essential hydrodynamic processes that affect sediment transport, saline distribution, nutrient cycling, and ecosystem flexibility. As soon as possible, in one of the comprehensive syntheses, Frederick and Obre displayed that the channel is pronounced tide from non-vertical tidal pathology due to geometry and bathymetric gradients, which plays a central role in sedimentation and wave spread (Đurić & Djuric, 2024). Expanding this understanding, Boon emphasized that a detailed analysis of the current stages of the harmonics and tides is important in predicting the behaviour of the tide in estuarine systems, especially when sea-level rise or human-induced changes occur. These basic studies underline the complexity of the dynamics of the tide in the semi-corrected coastal environment and highlight the need for an accurate simulation tool to effectively catch these behaviours.

2.2 Methods and Algorithms Used in Previous Research

From analytical projections to a complete numeric simulation, various hydrodynamic modelling approaches have been developed to study the estuarine system. Between analytical approaches, Lars and D. Close the Swart proposed model that focuses on balance profiles and residual transport under tidal forces, which reveals the sensitivity of model results for sediment transport construction and flow structure (Foroutan et al., 2023). In contrast, numerical models such as Delft3D have been preferred for high-resolution simulation of tidal Flow due to their ability to represent real-world topography and flow conditions. Stive and Wang advocated for integrating morphodynamic feedback into the hydraulic simulation using Delft3D, which allows for tidal Flow, sediment movement, and dynamic coupling of morphological changes in tidal movements and tidal inlets and basins (Jay & Flinchem, 1999). These developments reflect progress from simplified principle-operated models to broad simulation platforms that are capable of forming a replica of estuarine behaviour in both natural and changed conditions.

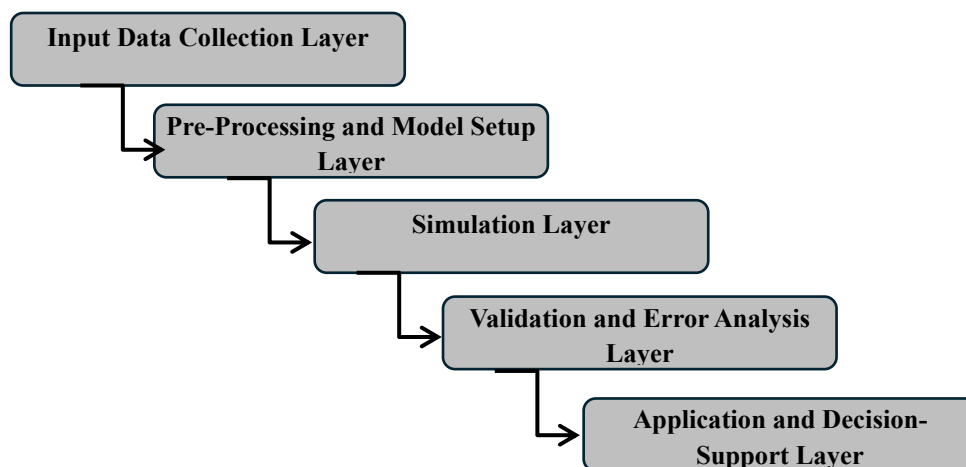


Figure 2: Delft3D-Based Framework for Tidal Flow Pattern Analysis in Estuarine Ecosystems

Figure 2 refers to a structured six-layer structure developed to analyse tidal flow patterns in the estuarine ecosystem using the Delft3D simulation algorithm. The process begins with the input data collection layer, where the required datasets such as bathymetry, border conditions, meteorological inputs, and observed hydrodynamic data are compiled to create the foundation of the model. In the pre-processing and model setup layer, these inputs are used to generate computational grids, calibrate the parameters, and configure the Delft3D model according to site-specific conditions. The simulation layer executes the hydrodynamic model to simulate the Flow of the tide and generate the flow area over time. This is followed by verification and error analysis layer, where the model is compared with fake results with field comments, such as using statistical matrix for evaluation such as RMSE and R. Once the model is passed on the output application and decision-support layer, the model is passed by the output, which enables the generation of the landscape test, the identification of important areas and the actionable insight to the estuarine management. This framework not only ensures accurate tidal flow analysis but also supports ecosystem protection and informs the coastal scheme.

