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Hydrodynamic and Sedimentation Modeling for Capacity Optimization of OR1, OR2, and Fertilizer Berths at Visakhapatnam Port, India

M. Phani Kumar[1],*, Kapil Walke[2], Prabhat Chandra[3]

Abstract

This study presents comprehensive hydrodynamic and sediment transport modeling undertaken to assess the impact of proposed deepening and development at the Western Arm of the Visakhapatnam Inner Harbor, India, encompassing OR1, OR2, and Fertilizer berths. The work, carried out by the Central Water and Power Research Station (CWPRS) for the Visakhapatnam Port, utilized the MIKE 21 Flexible Mesh (FM) finite-volume model to simulate hydrodynamic and siltation conditions under existing and proposed scenarios. The models incorporated tidal forcing, stream inflows, and morphological processes to evaluate the potential impacts on capacity utilization and environmental equilibrium. Results demonstrated minimal variation in tidal prisms and a marginal increase in siltation (≈3,000 m³ annually) under proposed conditions. Additional simulations on dredged material disposal revealed stable dispersion patterns, with bed thickness increases remaining within 20 cm after one month of continuous dumping. The findings confirm the technical feasibility and environmental sustainability of the proposed development, supporting the optimization of port operations while ensuring morphological stability.

Keywords: Dredging, harbor engineering, hydrodynamic modeling, MIKE 21 FM, sediment transport, siltation, Visakhapatnam Port

INTRODUCTION

The Visakhapatnam Port, located on the east coast of India, serves as one of the country's major maritime gateways, handling a wide variety of cargo, including ore, fertilizers, and petroleum products [1–4]. The port's inner harbor comprises three distinct arms: Northern, Western, and North-Western; each housing specialized berths and terminals. The optimization of berth capacity within the Western Arm, particularly at OR1, OR2, and the Fertilizer berths, has become imperative to meet increasing cargo demands and enhance port throughput efficiency [5–7]. The Visakhapatnam Port commissioned the Central Water and Power Research Station (CWPRS), Pune, to conduct detailed mathematical model studies to evaluate the hydrodynamic behavior, siltation tendencies, and sediment disposal strategies associated with the proposed deepening activities [1–4].

Studies in this regard have mandated the obtaining of coastal regulation zone (CRZ)

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clearance from the Andhra Pradesh Coastal Zone Management Authority (APCZMA) [8–11]. Previous studies at Visakhapatnam had established that alongshore sediment transport, driven by the southwest and northeast monsoons, was effectively managed by a sand trap and bypassing system [12–15]. However, with plans to deepen the Western Arm to accommodate larger vessels, it became essential to assess any potential changes in hydrodynamics and sedimentation. Therefore, the present study focused on (i) assessing hydrodynamic variations due to the proposed deepening, (ii) estimating the resultant siltation in the Western Arm, and (iii) evaluating the environmental effects of dredge disposal in offshore dumping grounds. A mathematical modeling approach was chosen to capture complex tidal-stream interactions and sediment dynamics without physical model constraints [5–7].

STUDY AREA AND DATA

Site Description

The Visakhapatnam Inner Harbor was developed by dredging the Narava River, creating a lagoon-type basin with three arms: the northern, western, and north-western arms. The outer harbor layout is protected by a system of breakwaters, including the south (1543 m), east (1069 m), and north (412 m) breakwaters. The Meghadrigedda and Kondagedda streams discharge into the inner harbor basin, mainly influencing the middle and western arms (Figure 1) [8, 9].

Wave observations along the coast indicate predominant approach directions from the south and southwest, with significant wave heights of approximately 0.9 m during the southwest (SW) monsoon and 0.5 m during the northeast (NE) monsoon. The mean wave period ranges from 4 to 8 s, and the net annual littoral drift is approximately 0.6 million cubic meters northward. To counteract the impact of this drift, a sand trap with a capacity of 0.6 million m³ is maintained on the southern side of the outer basin, with periodic dredging and partial bypassing to nourish the down-drift northern beaches. Historical dredging records between 2004 and 2010 confirm that this system effectively controls the ingress of sea-borne sediments into the inner harbor (Figure 2) [10, 11].

Bathymetry and Hydrodynamic Conditions

The Western Arm, located in the Inner Harbor, experiences limited tidal exchange/smaller tidal prism due to its configuration. Bathymetric data for the harbor area were provided by Visakhapatnam Port as scatter data and converted into gridded surfaces for model input (Figures 3 and 4). Measured data on waves, wind, and tides were integrated into the model setup. The region is influenced by tidal ranges of

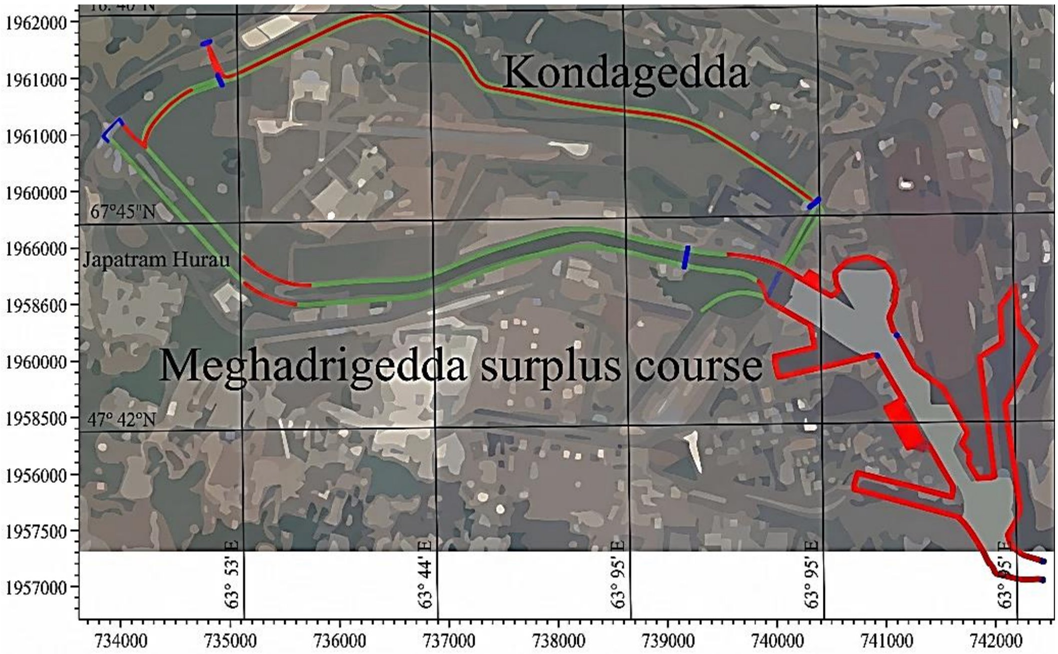


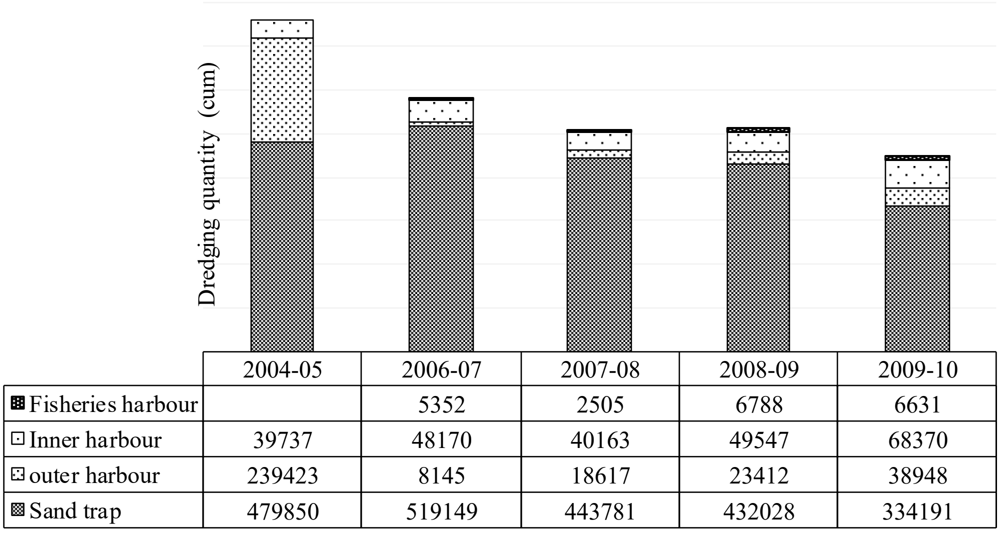
Figure 1. Streams debouching into the inner harbor basin of Visakhapatnam.

approximately 1.5 m, with peak current velocities generally below 0.2 m/s in the inner basins. The combined freshwater from the Meghadrigedda and Kondagedda streams during the monsoon contributes significantly to the inflow hydrodynamics, especially in the North-Western Arm [12–14].

METHODOLOGY

Modeling Framework

A two-dimensional hydrodynamic and sediment transport model was developed using the MIKE 21 Flexible Mesh (FM) software package from DHI. The model domain extended approximately 5 km alongshore and offshore, encompassing both harbor and nearshore regions (Figure 5). A fine mesh was applied within the harbor to accurately capture flow dynamics, whereas coarser grids were used offshore to optimize computational efficiency. The MIKE 21 FM Hydrodynamic (HD) module simulated depth-integrated flows governed by the shallow water equations, whereas the Mud Transport (MT) module simulated sediment movement and deposition. The model solved the continuity and momentum equations under tidal and fluvial forcing, accounting for bed friction, Coriolis effects, and density variations [15].



	2004-05	2006-07	2007-08	2008-09	2009-10
▦ Fisheries harbour		5352	2505	6788	6631
☐ Inner harbour	39737	48170	40163	49547	68370
⊡ outer harbour	239423	8145	18617	23412	38948
▩ Sand trap	479850	519149	443781	432028	334191

Figure 2. Dredging quantities in different regions of Visakhapatnam Port during 2004–2010.

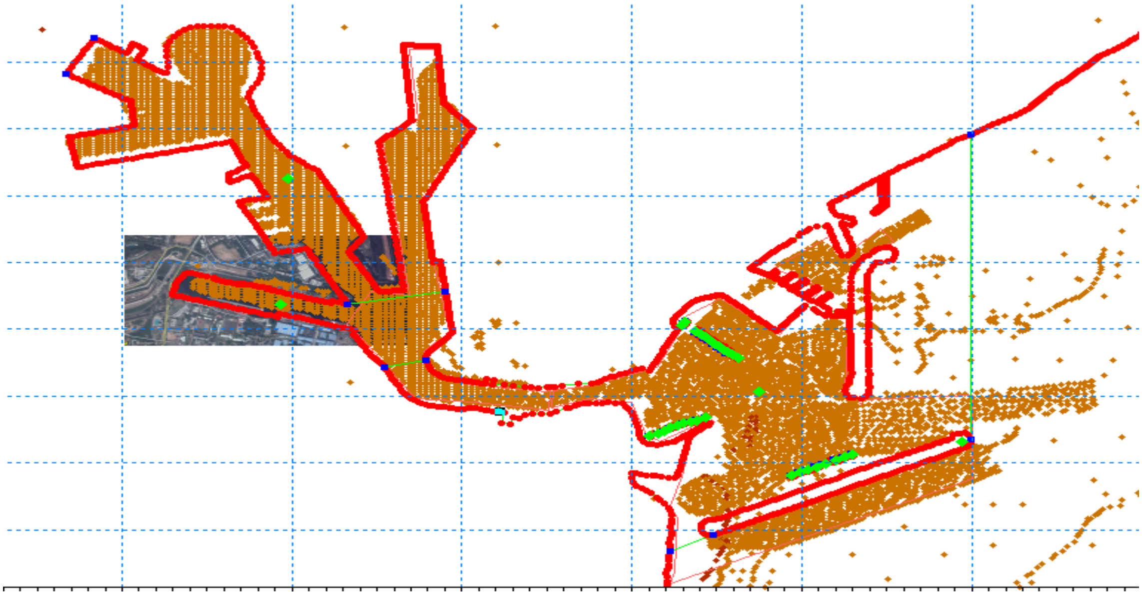


Figure 3. Port area, along with scatter data utilized to generate model bathymetry.

