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Hydrodynamic Modelling of Tides and Tidal Currents in Cochin Estuary

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ABSTRACT

The present study utilized two-dimensional numerical modelling to understand the tides and tidal currents in the Cochin estuary. The model shows a relatively good comparison with observation. In the estuary, the dominant constituent is M2 followed by K1, S2, and O1. The Form Numbers indicated that the tide is mixed, the mainly semi-diurnal tide having values ranging from 0.80 - 0.85, with the lowest Form number at the mouth of the estuary. The study reveals a significant relationship between dredge depth and tidal current speed in the narrow region of the mouth of the Cochin estuary. It is found that when the depth is decreased to 5 m and is increased to 20 m at mouth the current speed increases about 0.06 m/s and decreases about 0.24 m/s respectively. Tidal velocity is about 0.3 m/s near the inlet and a decreasing towards upstream. Tidal current analysis for M2 shows, U amplitude of 0.3 m/s at the mouth of the estuary, decreasing to 0.03 m/s in the northern and southern arms, while V amplitude ranges from 0.03 – 0.21 m/s towards the northern arm. For K1, the U amplitude reduces from 0.15 m/s at the mouth of the estuary to 0.03 m/s in both the arms with V amplitude higher in the northern arm than the southern arm. This research will enhance our understanding of tidal hydrodynamics in the estuary, contributing to sustainable estuarine management.

Keywords: Tidal current; Tidal constituents; Numerical modelling; Cochin estuary

1. INTRODUCTION

A comprehensive study on tidal dynamics is essential for understanding oceanographic phenomena, in coastal and estuarine waters. The Cochin estuary system, located on India's southwest coast, is a semi-enclosed coastal body of water that connects to the open sea and receives freshwater from land drainage. The natural bar was dredged in 1936 to make room for Cochin Port, and the channel is now maintained at a 14 mtr draft to handle ocean-going vessels[1]. Human activities, including navigation channel dredging, sand dredging, and land reclamation, have significantly altered the landscape of the system[2]. The estuary's broadness ranges from 450 m to 4 km, and the average depth is 1.5 m. The water depths range from 15 meters at the Cochin inlet to 3 m near the headwaters (levels are determined reference to chart datum)[3].

Six rivers, numerous interconnecting waterways, and two inlets on the northern side of the estuary-Munambam and Cochin Inlet in the middle-contribute to the complex topography of the Cochin estuary. Various studies have investigated the physical, chemical, biological, and geological properties in the Cochin Estuary focusing on tidal influences on these parameters[5,8-12,14]. Srinivas and Kumar[7], analyzed the sea level data collected at two adjacent locations and described the spring-neap variation of tides at the lower reaches of the Cochin estuarine system.

The main goal of this study is to carefully examine the Cochin Estuary's tidal hydrodynamics using a 2D numerical model. The spatio-temporal variability of tides and tidal currents has not been thoroughly addressed in previous studies, which predominantly relied on point data or utilized one-dimensional (1D) numerical models. In contrast, this study provides a comprehensive understanding of the spatio-temporal variability of tides and tidal currents by employing a two-dimensional (2D) numerical model. This approach allows for a more detailed analysis of how tides and tidal currents vary across different regions of the estuary, which is crucial for studying water movement, sediment transport, and ecological processes influenced by tides and tidal currents, offering valuable insights that were previously lacking in the literature.

2. METHODOLOGY

A 2D numerical model implemented to study the spatio-temporal variability of tide and tidal currents using the MIKE 21 FM (Flexible Mesh) model. The model simulated for a period from 16 December 2020 to 31st January 2021. The first fifteen days were not considered in the analysis to avoid the spin-up effect. MIKE21 has been widely used for estuary and coastal areas to understand coastal hydrodynamics[6]. Model domain extends from 9.86° N to 10.08° N (off kochi) covering a length of about 25 kms of coastal stretch. The offshore extent reaches up to approximately 10 km from the coast extending to a water depth of 20 m. The mesh generator module was used to construct the model grid and bathymetry data used for the domain was obtained from C-MAP. The domain has three boundaries viz, North, South, and western boundary (Fig. 1), forced with the tidal level as input. The tidal levels were

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extracted from the global tidal model in the MIKE toolbox. The model calibration is adjusted by varying bed resistance parameters within physical boundaries until a satisfactory agreement between simulated and observed water levels is obtained. The model setting parameters are given in Table 1[13].