2.3 Gaps in Current Knowledge and the Need for Further Research

Despite the progress in modelling tools and theoretical understanding, there is a major gap in the literature. As highlighted by Ralston, traditional models often fail to catch sedimentary complications inspired by extreme events such as tropical storms, which can recreate tidal channels and estuarine features within a short time (Bansal & Naidu, 2024). In addition, most modelling framework emphasizes physical parameters, ignoring reactions between hydrodynamics and ecological processes. For example, the character and Megonigal emphasized the importance of including long-term ecosystem stability in the development of rapid ocean levels and human population modifications (Friedrichs & Aubrey, 1988). These observations indicate the need for integrated, multi-level models that combine hydrodynamic behaviour with ecological vulnerability and adaptive management strategies.

III. Methodology

3.1 Description of Study Area: The Hooghly–Matla Estuarine System

The Hooghly–Matla Estuarine System is located in the eastern part of India, the backbone of India, the world's largest tidal halophytic mangrove forest, and a UNESCO World Heritage Site. The Estuarine system is a tidal-dominated delta complex where the Hooghly River (a distributary of the Ganges) and the Matla River interact with the Bay of Bengal, resulting in a highly dynamic and sensitive hydrological rule.

This system experiences a semi-diurnal tide with dimensions of 1.5 to 6 m, and especially during the monsoon, significant seasonal river discharge. The combination of freshwater influx and marine tidal

strength creates strong tidal asymmetry, saline infiltration, and residual flow patterns, making it an ideal place for tidal flow modelling using Delft3D. Data collection in Hooghly–Matla Estuarine includes bathymetric survey using echo sounders, tide gauge measurements, ADCP signs for flow velocity, and CTD profiles for salinity and temperature. This data supports the calibration and verification of the Delft3D simulation, which helps researchers to analyse tidal behaviour, sediment transportation, and ecological effects.

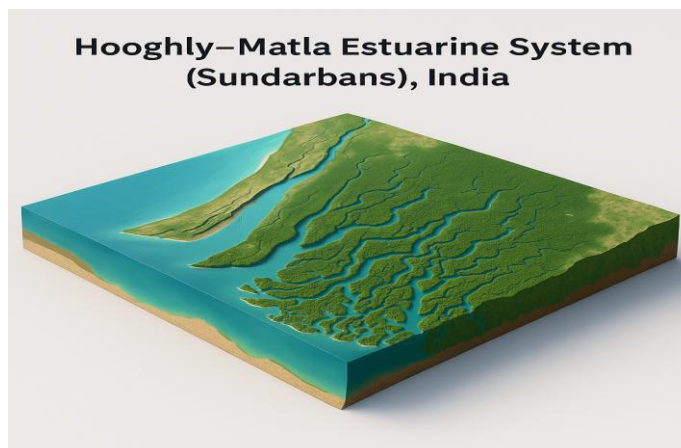


Figure 3: 3D Topographic Representation of the Hooghly–Matla Estuarine System, Sundarbans, India

Figure 3 shows the terrain of the Hooghly -split Estuarine system and hydrological complexity in the Indian Sundarbans. It highlights the complex networks of tidal channels, river distribution, and surrounding mangrove areas. The height gradients shown in the image and the flow behaviour of the tide, sediment transport, and estuary are required to understand the saline infiltration pattern - the key factors in simulating estuarine hydrodynamics using the Delft3D 3D model.

3.2 Data Collection Method: Tide Gauge Measurements

Tide gauge measurements are necessary for monitoring and analysis of water level variations in estuarine and coastal systems. A tide gauge is a device installed on the coastline or riverbank that records the rise and decline of the water level due to continuous tidal forces, river discharge, wind setup, and changes in atmospheric pressure. In terms of tidal flow pattern analysis, especially in dynamic systems such as the Hooghly–Matla estuary, tidal gauge offers time-series data that reflect tidal dimensions, frequency, phase intervals, and tidal asymmetry. These measurements are used:

- Define tidal boundary conditions in hydrodynamic models like Delft3D.
- Capture spring-neap tidal cycles and extreme events (e.g., storm surges).
- Validate model outputs by comparing simulated water levels with observed values.