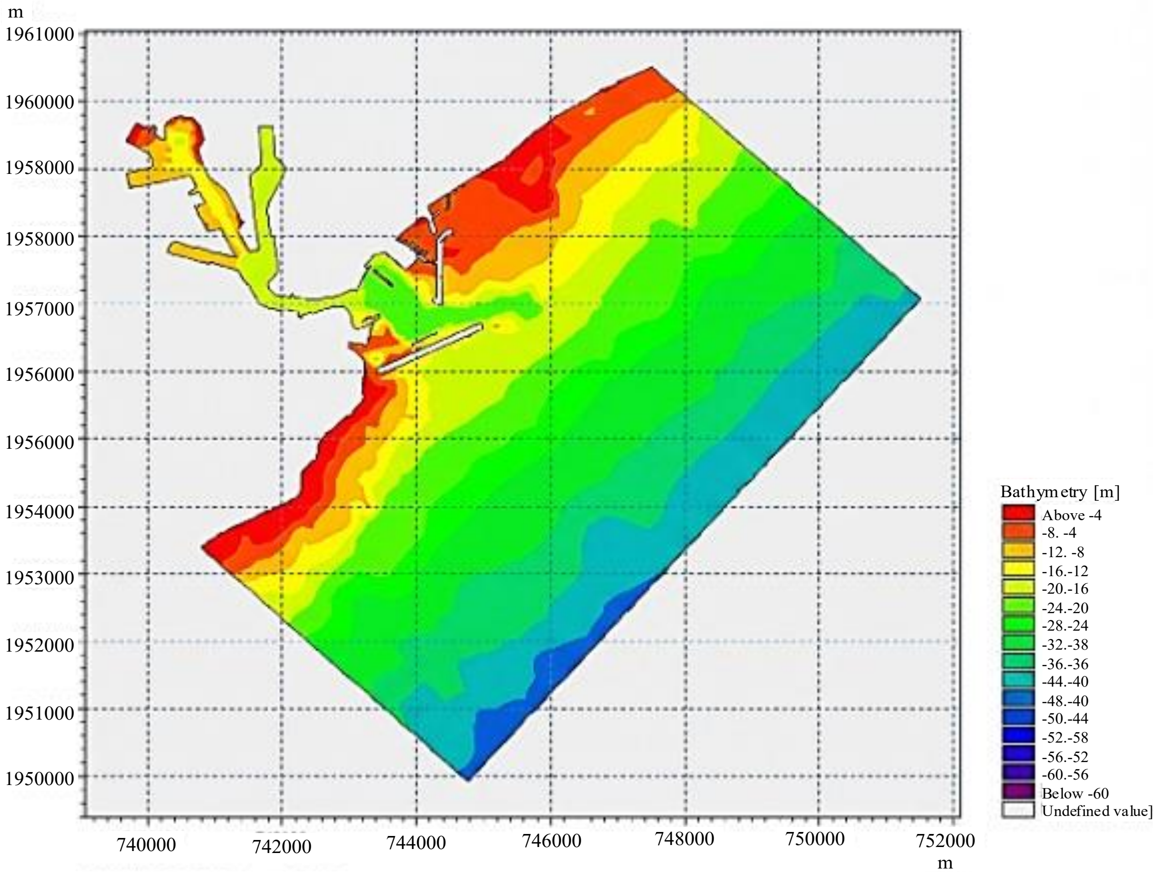


Figure 4. Bathymetry of the port area under existing conditions of the Western Arm.

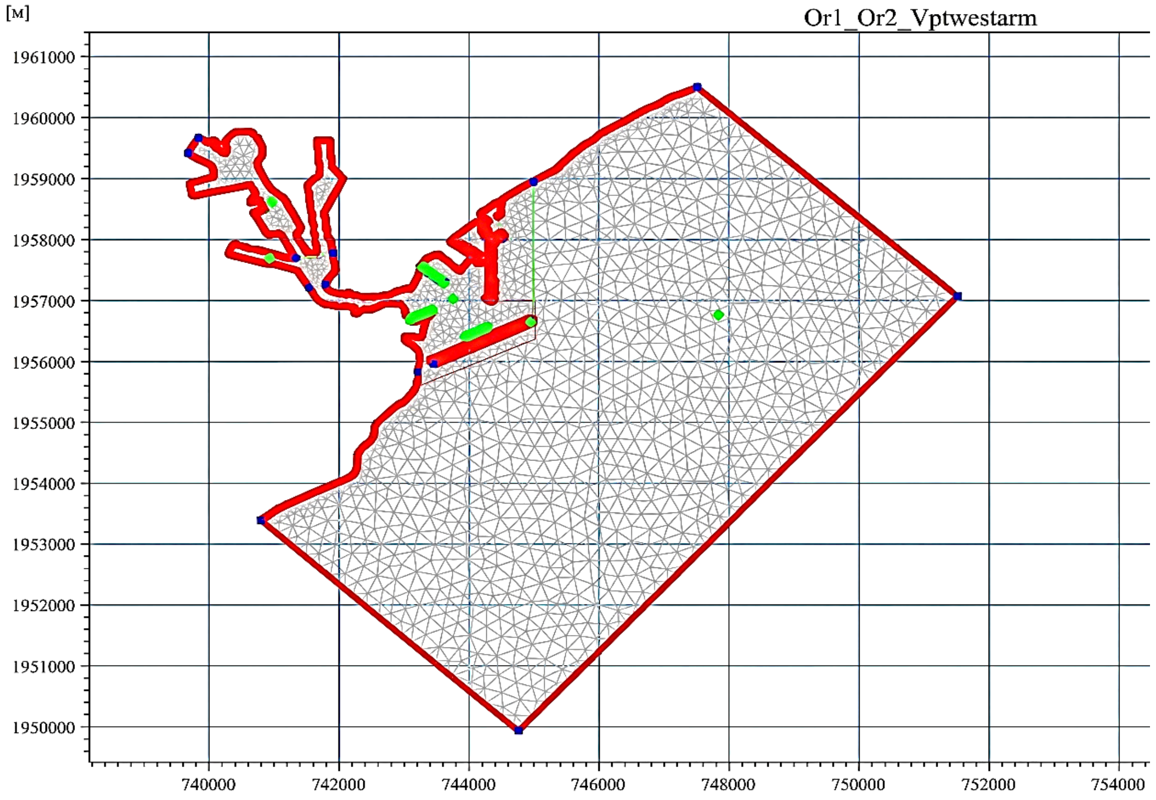


Figure 5. Model domain for the proposed development in the Western Arm.

Boundary Conditions and Calibration

Standard upstream discharge boundaries were defined using a hydrograph representing the combined peak flood discharge of 1900 m³/s (Meghadrigedda: 1500 m³/s, Kondagedda: 400 m³/s) (Figure 6). Tidal boundary conditions were extracted using a global tide model (Figure 7). The model contained 8719 elements and 5418 nodes. Calibration was performed against observed current patterns, with friction coefficients adjusted spatially to achieve stable and realistic flow fields. The friction factor increased near open boundaries to accurately simulate peak monsoon discharges.

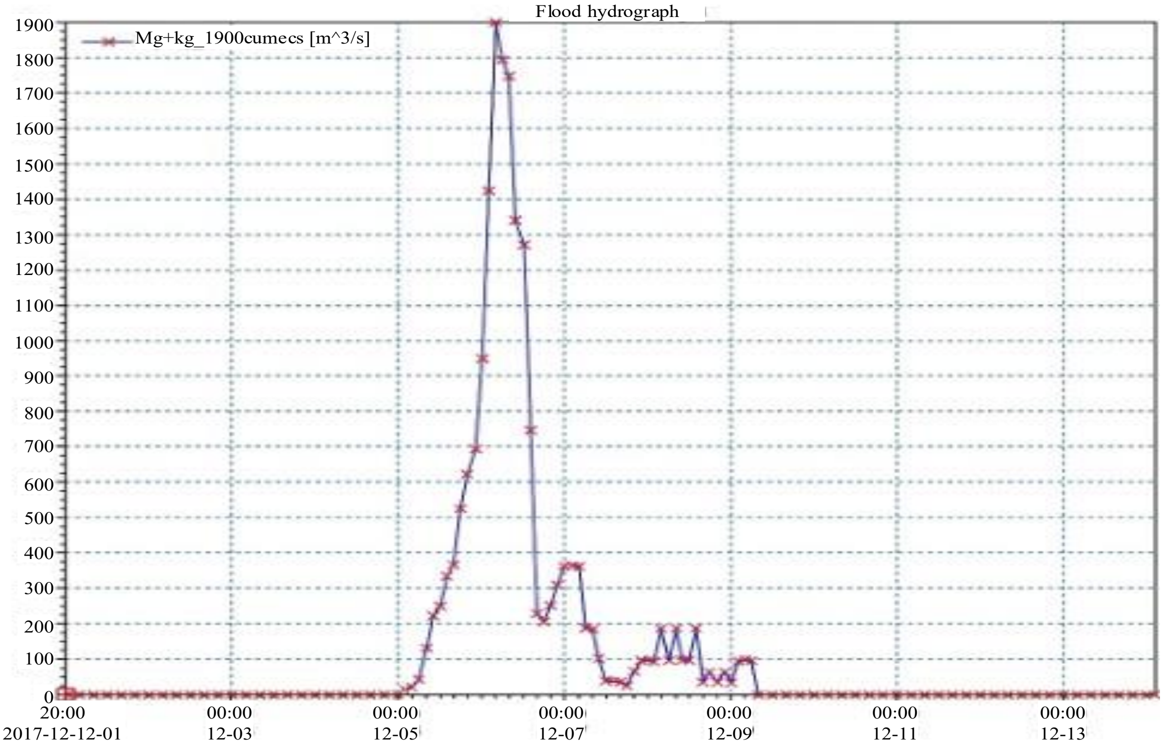


Figure 6. A hydrograph is adopted in the model as the upstream discharge boundary.

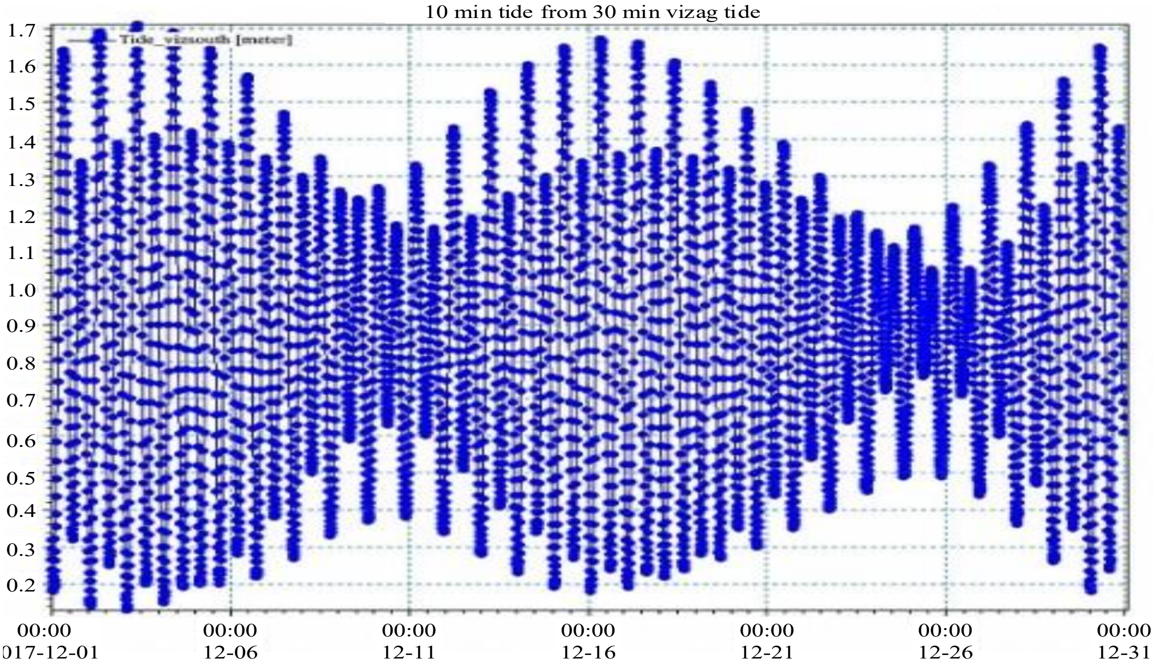


Figure 7. The tidal boundary is adopted in the model.