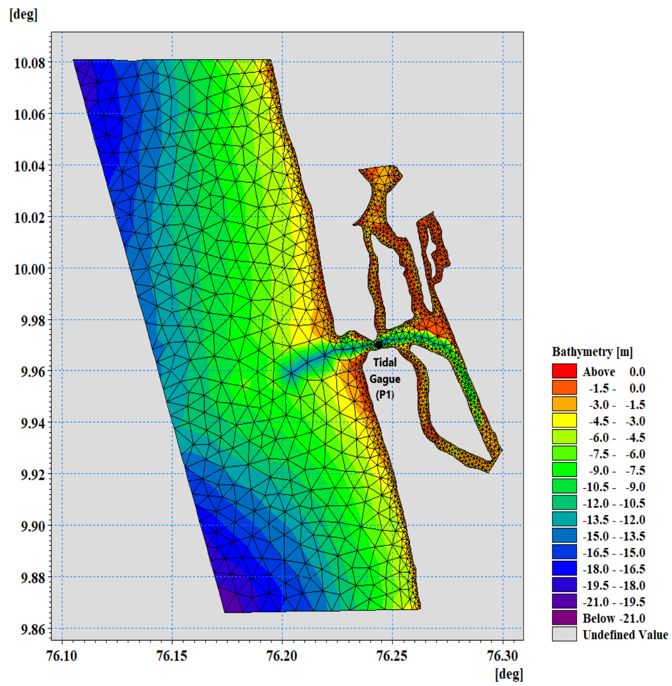


Figure 1. Tidal gauge (P1) 76.26°E & 9.96°N location with bathymetry data in simulated model.

The tidal elevation is extracted from the model (76.26°E & 9.96°N) and compared with the observations. U_TIDE was used for performing harmonic analysis based on tidal elevation and tidal current data. This approach enabled the extraction of the amplitude and phase of tidal constituents at each grid point. Furthermore, the MIKE harmonic analysis toolkit was utilized for cross-validation of the U_TIDE analysis results. Upon comparing the tidal constituents obtained from the two approaches, a robust correlation was seen.

Table 1. Setting parameters for the model

Parameter	Value
Module	Hydrodynamic module
Simulation period	01/01/2021 - 31/01/2021
Time step interval	3600 sec
Number of time steps	744
Flood and Dry	Drying depth - 0.005m Wetting depth - 0.1m
Eddy Viscosity	Samagorinsky formulation, constant - 0.28
Bed Resistance	Manning number, constant - 36m^(1/3)/s
Initial condition	Constant with initial surface elevation 0m
Boundary condition	North South West

3. RESULTS

3.1 Model Validation

The comparison between the simulated and observed water levels during the period from 1st January 2021 to 31[st] January 2021 shown in Fig. 2. Model reproduced the observed tide in a reasonable manner including their amplitude, phase, and spring-neap cycle.

The scatter plot comparing sea level from model and observation at point P1 shows a mean Absolute Error of 0.067 m with a Root Mean Square Error of 0.083 m (Fig. 3). The coefficient of determination, coefficient of efficiency, and Index of agreement are 0.91, 0.90, 0.97 respectively.

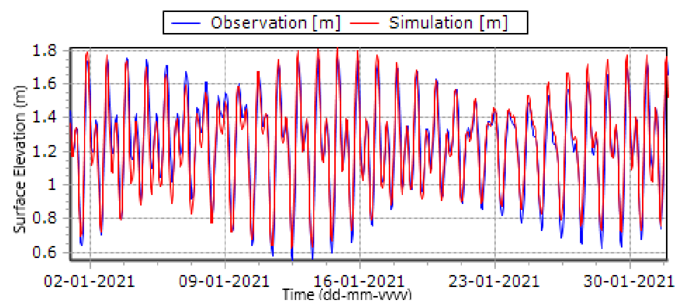


Figure 2. Comparison of observed and model simulated water level at the calibration point (P1)