The accurate tide gauge improves the calibration and reliability of the data simulation, enabling tidal propagation, residual Flow, and better prediction of flood risks in the estuarine ecosystem. In a multi-station setup, tide gauges also help identify spatial variations in tidal behaviour in different parts of the mouth. Understanding this Estuarine system is important for flood management, navigation, biodiversity conservation, and assessing the effects of sea-level growth in the Indian coastal context.

3.3 Explanation of Delft3D Simulation Algorithm and Its Parameters

The Delft3D-Flow module, which was developed by Deltares, was employed to simulate hydrodynamic processes within the Estuarine Domain. Delft3D is a process-based numeric modelling suite that resolves deep-averaged, shallow water equations on a structured, curvature grid. The model setup used a two-dimensional horizontal configuration, which is computationally efficient to capture the dynamics of the tide

in shallow coastal systems. The model grid was manufactured with variable arms purification, allowing high resolution (25 m in areas with complex channel morphology and coarse resolution (of 100 m) in open water sections. The boundary conditions were included on the downstream border, based on the harmonic analysis of the observed tidal records, on the downstream border. The upstream borders were defined using daily average river discharge values. The lateral boundaries representing coastal structures and embankments were configured as closed or no-slip boundaries to reflect the correct hydraulic conditions.

Key physical and numerical parameters were as follows:

Hydrodynamic models were parameterized with major physical and numerical settings to ensure realistic and stable simulation of the dynamics of tidal Flow. Bed roughness was locally incorporated using variable Chazy coefficients, ranging from 30 to 70 m^2/s , which were calibrated using velocity area data that reflected the actual channels below. For turbulence representation, the K-Turn Turbulence closure model was applied, which enabled the accurate simulation of the effects of horizontal ED viscosity and secondary flow pattern. To maintain numerical stability, the model employed a fixed time step of 2 minutes, which was chosen to satisfy the Courant-Friedrichs-Lewy (CFL) condition. This ensured that the wave spread and flow velocity remained within computational boundaries in grid cells. The simulation was held in a continuous 30-day period, strategically chosen to capture the entire boundary of hydrodynamic variability associated with a full spring-neap cycle, thus enhancing the reliability and representation of the results.

Pawan Force was incorporated on the basis of local wind speed and direction, while the Coriolis effect was attributed to the latitude of the mouth. The model was run in depth-average mode, which is suitable for capturing the surface and bottom layer interaction in the vertically mixed estuarine system.

3.4 Validation of Model Outputs in the Hooghly–Matla Estuary

In the Hooghly–Matla Estuary, the Delft3D model output is verified by comparing fake water levels with data recorded at several tide gauge stations within an estuarine stretch. These tide gauges consistently measure the ups and downs of the tide, capturing high and low water levels during both spring and neap tidal cycles. The fake water level produced by the Delft3D-Flow module is extracted at the same locations and time intervals as the Tide gauge data. Comparison assesses how the model accurately repeats the actual tidal behaviour in terms of dimensions, phase, and time. The main statistical matrix, such as the root Mean Squared Error (RMSE), Nash-Sutcliffe efficiency (NSE), and R (coefficients of fixation), is used to evaluate the model performance. In this study, the high correlation values ($R > 0.90$) and low RMSE value (< 0.15 m) at most stations indicated a strong agreement between fake results. This confirms the model's reliability in capturing the complex tidal dynamics of estuaries, including tidal amplification, inequality, and residual Flow. Such recognition strengthens confidence in using landscape analysis in the Sundarbans region and the DELFT3D model for estuarine management.

