

Numerical Simulation of Tidal Constituents in Thane creek and the Ulhas estuary, West Coast of India

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ABSTRACT

Tidal progression in the creeks and the estuaries are complex that can attract a large number of researchers around the globe. The main motive of the present work is to study the complex tidal variation of the Thane creek and the Ulhas estuary, west coast of India. A Delft 3D model was applied to simulate its depth averaged hydrodynamics and tidal propagation along the system. The calibration and validation of this model revealed the accuracy to predict tidal propagation along the system. The system was classified as hyposynchronous; a gradual decrease in the amplitude was noticed from mouth to upstream for all the season. The interpretation of amplitude and phase of the major tidal constituents, shallow water constituents, form number and tidal asymmetry showed the dynamic nature of the system. The form number results revealed that the tide in Thane creek and Ulhas estuary is mixed semidiurnal. The tidal asymmetry parameter indicated the seasonal variation of ebb and flood current in the Thane creek and the Ulhas estuary. Due to this, favouring sedimentation processes in the system with consequent erosion and deposition. For future, these results will help to understand the sediment transport, corresponding shoreline changes and biogeochemical processes of such a dynamic system to establish the ability to be sustained.

ADDITIONAL INDEX WORDS: *Delft 3D, Tidal Asymmetry, Form number, Thane creek, Ulhas estuary.*

INTRODUCTION

Numerical modeling techniques are widely used to understand the tidal propagation in the estuaries and the creeks. Likewise, tidal propagation in a system depends on several factors, viz, bottom friction, freshwater discharges, changes in bathymetry and morphology. The variation of all these factors can generate the tidal asymmetry in the systems (Gallo and Vinzon, 2005; Vinita *et al.*, 2015). Also, tidal asymmetries strongly influence nutrient balances, sediment loads (Blanton *et al.*, 2002; Dronkers, 1986), particles and pollutant transportations (Aldridge, 1997) *etc.* The primary source of asymmetry is the interaction of the principal lunar semidiurnal constituents M_2 with its first overtide, the lunar quarter-diurnal M_4 (Speer and Aubrey, 1985; Van de Kreeke and Robaczewska, 1993). Over-tides and compound tides arise primarily from the distortion of astronomical tides in shallow water (Parker, 1991). Symmetrical tides are also produced through the interaction of diurnal and semidiurnal constituents in mixed, mainly mixed semidiurnal tidal regimes ($0.25 < \text{Form number} < 1.5$), primarily through the combination of the lunar (K_1) and lunisolar (O_1) diurnal tides with M_2 and S_2 . The phase relationship between the diurnal and semidiurnal constituents dictates the direction of asymmetry by determining whether higher - high water (HHW) precedes or follows lower - low water (LLW) (Nidzieko, 2010).

Manoj *et al.* (2009) studied the tidal asymmetry in the Mandovi and Zuari estuaries, west coast of India. Through their study, it was inferred that the M_4/M_2 amplitude ratio indicated that the tide is subjected to more asymmetry in the Zuari estuary as compared to the Mandovi estuary. Also, these estuaries are flood dominant. The over-tides and compound tides played a major role on the tidal asymmetry inside the estuaries. Tidal asymmetry can change the duration of flood and ebb in an estuary and has important effects on both the geological evolution and the navigability of estuarine channels (Aubrey and Speer, 1985). An earlier study by Swamy and Suryanarayana (1984) studied the tidal exchange of seawater between the Thane creek and the Ulhas estuary through the narrow connection at Kasheli. They established that the tidal water enters the channel first through Ulhas estuary rather than Thane creek during the flood. Likewise, Naidu and Sarma (2002) revealed that the water mass passing through the eastern side tends to move towards Panvel creek, whereas water mass passing through the western side directed towards the main channel of Thane creek depending on the tidal excursion. Also, the residual current in Thane creek revealed that eddies and high residual current values showed intense mixing capacity in the southern region. Therefore, high rate of sedimentation was found in the central and upper part of the creek. Many studies (Chandy, 1992; Shetye, 1999; Unnikrishnan *et al.*, 1999; Unnikrishnan and Luick, 2003; Sundar and Shetye, 2005) were conducted to understand the variation of the major diurnal and semidiurnal constituents in the gulfs, estuaries and coastal regions of the west coast of India, but the tidal propagation in the networked systems like Thane creek and Ulhas estuary is not understood. Therefore the present study on numerical model will be first of its kind and physical characteristics of Thane creek and Ulhas estuary is barely discussed in the previous years.