The Root Mean Square Error (RMSE) was calculated for each constituent using the Eqn. (1)[4],

$$RMSE = \sqrt{\{0.5(A_0^2 + A_m^2) - A_0 A_m \operatorname{Cos}(G_o - G_m)\}} \tag{1}$$

where,

A_o = Amplitude Observation
A_m = Amplitude Model
G_o = Phase Observation
G_m = Phase Model

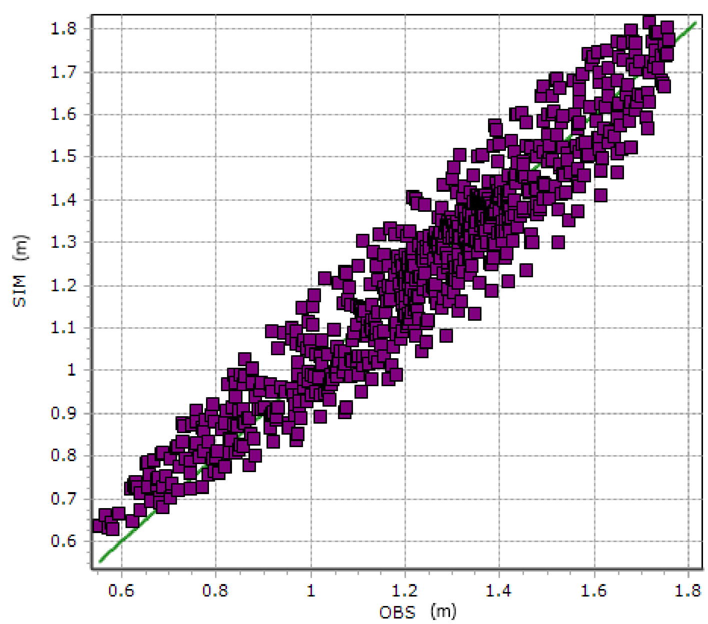
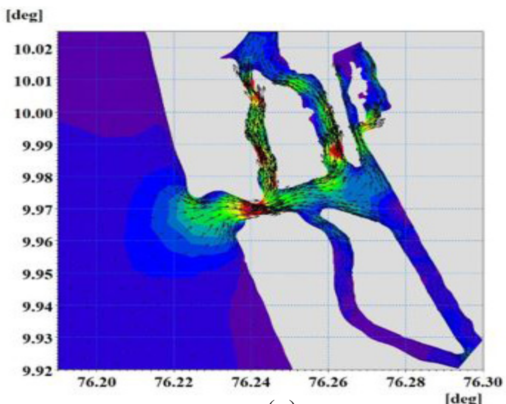


Figure 3. Scatter plot of observed and model-simulated water level.

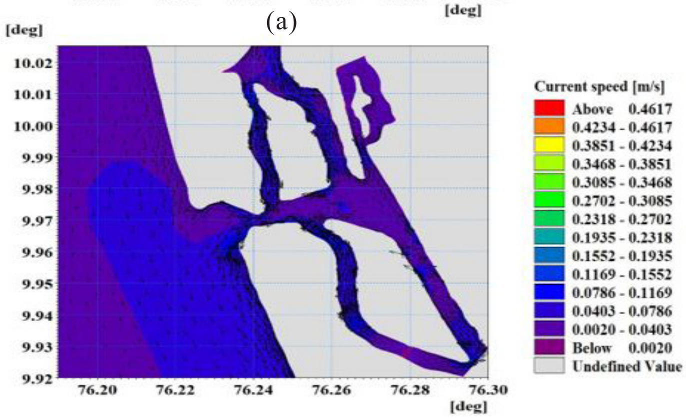
Table 2 shows the comparison of amplitude and phase of four major constituents from the observation and model. The model shows good agreement with the observations with an

Table 2. Amplitude and Phase of major tidal constituents in cm

Constituent	Amp Obs (cm)	Amp Model (cm)	Phase Obs (cm)	Phase Model (cm)	RMSE (cm)
M2	24.02	24.58	195.61	179.17	32.11
S2	8.94	10.00	252.04	238.79	4.55
K1	20.17	19.34	339.98	327.42	0.60
O1	10.40	9.26	346.08	335.84	12.77