Model Scenarios

Two main model scenarios were simulated as illustrated below.

1. *Existing condition*: Western Arm at –10.7 m draft, representing the current port configuration
2. *Proposed condition*: Deepened Western Arm at –16.1 m with OR1 and OR2 shifted landward by approximately 12 m (Figures 8–10)

The HD model outputs were coupled to the MT model to simulate siltation over annual cycles, considering both dry and monsoon periods. For dredge disposal studies, an extended domain (16 × 13 km), including the designated dumping ground, was modeled, featuring a fine grid resolution at the disposal area (Figures 11 and 12).

RESULTS AND DISCUSSION

Hydrodynamics

The baseline model (existing condition) accurately reproduced the observed flow circulation within the harbor basin. Flood currents entered primarily through the southern entrance gap of the shore-detached breakwater and propagated into the inner harbor. The North-Western Arm exhibited the strongest currents, while both the Northern and Western Arms experienced weaker, quasi-stagnant flow conditions (Figures 13 and 14).

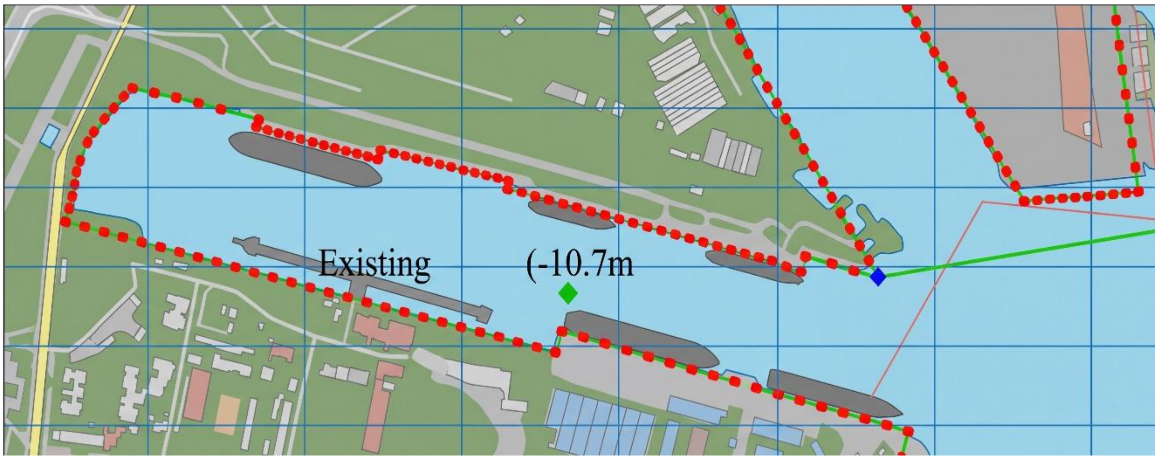


Figure 8. Model set up for existing condition—Western Arm.

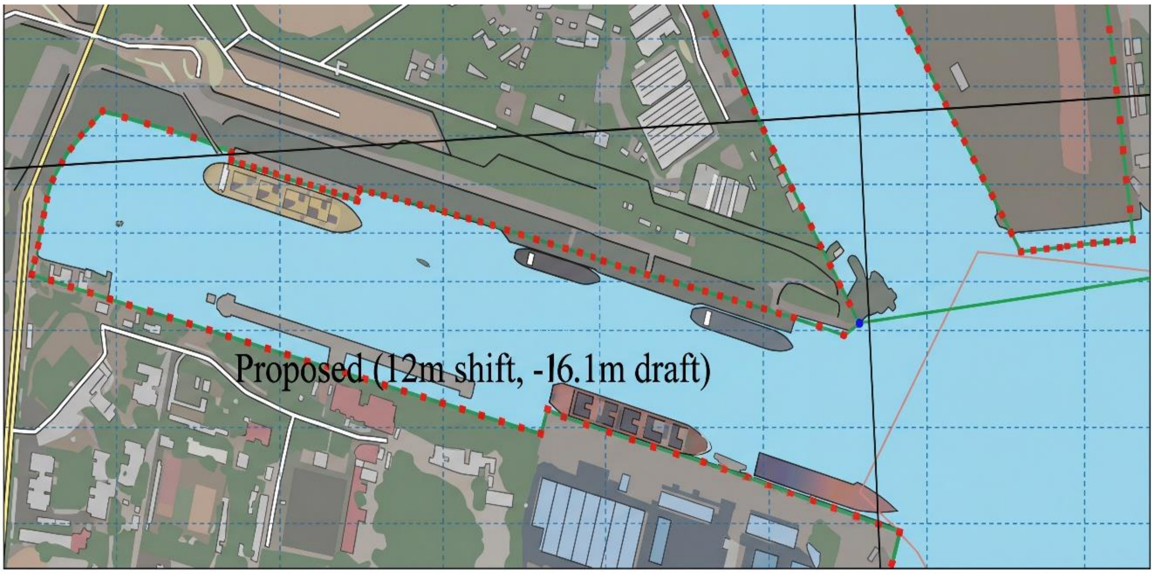


Figure 9. Model set up for proposed development in the Western Arm.

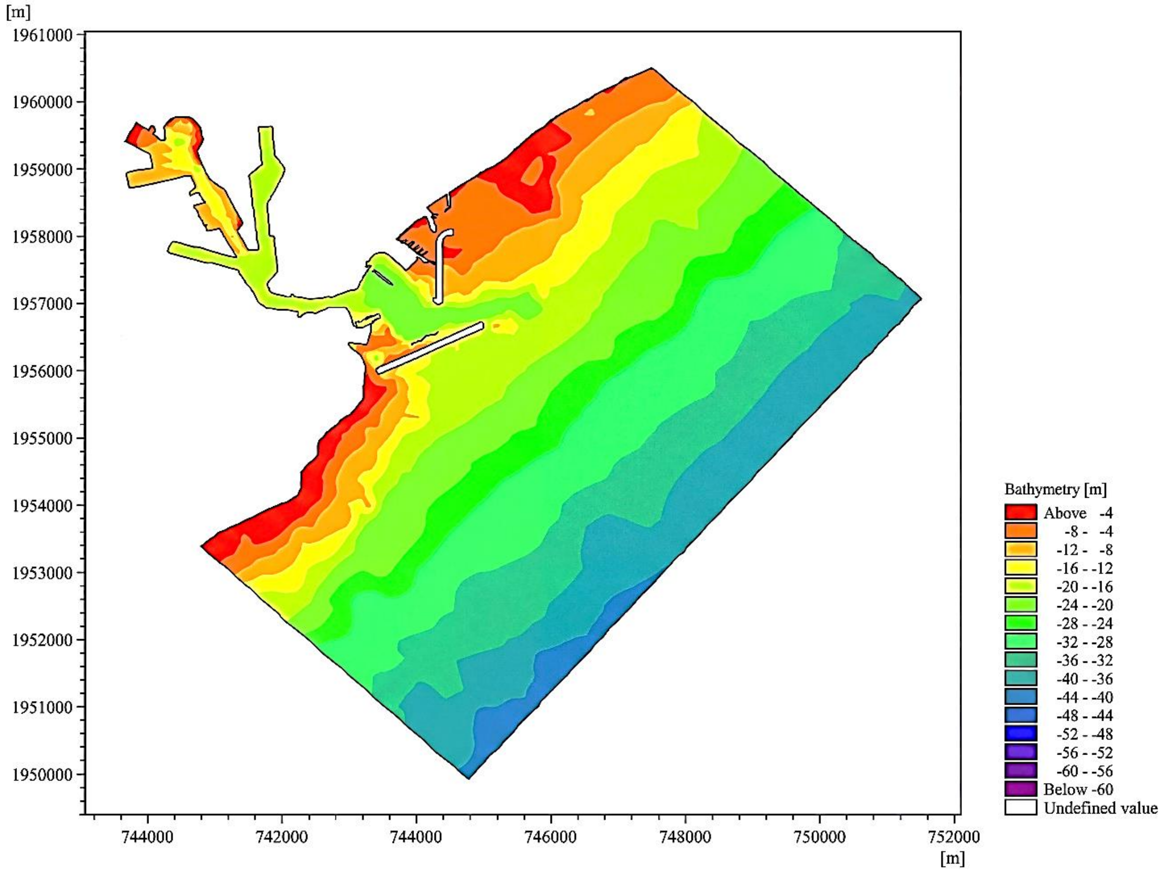


Figure 10. Bathymetry of the basin after deepening (OR1, OR2, and Fertilizer Berths).

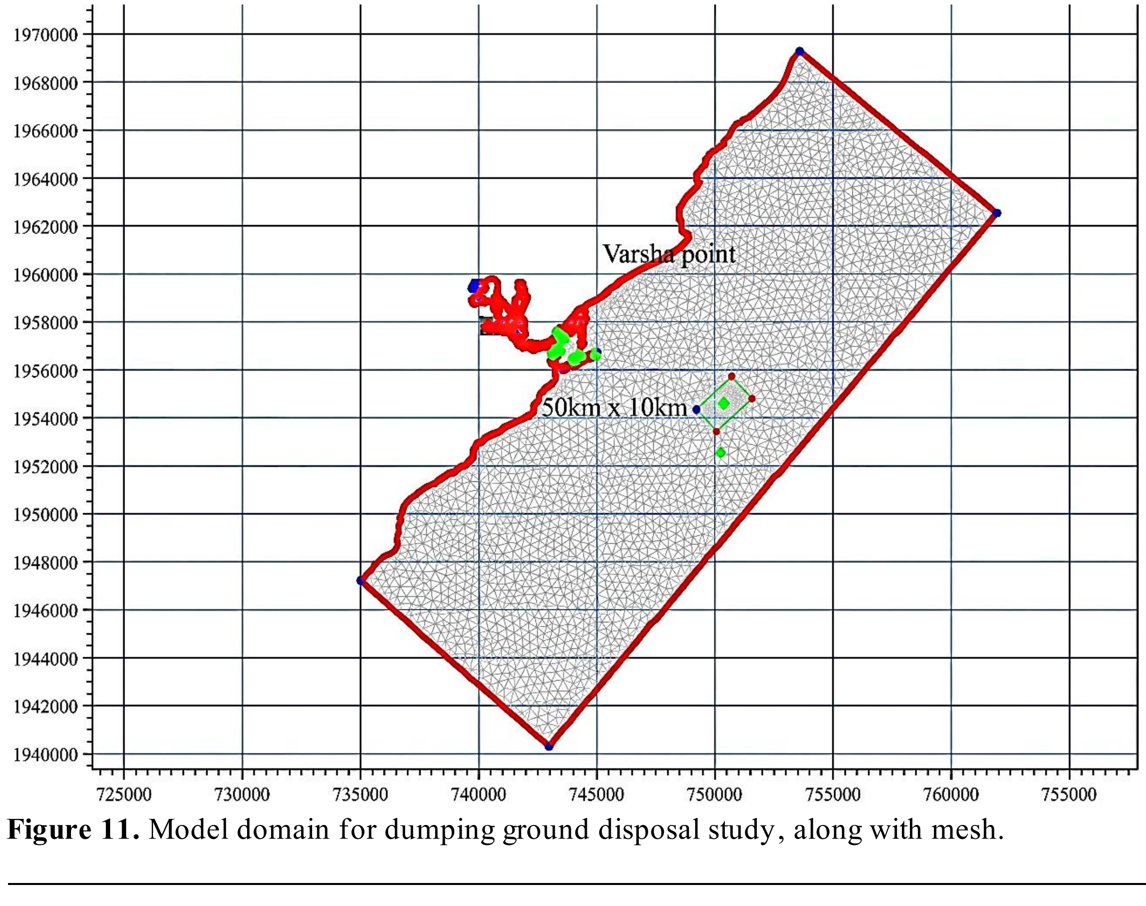


Figure 11. Model domain for dumping ground disposal study, along with mesh.