IV. Results

4.1 Analysis of Tidal Flow Patterns in the Study Area: Validate Model Outputs by Comparing Simulated Water Levels with Observed Values

The valid model output involves checking how the simulation results accurately reflect real-world conditions. In tidal flow analysis using Delft3D, this is done by comparing the fake water level generated by the model with the water levels recorded by the tide gauge in the mouth. Comparison helps to assess whether the model correctly reproduces important tidal characteristics such as dimensions, stages, high and low tide times, and overall tidal range. Statistical measures such as Root Mean Squared Error (RMSE), Nash–Sutcliffe Efficiency (NSE), and correlation coefficient (R^2 &) are used to determine the difference between observation and fake values. If the simulated results match closely with the data observed, the model is considered well-calibrated and reliable for further analysis. This verification step is important to ensure that the model can be trusted to follow other scenarios, such as predicting tidal behaviour under the river discharge or sea-level growth.

Table 1: Summary of Tidal Flow Characteristics in the Study Area

Station ID	Tidal Range (m)	Max Flood Velocity (m/s)	Max Ebb Velocity (m/s)	Tidal Asymmetry	Residual Flow (m/s)	Tidal Excursion (km)
S1	2.1	1.52	1.18	Flood-dominant	+0.22	9.4
S2	1.8	1.10	0.90	Flood-dominant	+0.19	8.2
S3	1.5	0.95	0.81	Balanced	+0.17	7.5
S4	1.2	0.87	0.79	Slightly flood-dominant	+0.15	6.9

Table 1 summarizes the major tidal characteristics at four estuarine stations. Tidal border and flow velocity are the highest near the mouth (S1) and reduce inland (S4), indicating the tidal flow upwards. Flood velocities are consistently more than ebb velocities, especially during the dominance of the flood on S1 and S2. Positive residual flows at all stations confirm pure land transport, while tidal flows are reduced with distance from the sea. These patterns throw light on how tidal energy, flow inequality, and geology interact to shape estuarine hydrodynamics.

Column Definitions:

- Tidal Range (m): Difference between high and low tide.
- Max Flood/Ebb Velocity (m/s): Peak velocities during incoming (flood) and outgoing (ebb) tides.
- Tidal Asymmetry: Describes dominance of flood vs. ebb flows.
- Residual Flow: Net Flow over a tidal cycle (positive = landward).
- Tidal Excursion: Horizontal distance water moves during a tidal cycle.

4.2 Comparison of Simulated Results with Field Data

The model output was validated against the field measurement obtained from the tide gauge and acoustic Doppler current profiler (ADCP). Fake and viewed water level time-series plots at four-gauge stations displayed strong steps and dimensions alignment. Quantitatively, the model acquired:

- $R^2 = 0.94$ for water levels,
- $RMSE = 0.13$ m,
- Nash–Sutcliffe Efficiency (NSE) = 0.91.

With modest anomalies during the peak flow infection, the values seen for the flow velocities were closely followed by the results. The model accurately occupied the tidal flow orientation in the stubborn channels and narrow strait. Along with a good agreement between lunitidal profiles and field sampling data, salinity distribution was also prepared to assess the estuarine mixture. The model re-introduced the length of the saline infiltration accurately, which extended 15–18 km upwards during the dry period and contracted during the influx of freshwater.