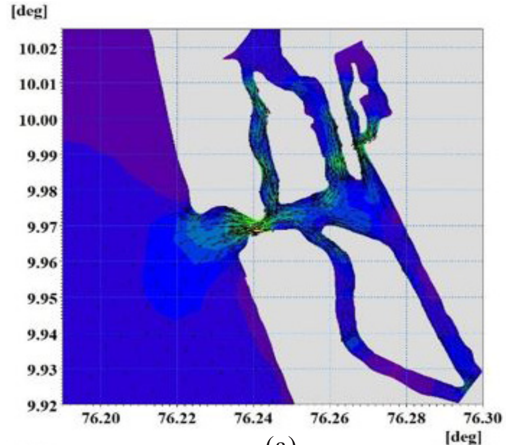


(a)

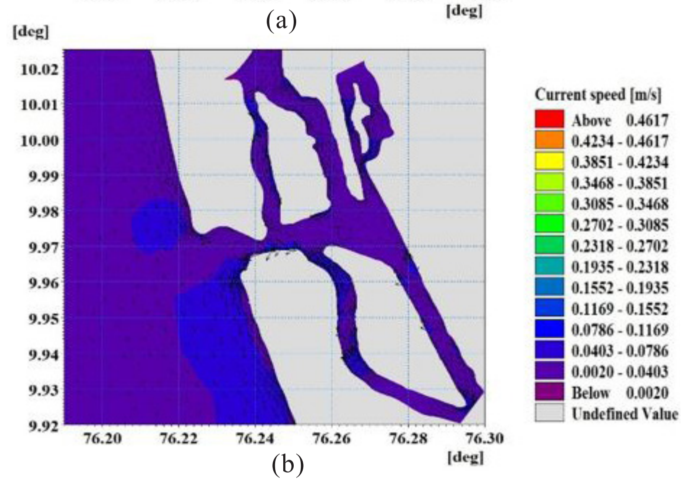


(b)

Figure 4. Spatial map of barotropic tidal currents (m/s) (a) Barotropic tidal currents during flood tide (13-01-2021) in spring phase; and (b) Barotropic tidal currents during ebb tide (13-01-2021) in spring phase.



(a)



(b)

Figure 5. Barotropic tidal current similar to Fig. 4 but for neap phase (a) flood tide (20-01-2021); and (b) ebb tide (20-01-2021).

RMSE 32.11 cm for the M2 Constituent, followed by O1 with 12.77 cm. whereas the RMSE values for S2 and K1 do not exceed 5 cm.

3.2 Spring – Neap Variability

Figure 4 (5) shows the flood and ebb tidal current during spring (neap) phase.

It is observed that the maximum velocities occurred at the narrow region of the mouth of the estuary with a value of 0.52 m/s during both flood and ebb. For both the spring and neap,

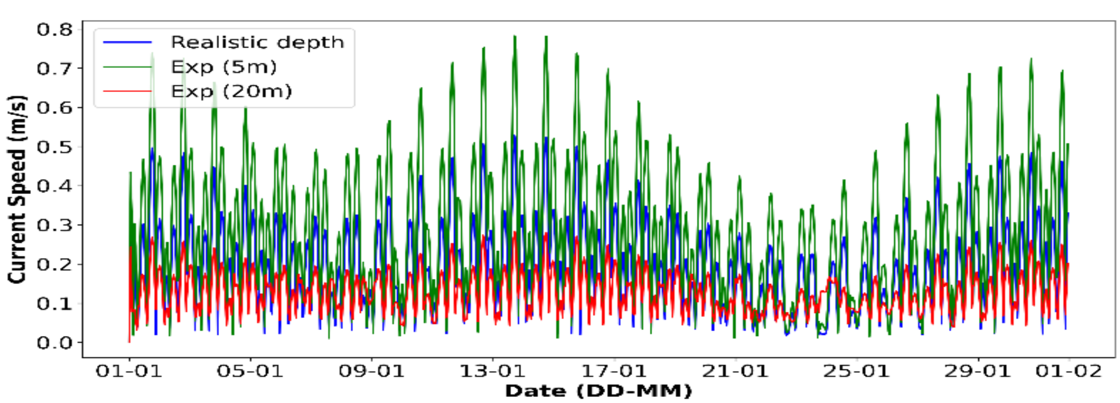


Figure 6. Spatial average of magnitude of tidal currents over mouth region (76.229˚E - 76.252˚E, 9.966˚N - 9.975˚N) from realistic (blue) and experimental run with dredge depth 5 m (green), dredge depth 20 m (red) respectively.