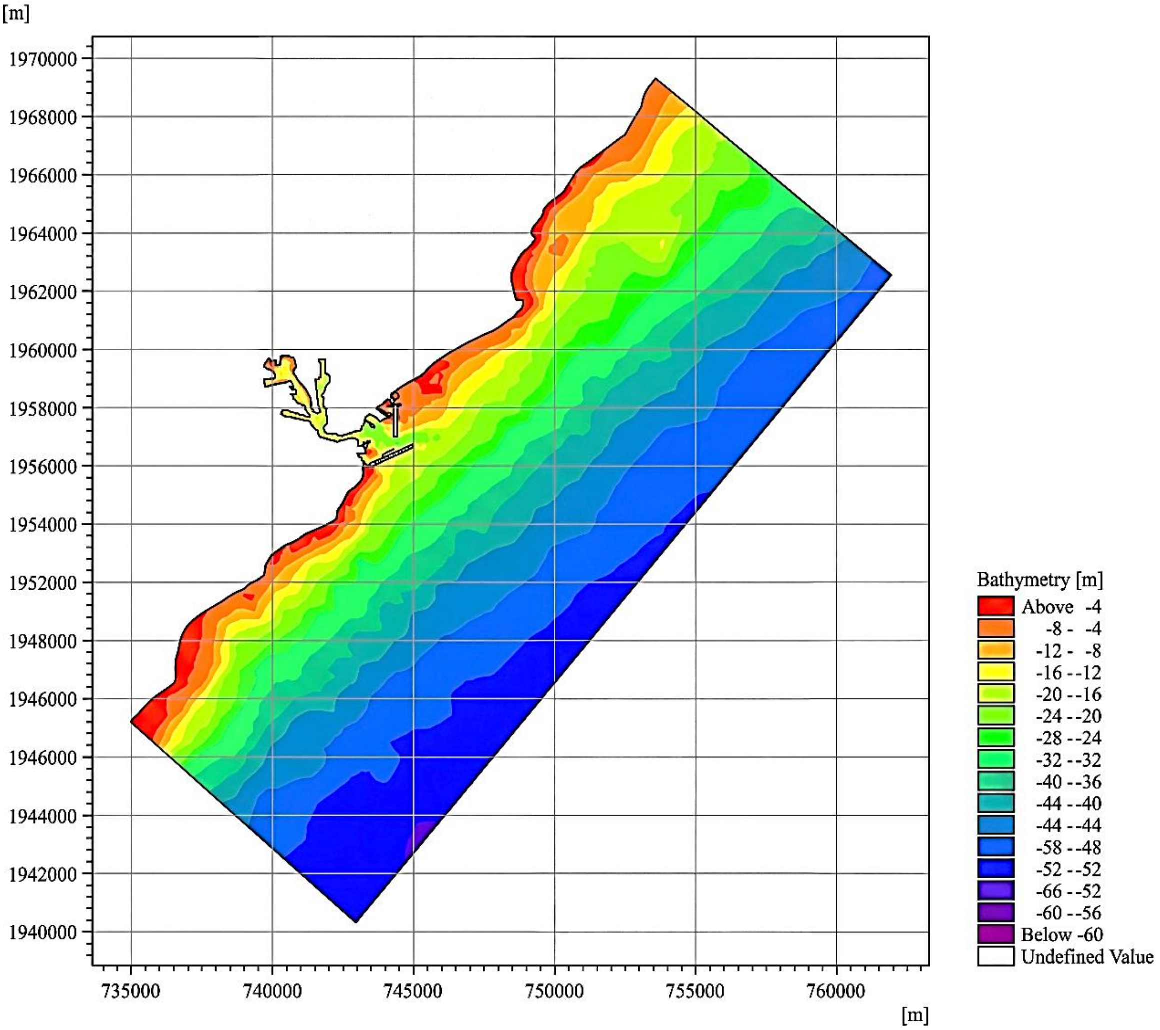


Figure 12. Bathymetry in the model domain for the dumping ground disposal study.

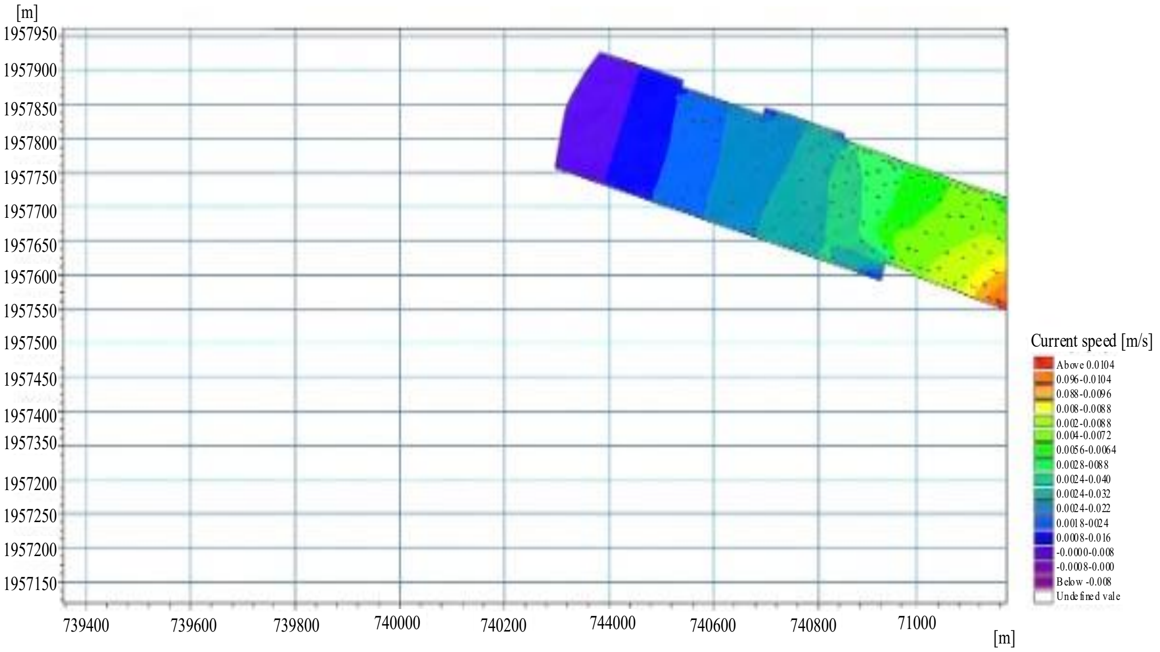


Figure 13. Flow patterns for a typical time step under existing conditions: inner and outer harbors.

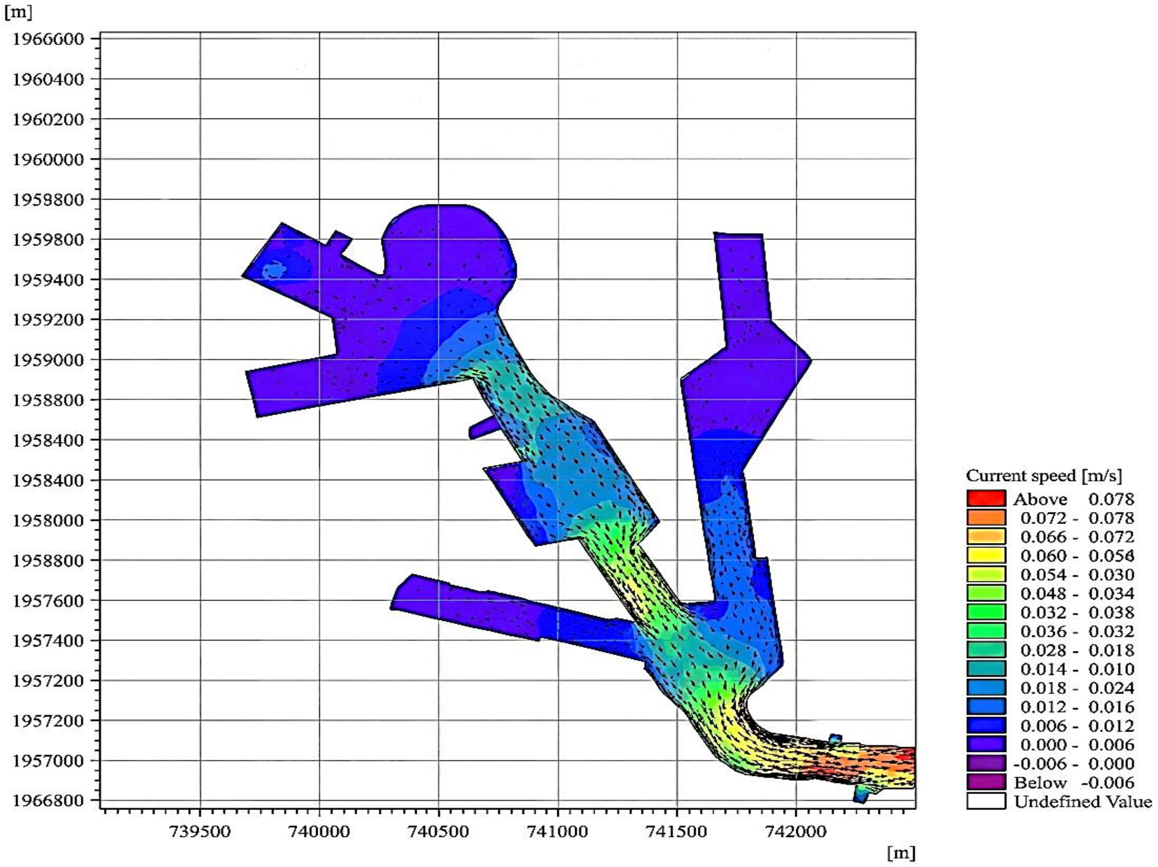


Figure 14. The current pattern in the inner basin is under the existing condition.

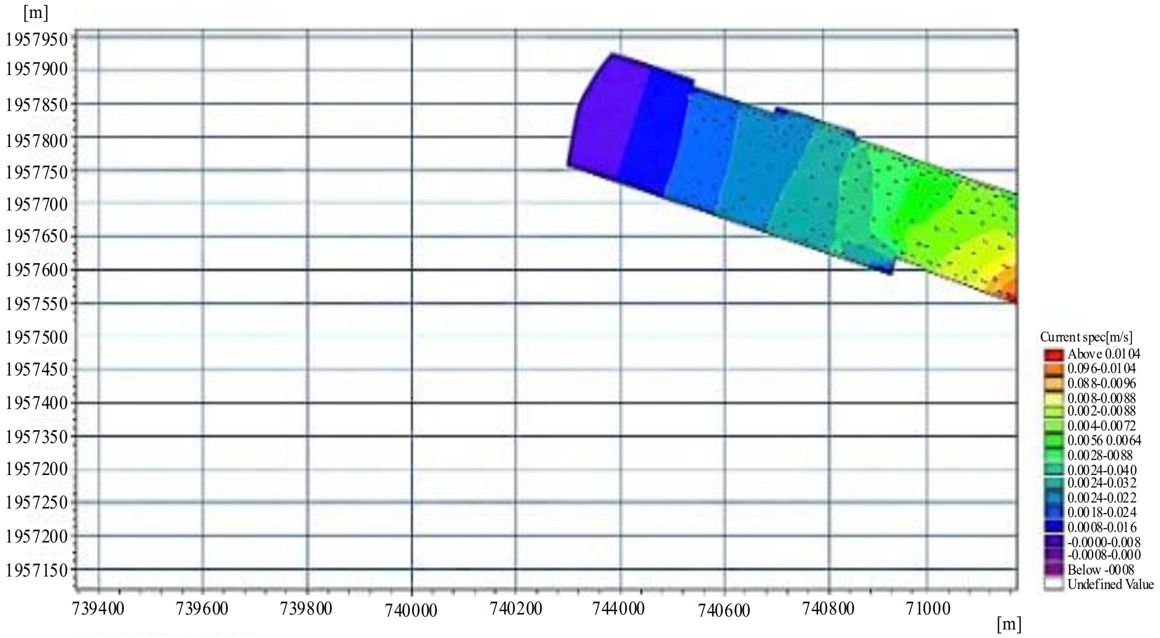


Figure 15. Close-up view of the currents in the Western Arm—existing condition.