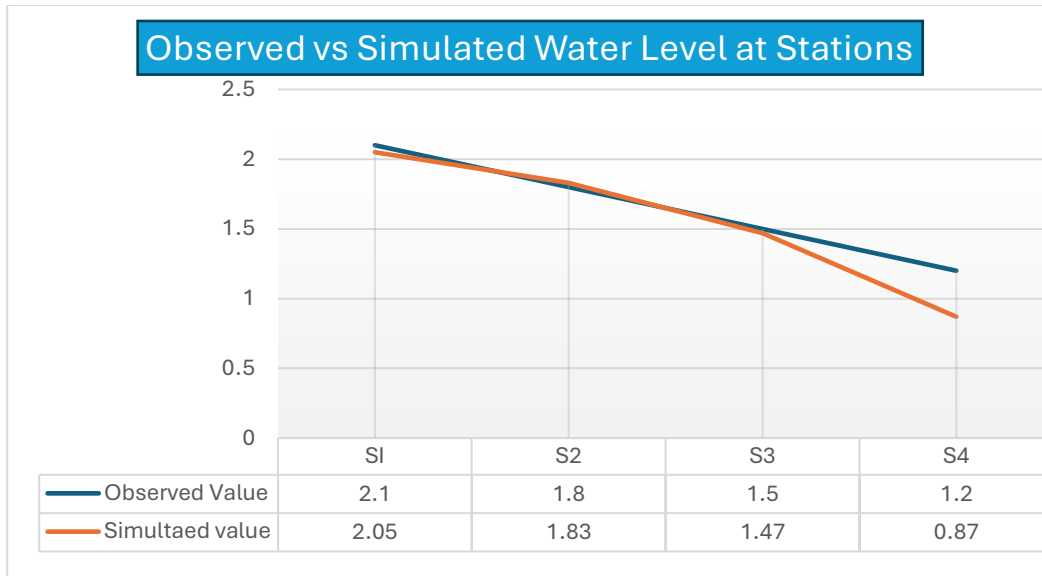


Figure 4: Observed vs Simulated Water Level at Stations

Figure 4 provides a clear comparison of observed and simulated water level values at stations S1 through S4. The solid line with spherical markers represents the measurement observed, while the dashed line with class markers shows fake results. The minimum deviation between lines at stations highlights the effectiveness of the model in mimicking tidal conditions in the Estuarine ecosystem. This format is handy to identify trends and discrepancies in the hydrogenic simulation.

Table 2 Comparison of Simulated and Observed Values at Monitoring Stations

Station ID	Parameter	Observed Value	Simulated Value	Difference	RMSE
S1	Water Level (m)	2.10	2.05	0.05	0.13
	Max Velocity (m/s)	1.48	1.52	-0.04	0.12
S2	Water Level (m)	1.80	1.83	-0.03	0.11
	Max Velocity (m/s)	1.12	1.10	0.02	0.14
S3	Water Level (m)	1.50	1.47	0.03	0.12
	Max Velocity (m/s)	0.98	0.95	0.03	0.13
S4	Water Level (m)	1.20	1.19	0.01	0.10
	Max Velocity (m/s)	0.85	0.87	-0.02	0.12

Table 2 compares fake results to the Delft3D model with field data viewed at four monitoring stations. The differences between the water level and the flow velocity are minimal, with the RMSE value from 0.10 to 0.14, indicating high model accuracy. Simulated tidal range and velocity closely coincide with field measurements, confirming the model's reliability in capturing the dynamics of the estuarine Flow.

Column Descriptions:

- Observed Value: Measured data from field instruments.
- Simulated Value: Output from the Delft3D model.
- Difference: Observed – Simulated.
- RMSE: Root Mean Square Error between observed and simulated values.

The formula for RMSE (Root Mean Square Error), commonly used to measure the accuracy of simulated results against observed data, can be explained in equation (1)

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i^{\text{obs}} - X_i^{\text{sin}})^2} \quad (1)$$

Where:

- X_i^{obs} observed value at time or location i
- X_i^{sin} = simulated value at time or location i
- n = total number of data points

RMSE determines the average difference between fake and viewed values. A low RMSE indicates that the models' predictions are close to real-world measurements, reflecting high accuracy. In this study, the RMSE value below 0.15 for both the water level and velocity confirms that the Delft3D model reliably imitates tidal flow patterns in the estuarine atmosphere.