ebb-flood conditions spatial plots shows that the velocity was maximum at the narrow region of the mouth of the estuary and it gradually decreased at a range of 0.14 m/s - 0.18 m/s towards the northern arm and further decreased to a range of 0.02 - 0.06 m/s towards the southern arm. The orientation of the channel is along east-west direction, the flood -ebb flow is dominated in the northeast - southwest direction. The flood was directed toward the northern arm and southern arm, while the ebb flows towards the mouth of the estuary.

3.3 Dredge Depth and Current Speed

The narrow channel at the mouth, where the maximum velocity is observed, is currently undergoing dredging. The model depth in the region is approximately 10 meters. To assess the impact of changes in water depth due to dredging on tidal current speed, we conducted two simulations. In the first simulation, we reduced the model depth to 5 mtr at grid points where the highest velocity was observed. In the second simulation, we increased the depth to 20 mtr. All other parameters were kept the same as the original run.

The comparisons revealed a significant influence of channel depth on current speed. When the depth was reduced by 5 mtr, the current speed increased to a maximum of 0.78 m/s, compared to 0.52 m/s (Fig. 6). This indicates that reducing the bathymetry led to an increase in current speed by 0.26 m/s. Conversely, when the depth was increased to 20 mtr, the current speed decreased. Specifically, at a depth of 20 mtr, the current speed dropped from 0.52 m/s to 0.28 m/s (Fig. 6). This shows that increasing the depth resulted in a decrease in current speed by 0.24 m/s. These findings clearly demonstrate that depth changes significantly influence current speed in the Cochin Estuary.

3.4 Tidal Constituents

3.4.1 Tidal Elevation

Water level readings were subjected to harmonic analysis to ascertain the amplitude and phase of the principal tidal constituents M2, K1, S2, and O1. The findings are provided as spatial maps that depict the distribution of tidal constituent amplitude and phase throughout the study domain. The M2 constituent shows the maximum amplitude followed by K1. The maximum amplitude of M2 and K1 constituents are observed as 0.26 m and 0.20 m respectively (Fig. 7(a)). The phase angle range for the M2 tidal constituent is observed between 160° and 200° for the Cochin estuary (Fig. 7(b)). S2 and O1 were the next most significant. The relative importance of the diurnal and the semi-diurnal tidal constituents is expressed in terms of Form Number (F) Eqn. (2)[9].

$$F = \frac{HK1 + HO1}{HM2 + HS2} \tag{2}$$

HK1, HO1, HM2 and HS2 are the amplitudes of K1, O1, M2 and S2. The Form Numbers indicated that the tide is mixed, mainly semi-diurnal tide having values ranging from 0.80 - 0.85, with the lowest Form number at the mouth.

3.4.2 Tidal Current

Harmonic analysis of current is used to determine the amplitudes and phases of major tidal constituents over the domain. The distribution of tidal constituent amplitudes and phases is displayed in spatial plots. M2 is the largest tidal constituent followed by K1, S2, and O1. S2 and K1 have nearly comparable amplitudes, while O1 is the weakest among all the major tidal constituents.

Figure 8 shows that a maximum eastward component of M2 current is 0.3 m/s and is observed at the narrow part of