Under the proposed deepening scenario, current patterns (Figures 16–18) remained nearly identical to those of the existing condition. The peak tidal influx and efflux at the inner entrance were 277 and 261 m^3/s, respectively. Within the Western Arm, tidal exchange was limited to 19–20 m^3/s during flood and ebb, indicating little hydrodynamic alteration due to deepening (Table 1).

Table 1. Peak tidal fluxes (discharges in cubic meters per second) at typical cross-sections.

Cross section	Tidal influx	Tidal efflux
Inner Entrance	277	261
North-Western Arm	140	132
Northern Arm	54	50
Western Arm	19	18

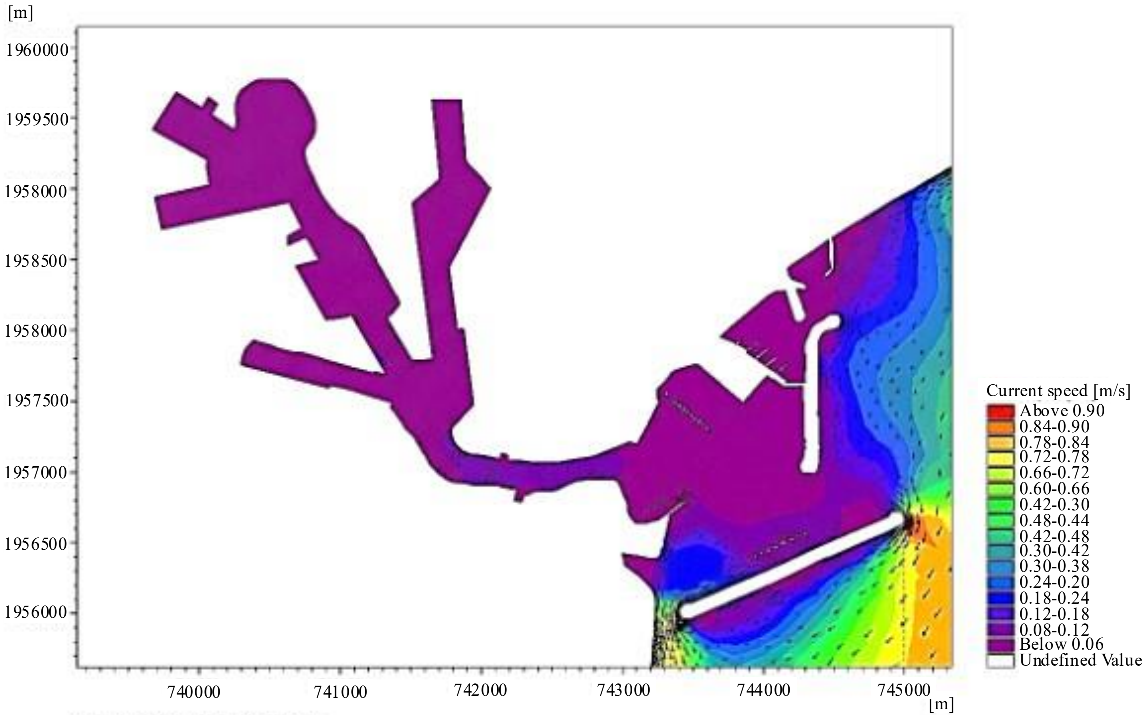


Figure 16. Flow pattern for a typical time step under the proposed condition: inner and outer harbors.

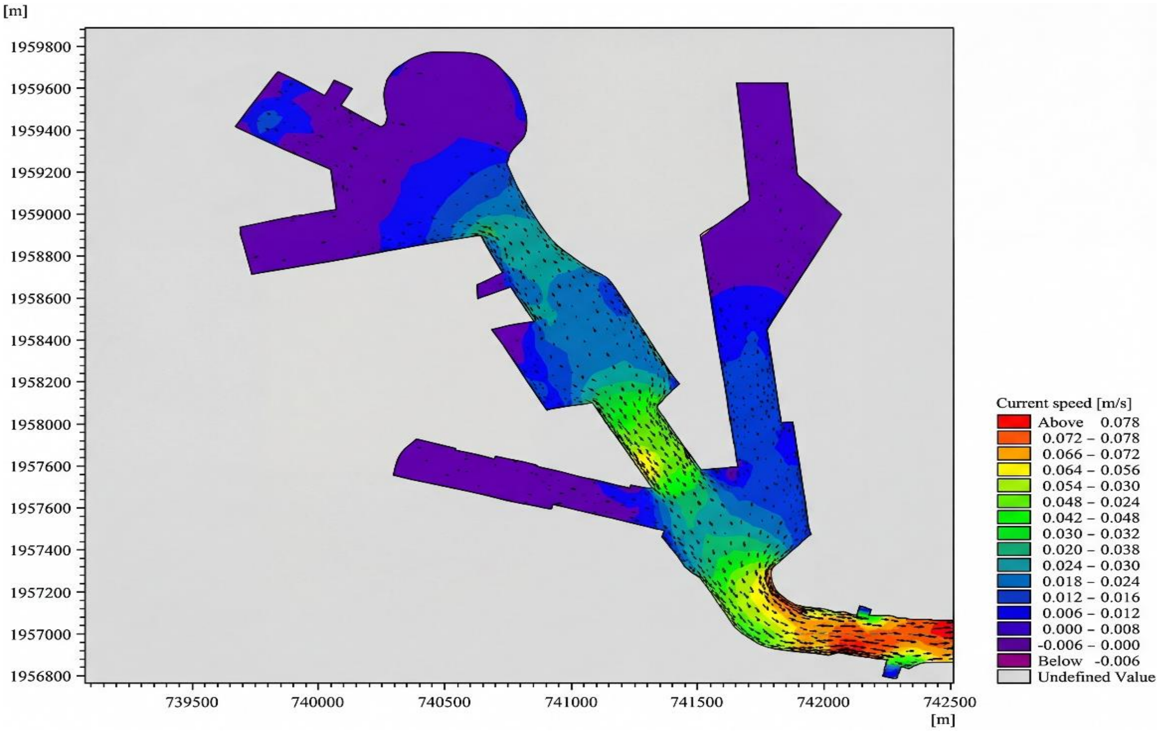


Figure 17. Current pattern in the inner basin under the proposed condition.

Tidal Prism Distribution

The analysis of the simulated tidal discharge (flux) at the selected cross-sections (Figure 19) showed a consistent tidal prism distribution across scenarios. Over 50% of the total tidal volume entered through the North-Western Arm, whereas less than 10% reached the Western Arm. This confirmed that the proposed deepening would not impact the harbor's natural flushing capacity.

Siltation Estimates

The model-derived siltation results for the existing and proposed conditions (Table 2) revealed a total annual sedimentation of approximately 480,287 m^3 under the current scenario and 484,487 m^3 post-development. The incremental change of approximately 3,000 m^3 per year in the Western Arm was within operationally manageable limits.

- *Existing condition*: Western Arm = 17,749 m^3/year
- *Proposed condition*: Western Arm = 20,983 m^3/year

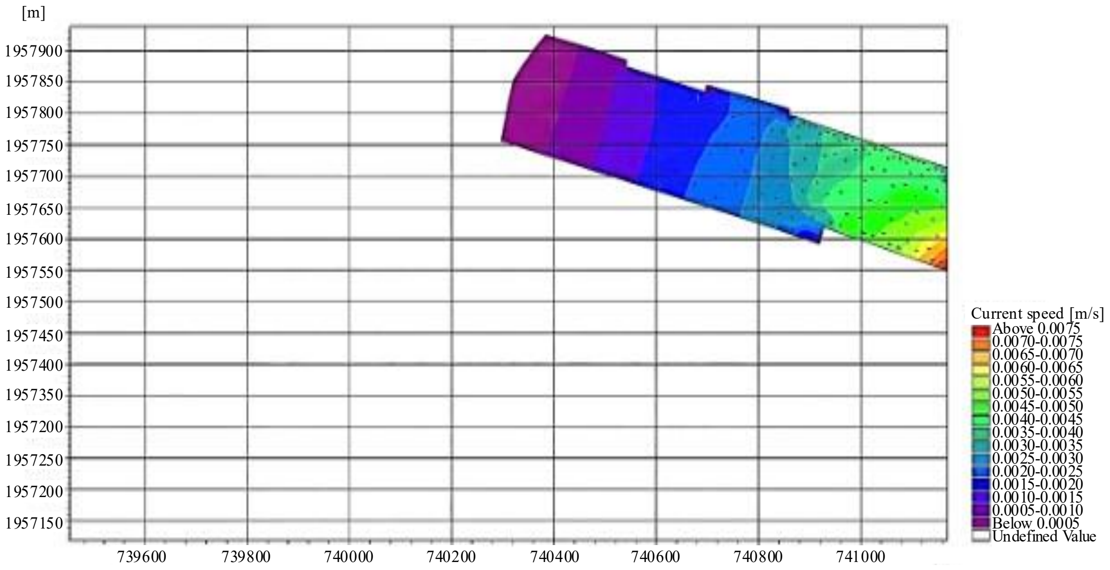


Figure 18. Close-up view of the currents in the Western Arm—proposed condition.

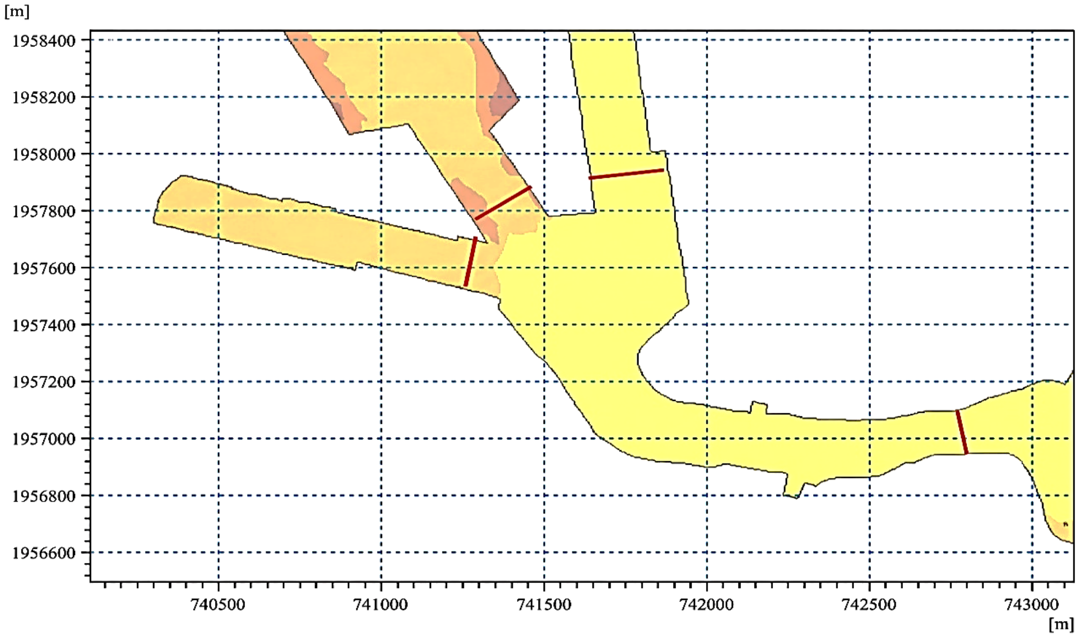


Figure 19. Locations of cross-sections for the extraction of discharge flux.

Monthly siltation plots (Figures 20–23) demonstrated increased deposition during monsoon periods, largely attributed to stream-borne sediments.

Dredge Disposal Modeling

For the dredge disposal analysis, an independent hydrodynamic and MT model was configured over a larger spatial domain covering the dumping ground (Figures 24–27). The dumping process was modeled as a source term representing discharge from a 1100 m³ trailer suction hopper dredger (TSHD), operating at a rate of eight dumps per day for four months. Calibration used results from previous radioactive tracer studies (CWPRS, 2011) to ensure an accurate representation of sediment dispersion. The input parameters (Table 2) included sediment density (1900 kg/m³), critical shear stress for erosion (0.5 N/m²), and deposition (0.1 N/m²).

Table 2. Area-wise siltation computed from the model for existing and proposed conditions.