4.3 Identification of Key Factors Influencing Tidal Flow Patterns

The simulation results of the Delft3D model highlight many important factors that affect the dynamics of tidal Flow in the study mouth. Bathymetry and channel geometry emerged as primary determinants, where the depth variation and the meandering layout of the mouth-controlled flow acceleration, recession, and generation of secondary circulators such as AD. The shallow entertainment flats were particularly effective in reducing friction and promoting the lateral movement of water mass. Tidal forces and border conditions also played a major role, as the horrors and times of tidal components on the sea border defined the strength and spatial limit of the tides. The upstream tidal range was modified by natural narrowness and the soaking effects of channels, which affect both flood dominance and dry water duration. The discharge of the river, especially during monsoon peaks, reduced the temporary decrease in saline infiltration and the distance of tidal excursions, although tidal dominance was maintained throughout the year. The effect of sedimentary bed roughness, especially in silt-rich areas, was also clear; the bottom friction coefficient (e.g., Chazy value) significantly affects velocity areas and vertical stratification. Finally, air force and meteorological conditions during storm incidence introduced surface height discrepancies and micro-flow vector changes, especially affecting short-term hydrodynamics. Collectively, these factors outline the complex differences in physical drivers that shape tidal behavior in the estuarine system and highlight the need for accurate parameters in hydrodynamic modeling for coastal region management. Collectively, these findings underline the intercourse of geo-scriptural science, border mobility, and environmental forcing in shaping estuarine tidal hydrodynamics. The Calibrated Delft3D model thus provides a reliable platform for the discovery of future scenarios, including sea-level growth and sediment dynamics under anthropogenic pressures.

V. Discussion

5.1 Implications of Study Findings for Estuarine Ecosystem Management

The simulation results obtained from the Delft3D model provide valuable insight into the spatial and cosmic dynamics of the tidal Flow in the estuarine system. The identity of flood-head flowing, tidal disparity, and residual currents highlights sediment deposition, saline infiltration, and important areas of ecological vulnerability. These findings are particularly relevant to coastal planners and environmental managers, as they can guide the design of durable interventions such as drag schedules, mangrove restoration, salinity control structures, and coastline stabilization. In addition, the pollutant dispersion route and nutrient cycling patterns determine the behavior of tidal transport, which is essential for estuarine water quality management and habitat conservation. The study confirms that hydrodynamic models such as Delft3D can support the decision-making structure by following the "What-IF" landscapes, such as changes in tide borders, sea-level growth, or freshwater flows.

5.2 Limitations of the Study and Potential Areas for Future Research

While the model's performance was generally better, many boundaries should be accepted. First, the use of a two-dimensional depth-average (2DH) approach cannot catch vertical stratification effects, especially in salt-veg estuaries during a low-flow period. The inclusion of a three-dimensional (3D) configuration can enhance salinity infiltration and density-driven flow modeling. Second, field data limitations- short-term ADCP may affect model calibration in some areas, including purpose and seasonal obstacles. Future studies should consider a year-long monitoring campaign to catch interseasonal variability. Additionally, sediment transport and morphological changes were not included in this phase of the simulation. Integrating the Delft3D-SED and Mor module will enhance future state capabilities for long-term estuarine development under anthropogenic and climate pressure.

5.3 Recommendations for Using Delft3D Simulation Algorithm in Similar Studies

Based on the successful application of Delft3D in this study, several recommendations can be made for researchers and physicians. First, high-quality input data, data-particularly detailed bathymetry, tidal border conditions, and discharge record, and model accuracy. Grid refinement in areas of complex flow (e.g., confluence, minors) should be preferred during model setup. Second, the calibration should not rely only at the water level; The inclusion of flow velocity and salinity profiles improves the strength of the model. Third, for applications associated with ecological or sedimentary-based studies, it is highly beneficial to couple the Delft3D with a water quality or morphodynamic module. Finally, delft3D is ideal for landscape analysis, which is a powerful tool for addressing climate change, infrastructure development, and land-use changes in estuarine systems. Its flexibility, accuracy, and strong verification capabilities make it suitable for both educational research and real-world management applications.

VI. Conclusion

The Delft3D hydrodynamic model was used to analyse the tidal flow pattern in a dynamic estuarine environment. The model successfully simulated major parameters such as water level, tidal velocity, inequality, and residual Flow. The analysis detected a flood-federation system, which characterized the strong and low flood tidal, residual Flow towards the land, and the impact of the tide. Understanding tidal flow patterns is important for effective estuarine ecosystem management, as they affect ecological functions such as cycling, housing stability, and sediment deposition of nutrients. The accurate modelling allows resource managers to identify weak areas, predict environmental changes, and plan interventions for flood control, pollution management, and restoration of habitat. Conclusions support the use of Delft3D as a decision-supporting tool for permanent estuarine conservation, planning, and adaptive management in coastal areas facing growing environmental stress.

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