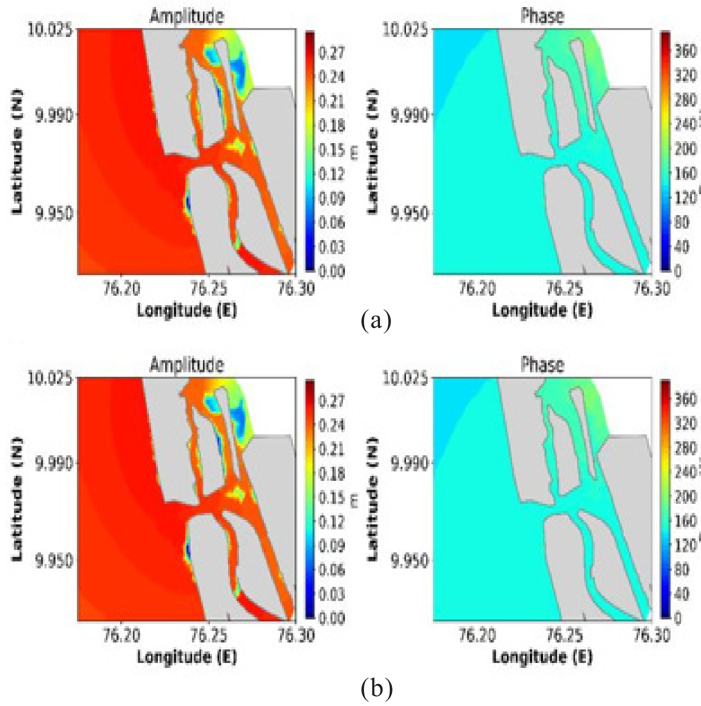


Figure 7. (a) Spatial plot of M2 constituent – Tidal height analysis; and (b) Spatial plot of K1 constituent – Tidal height analysis.

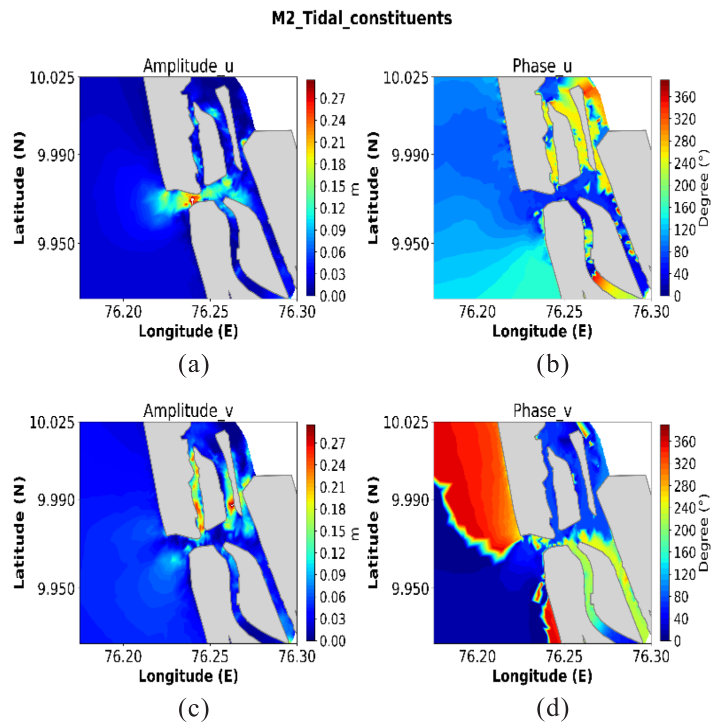


Figure 8. Spatial distribution of (a) amplitude; and (b) phase of M_2 constituent for U component. (c-d) Same as (a-b) but for V component.

the inlet. Along the channel upstream the amplitude decreases gradually. For both the northern and southern arm of the estuary the amplitude is not more than 0.1m/s for the northward component. The maximum value observed along the north arm of the estuary varies from 0.17m/s to 0.28 m/s and not much variation is observed in the southern arm and along the coast not much variation is observed. The phase observed for velocity component U is uniform along the channel with 80°, but in the case of the northern arm, there is a phase difference from 280° to 300° Also the U current is comparatively less over, and not much variation is observed in the southern arm. For the V phase, the southern arm has higher values.

For the tidal constituent K1 in the Cochin estuary, the highest U current amplitude of 0.15 m/s is observed at the estuary mouth, gradually decreasing upstream along the channel. U amplitude variations are minimal between the estuary's north and south arms. The U phase ranges from 240 degrees to 280° along the channel, extending towards the southern arm. In contrast, V current amplitude peaks in the northern arm, ranging from 0.12 m/s to 0.14 m/s, with the lowest values in the southern arm. Significant changes in the V phase are noted between these estuarine regions.