Area	**Siltation (m^3) for existing and proposed conditions (estimated from mathematical model)**					
	Existing condition (–10.7 m)			***Proposed condition (–16.1 m)***		
	Dry period	*Monsoon*	*Total year*	*Dry period*	*Monsoon*	*Total year*
Western Arm	11221	6528	17749	13958	7025	20983
Northern Arm	35477	9841	45318	35459	9578	45037
IH Turning Circle	16639	47548	64187	16771	48517	65288
N-W Arm	80424	272609	353033	80557	272622	353179
Total Of North, West, and TC	63337	63916	127254	66189	65119	131307
Total Per Annum	143762	336525	480287	146745	337741	484487

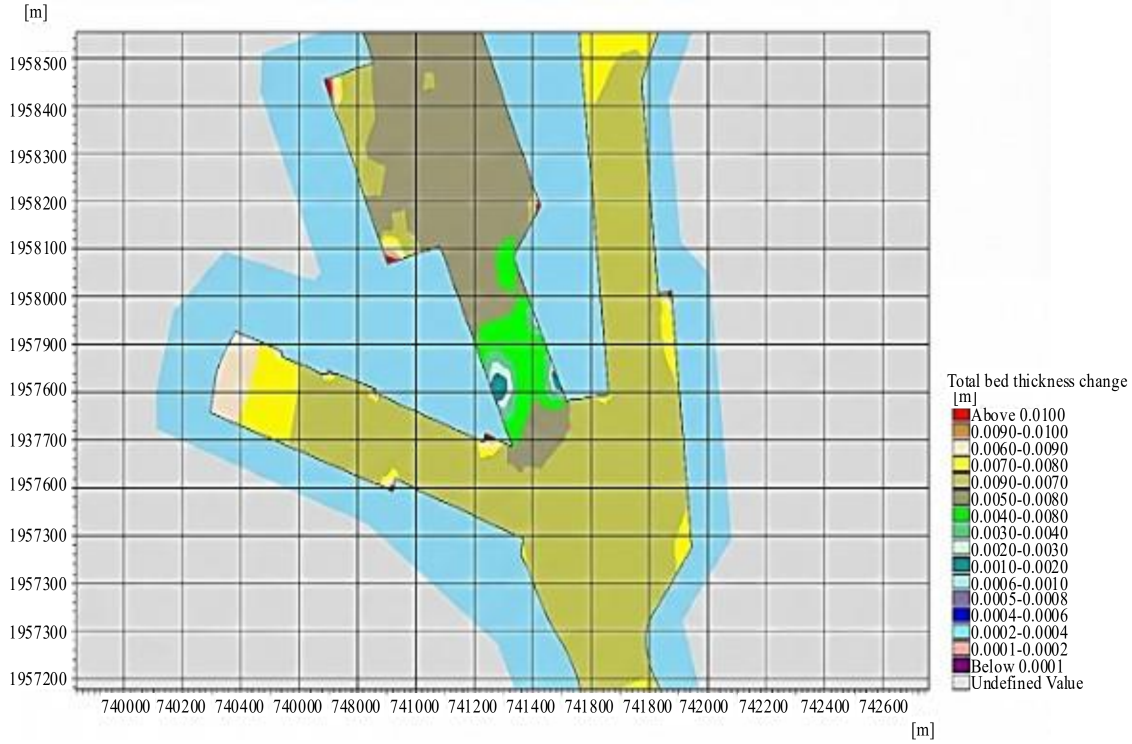


Figure 20. Monthly siltation pattern during the dry period near the facility under existing conditions.

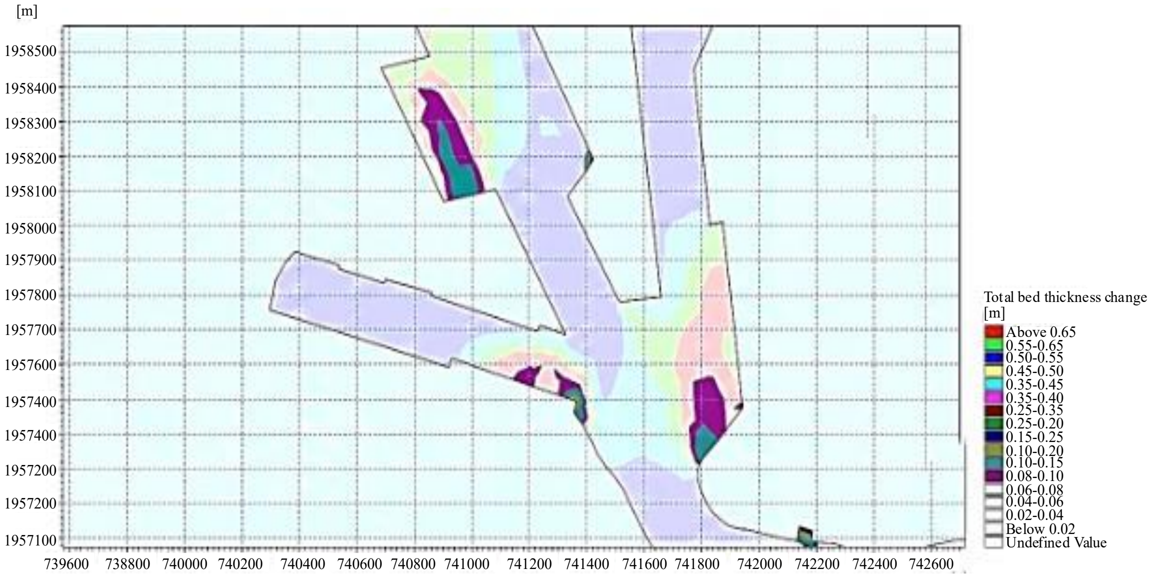


Figure 21. Monthly Siltation pattern during monsoon near the facility under existing conditions.

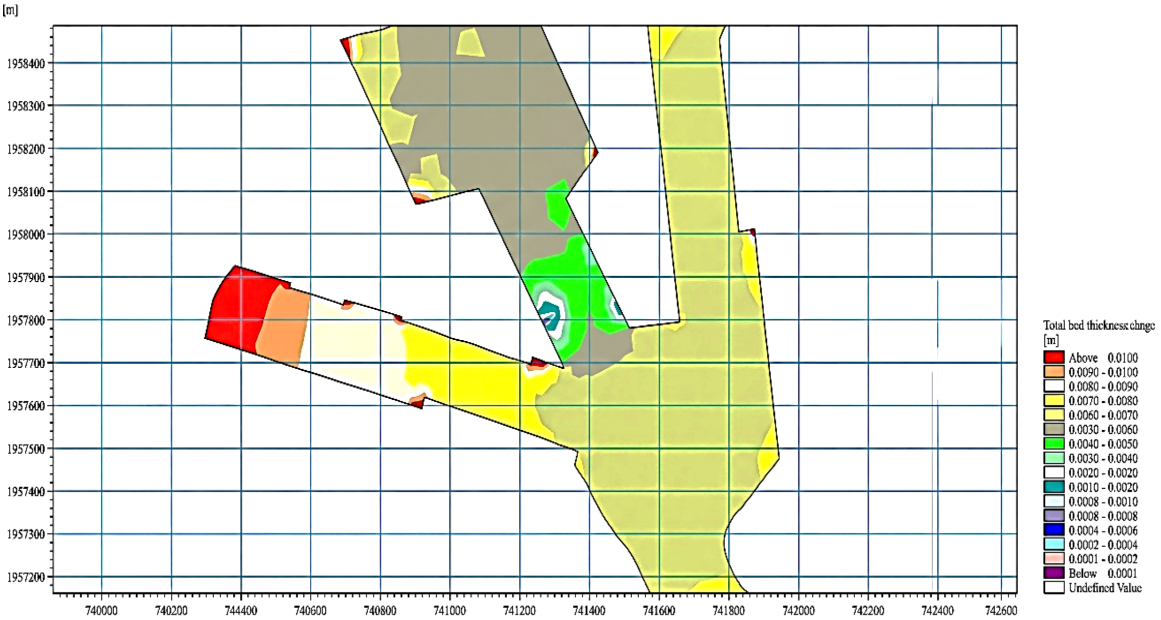


Figure 22. Monthly siltation pattern during the dry period near the facility under the proposed condition.

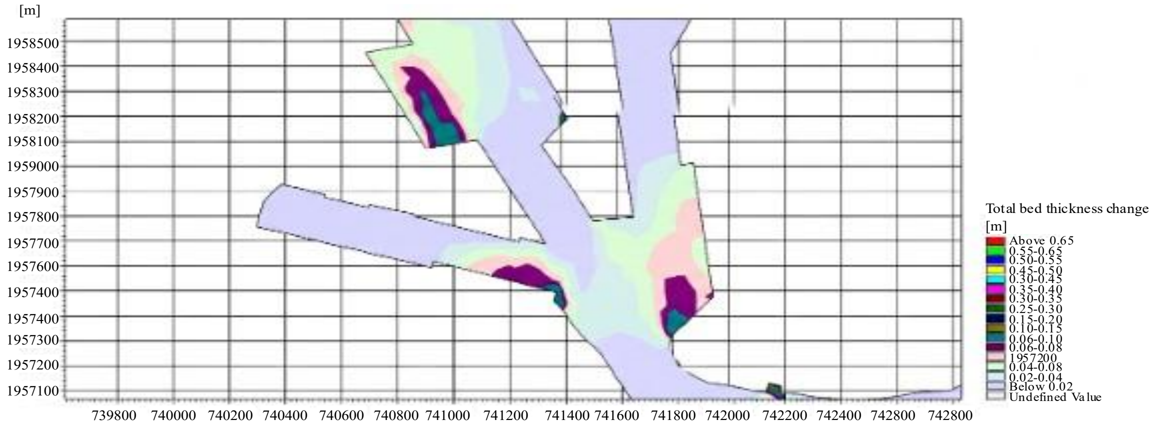


Figure 23. Monthly siltation pattern during monsoon near the facility under the proposed condition.

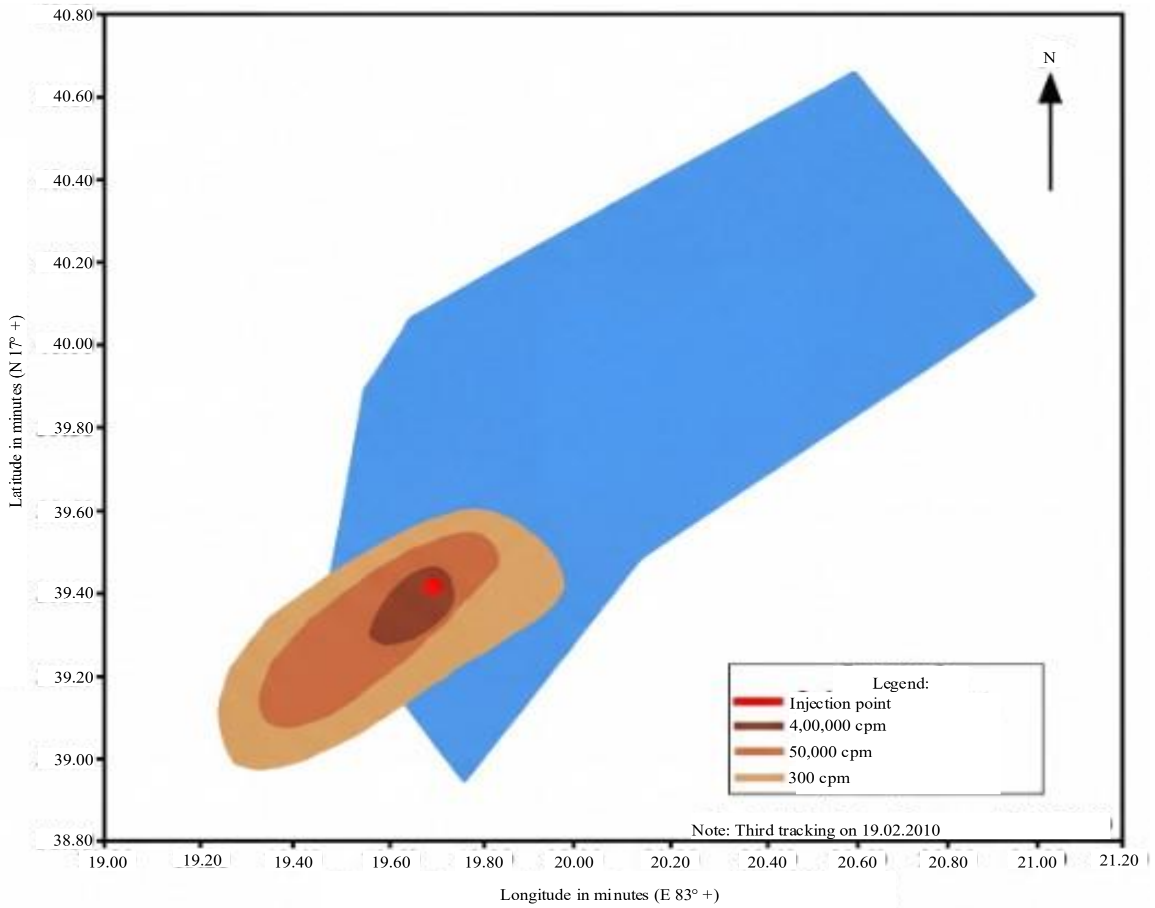


Figure 24. Bed transport/spreading pattern as per the radioactive tracer study at Visakhapatnam Port.

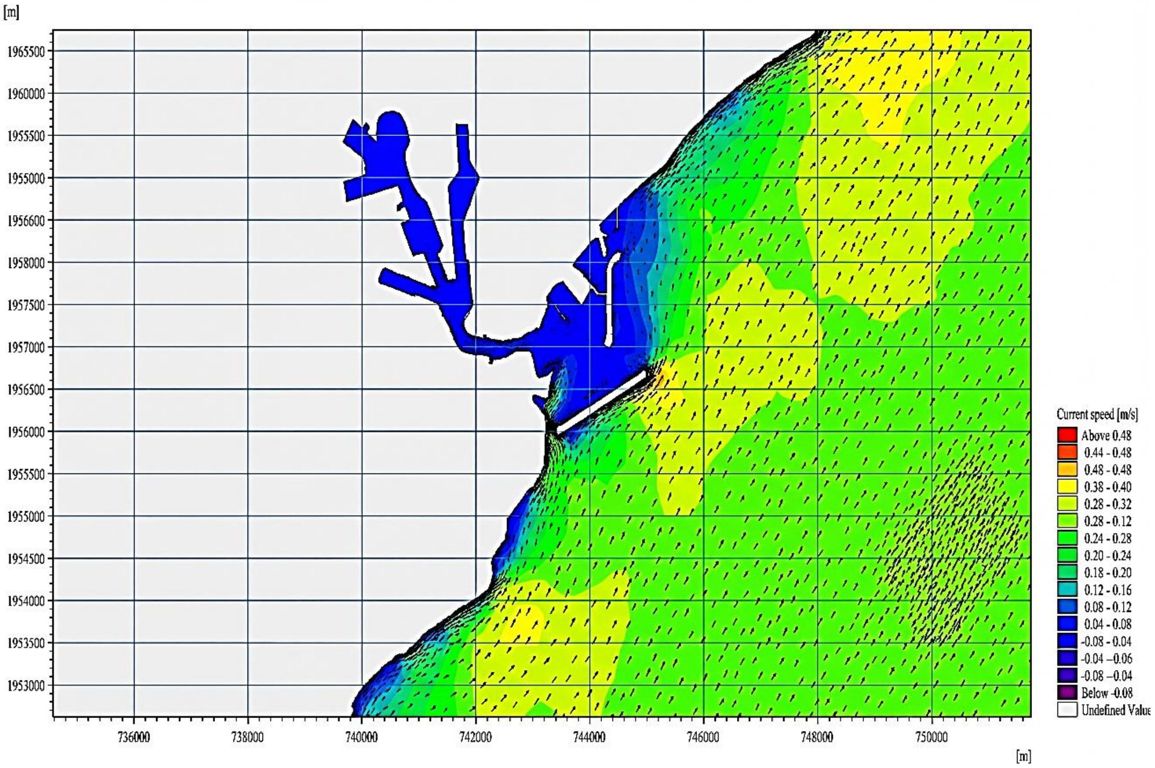


Figure 25. Current pattern in the model domain during simulation (tidal flood).

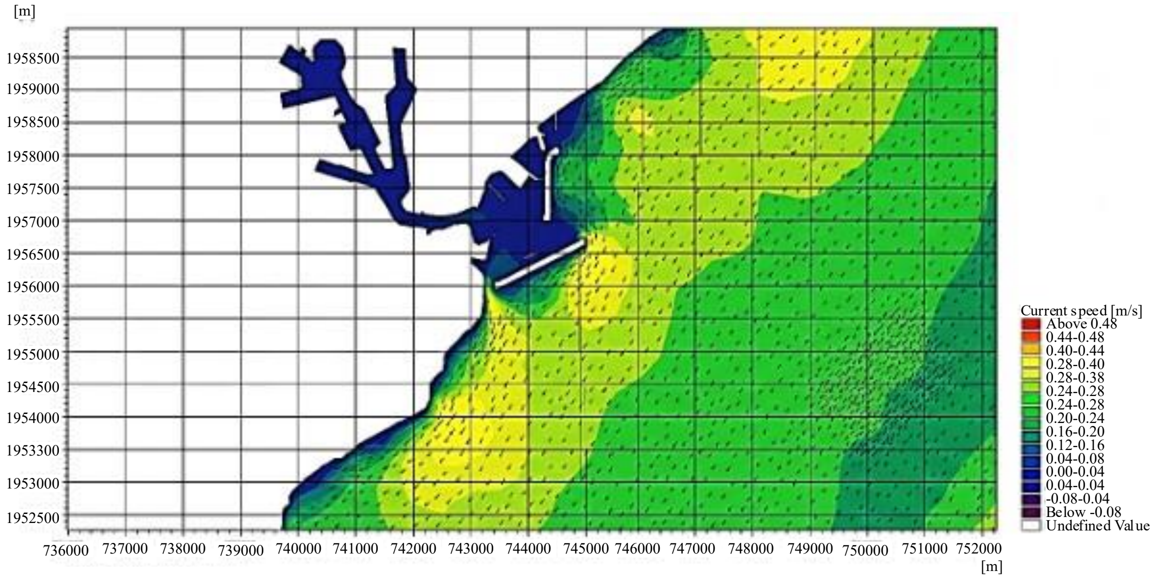
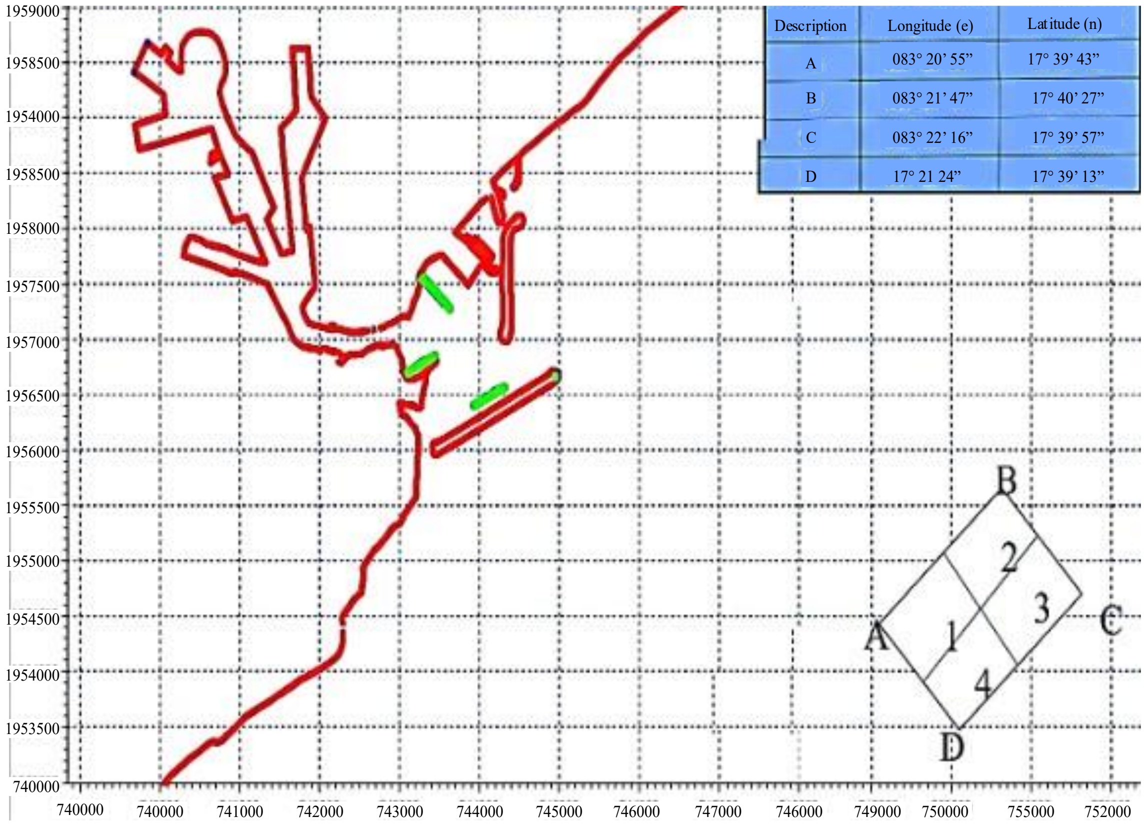


Figure 26. Current pattern in the model domain during simulation (tidal ebb).



Description	Longitude (e)	Latitude (n)
A	083° 20' 55"	17° 39' 43"
B	083° 21' 47"	17° 40' 27"
C	083° 22' 16"	17° 39' 57"
D	17° 21 24"	17° 39' 13"

Figure 27. Dumping ground area and sub-domains are earmarked.

Model simulations revealed that sediment dispersion followed the seabed contours, producing a maximum bed thickness change (TBTC) of approximately 20 cm at the dumping site after one month (Figures 28 and 29).

Dispersion extended approximately 500 m alongshore and 400 m cross-shore. Suspended Sediment Concentration (SSC) levels remained under 0.05 kg/m³ (Figures 30–32), confirming minimal environmental impact.

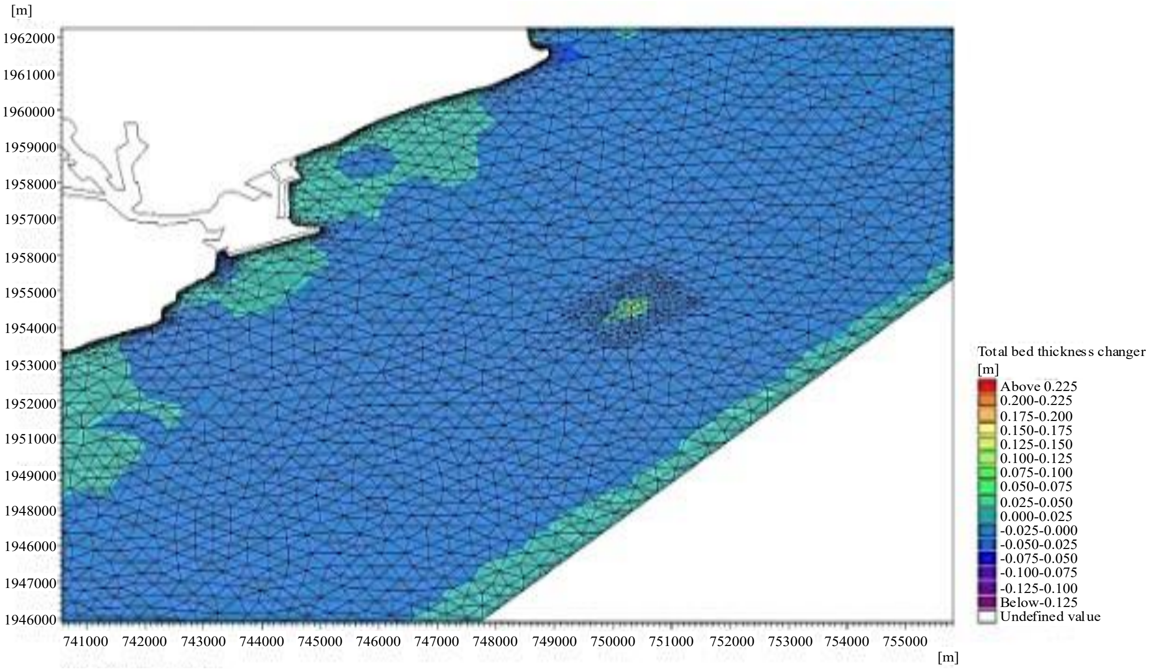


Figure 28. Bed thickness changes in the model domain at the end of one month.