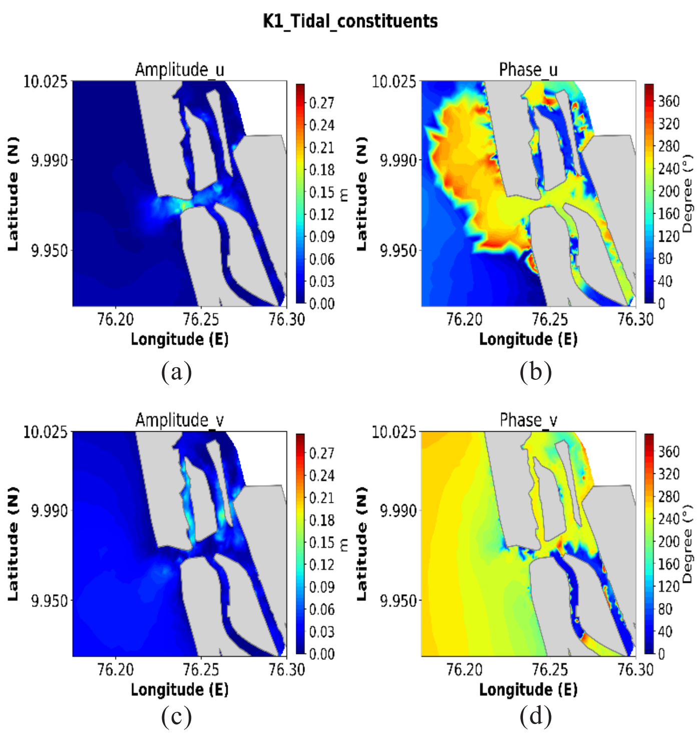


Figure 9. Same as Fig. 8 but for K_1 constituent.

5. SUMMARY AND CONCLUSIONS

The Cochin Estuary tidal dynamics simulation for January 2021 shows a good agreement with the observed data, highlighting the model's ability to accurately represent the key features of tidal fluctuations. The model fairly reproduces the observed tidal patterns, with Mean Absolute Error (MAE) of 0.067 m and a Root Mean Square Error (RMSE) of 0.083 m.

The observations of tidal currents in the Cochin Estuary reveal distinct patterns associated with the spring-neap cycle and the estuary's bathymetry. The data clearly show that the maximum velocities are concentrated in the narrow region at the mouth of the estuary, with peak values reaching 0.52 m/s during both flood and ebb tides. At the narrow opening of the Cochin Estuary, our study confirms a significant relationship between current speed and dredge depth. Dredge depth was reduced by 5 m, leading to a maximum measured current speed of 0.78 m/s, suggesting that current speeds increase at shallower depths. Conversely, the speed decreased to 0.28 m/s when the dredge depth increased to 20 m. These findings show that dredge depth significantly impacts current velocities, greater depths causing slower currents and shallower depths causing faster currents.

Shan Wang[15], *et al.*, also showed that the depth variation due to dredging can significantly modify the flow velocity in tidal channel.

The computed Form Numbers show a mixed tide regime that is primarily semi-diurnal, with the lowest values around the estuary mouth. A detailed harmonic study of water levels and currents demonstrates that amplitude of the M2 constituent is higher in the mouth and gradually decreases as one approaches the inlet; K1 and S2 constituents likewise exhibit a similar pattern. When taking into account the major tidal constituents, O1 did not show any discernible influence. Compared to the point-based 1D model analysis in Cochin estuary in the earlier study, our study shows significant spatial variation, indicating the importance of 2D model to resolve the tides in the estuary. The spatial maps of tidal constituent amplitude and phase show that M2 has the greatest amplitude (0.26 m), followed by K1 (0.20 m). The work confirms Vinitha et al.'s findings on the gradual shift in tidal characteristics along the estuary's main channel.

Future research will focus on Modelling suspended sediment distribution in the Cochin Estuary by incorporating sediment transport with tidal current analysis. We will use field sediment concentration and tidal current measurements for developing and validating numerical models. Assessing erosion-prone areas, estimating sediment behavior under multiple circumstances, and directing adaptive management techniques are the objectives of this research. Finally, our research will contribute to the comprehension of tidal dynamics and transport of sediments, thereby promoting sustainable estuary management.

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