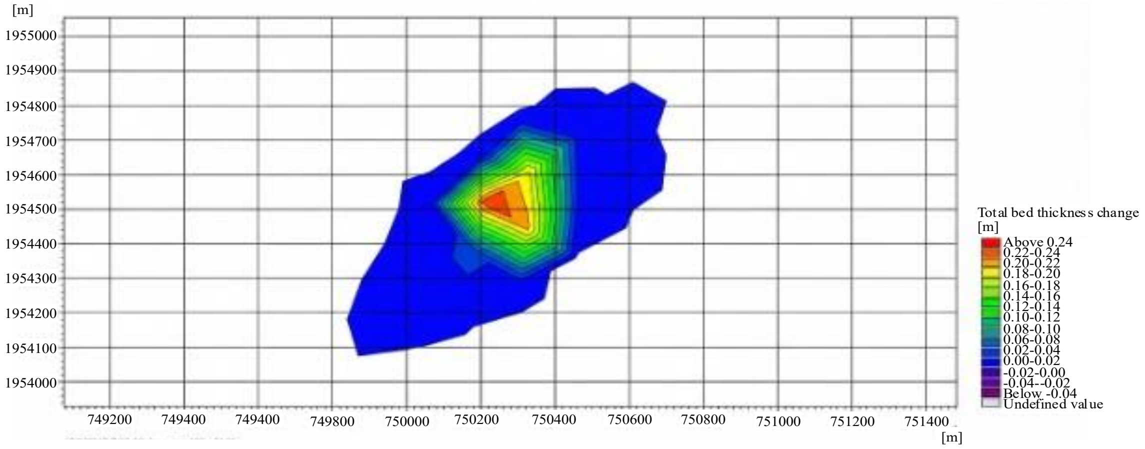


Figure 29. Bed thickness changes around the dumping location at the end of one month.

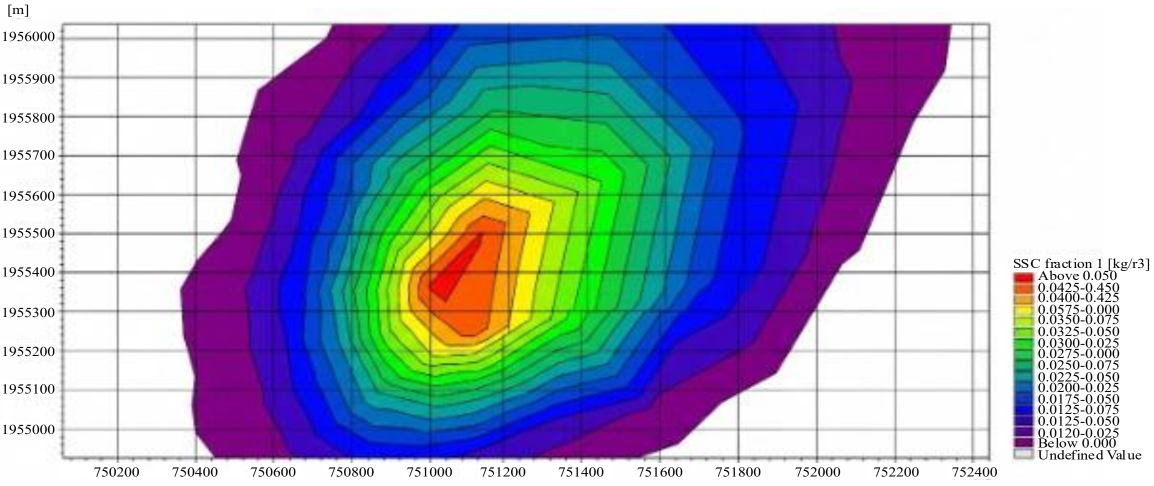


Figure 30. Suspended sediment concentration map during dumping.

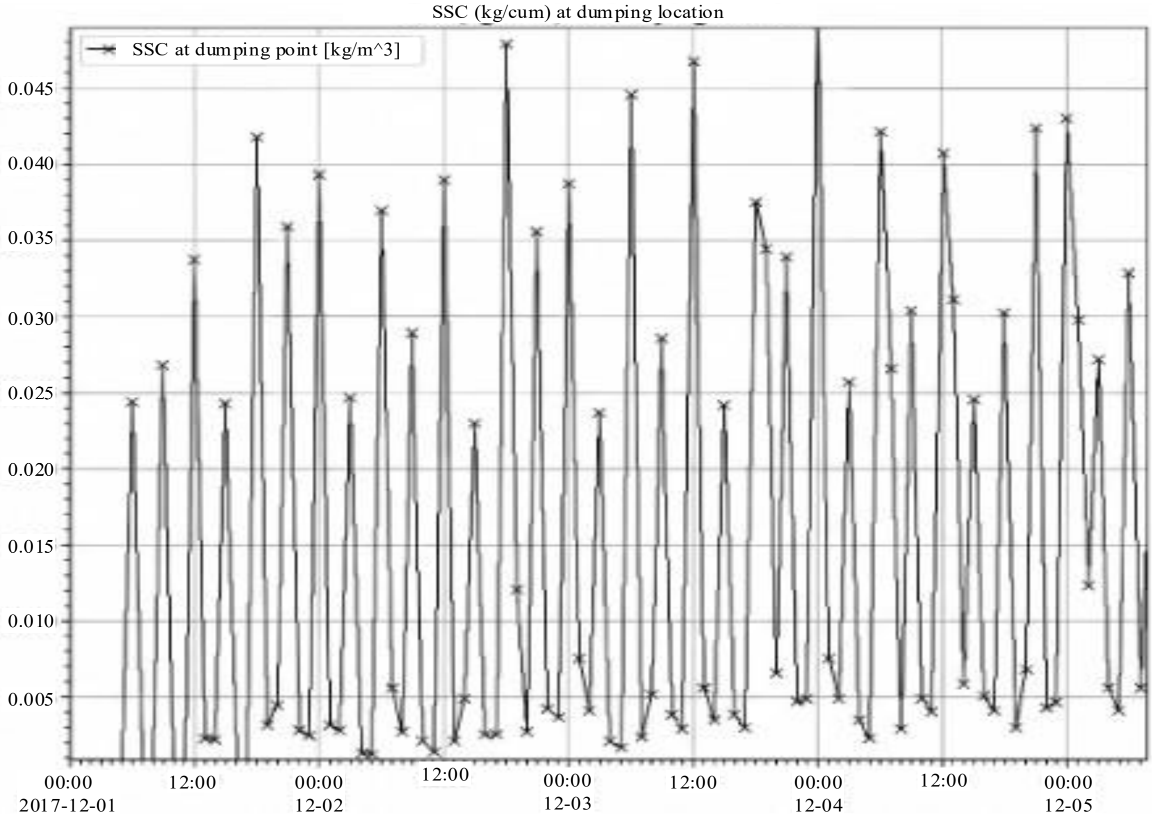


Figure 31. Suspended sediment concentration (SSC) at the dumping location.

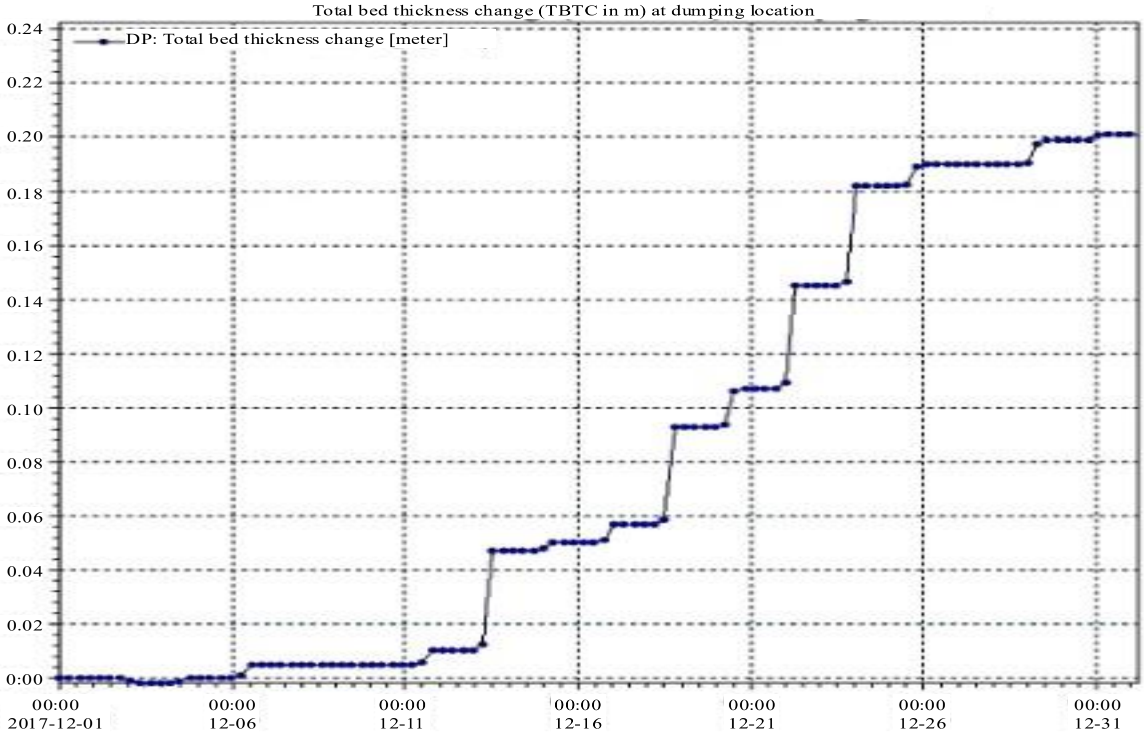


Figure 32. Bed thickness at dumping location (indicates temporal change).

ENVIRONMENTAL AND OPERATIONAL IMPLICATIONS

The modeling outcomes confirm that the proposed deepening of the Western Arm will not significantly alter the hydrodynamic or sedimentation regimes. The tidal prism remains nearly identical to the existing conditions, ensuring that natural flushing and sediment transport processes will continue unaffected. The observed increase in annual siltation is minor (≈3,000 m^3/year) and can be managed through routine maintenance dredging. Sediment transport within the harbor remains governed by stream inflows, whereas marine littoral contributions remain negligible because of the sand trap system. The dumping ground analysis confirms that spoil disposal at the existing site will not cause adverse morphological changes. The recommended rotational dumping strategy, distributing loads across four sub-domains (1 km × 0.6 km each), minimizes local accumulation and maintains benthic thickness below 20 cm. Environmental monitoring through periodic bathymetric surveys before and after disposal operations is strongly recommended to ensure compliance and validate model predictions.

CONCLUSIONS

The final findings and observations of this specific modeling study are detailed as follows:

1. The MIKE 21 FM Hydrodynamic and sediment transport model effectively reproduced the observed tidal and siltation characteristics of the Visakhapatnam Inner Harbor.
2. The proposed deepening of OR1, OR2, and Fertilizer Berths from –10.7 m to –16.1 m shows negligible influence on hydrodynamics and only a marginal increase in annual siltation of approximately 3,000 m^3.
3. The Western Arm contributes minimally to the overall tidal prism (≈7%) and exhibits slack-flow conditions with a tidal inflow of ≈20 m^3/s.
4. Sediment transport simulations show stable conditions with annual siltation ≈20,000 m^3, well within dredging capacity.
5. Dredged material disposal studies indicate TBTC ≈20 cm and SSC <0.05 kg/m^3, validating the safety of the designated dumping ground.
6. The rotational dumping approach across four sub-domains ensures environmentally sustainable sediment management.
7. The project is hydrodynamically and environmentally feasible for improving capacity utilization and long-term operational sustainability at Visakhapatnam Port.

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