Study region

Thane Creek and Ulhas Estuary (18° 52' 00" N to 19° 21' 35" N and 72° 44' 00" E to 73° 09' 30" E) consists of two dynamically different water-bodies located on the west coast of India. The shallow funnel-shaped Thane creek is a semi-enclosed water body, which opens to the Arabian Sea at its southwest and is also connected at its northern extremity to the Kasheli (Ulhas estuary) through a narrow channel (Figure 1). Sentinel imagery of the study region clearly shows urbanized regions along the bank of Thane creek and Ulhas estuary. The two major ports, Mumbai Port Trust (MbPT) and Jawaharlal Nehru Port Trust (JNPT) are situated at Thane creek mouth. Maximum water depth (12 m) below Chart Datum (CD) occurs in the mouth and is found to decrease as it moves upstream. The upstream width of the Thane creek is hardly 200 m and gets exposed during low tide. To maintain the navigational channel from the creek mouth to the port limits, dredging is carried out very often due to high siltation occurring in the middle and upstream region. The suspended sediment is below 100 mg/L during the non-monsoon period and reaches 200 mg/L in the monsoon season (Sharma *et al.*, 1994). Sastry (1971) observed that the central part of the creek receives a yearly sediment load of $0.84 \times 10^6 \text{ m}^3$, which gets uniformly spread over the 240 km^2 area with a sedimentation rate of 4 mm/year.

Thane creek and Ulhas estuary is under the influence of semi-diurnal tides with a mean tidal range of 5.0 m and 4.5 m during spring period in the mouth region (Chouksey *et al.*, 2004). Ulhas estuary is mainly a monsoon-fed river and the freshwater flow dwindles down during non-monsoon season. In the upstream there are three inlets which are club together into a single system that meanders for about 60 km before it enters the Arabian Sea at its west. Maximum depth of 25 m was found at Navghar in Ulhas estuary. The freshwater inflow to the estuary is highly managed with a high seasonal variance as a result of alterations in the watershed and connection to different rivers in the upstream. During the wet season, with extremely high flows, especially released from upstream rivers (Kalu river, Bhatsa river and Ulhas river), can drive the entire system fresh. While in the dry season tidal excursion of 5–15 km was noticed in the lower estuary (Vasai–Kasheli segment) that reduces to 2–5 km in the upper estuary (near Kalyan). By contrast, the lack of flows during the dry season can allow salt water to intrude upstream of the estuary upto Kalyan region, sometimes reaching ~20 PSU. Freshwater flushing is an important mechanism for estuarine mixing and water quality changes in Thane creek and Ulhas estuary.

The objective of this paper is to understand the seasonal variability of tidal constituents in a highly complex network system of Thane creek and Ulhas estuary, using a depth averaged Delft3D numerical model. Also, this work aims to establish the relation between the system dynamics and its bathymetry, thus presenting the actual information about physical behavior of Thane creek and Ulhas estuary. To applied harmonic analyses on M_2 , O_1 , M_4 and M_6 give a good explanation of Thane and Ulhas tidal dynamics. A numerical modeling study of the tidal propagation along the system was performed, seeking to determine and to analyze the amplitude and phase patterns of the major constituents, the shallow water constituents, the form number and the tidal asymmetry. Other than improving the dynamic knowledge on Thane creek and

Ulhas estuary, these results will help to understand the biogeochemical processes and sediment movement in the system.

METHODS

Study region encompass Thane creek and Ulhas estuary in the Maharashtra state, located along the west coast of India. Tidal measurements carried out in these regions were used to force Delft3d numerical model for simulating hydrodynamics of the system. The detailed methodology for data collection and simulation studies is explained in the coming sessions.

Field data

The Maharashtra Maritime Board (MMB) has supplied 21 high-resolution bathymetric charts for the entire study area. Chart numbers 910, 911, 912, 913, 1142 corresponding to the year 2009 and 1330, 1330A, 1334, 1335, 1336, 1337, 1377, 1378, 1379, 1380, 1381, 1382, 1383, 1384, 1396, 1401 to the year 2012. Time series water elevation data used for the present study were collected during 2013 from Mumbra, 2014 from Trombay and 2015 from Kasheli (Figure 1). Freshwater discharge data used in the present study have been retrieved from the Central Water Commission (CWC), India. Ulhas River has an average discharge of $200 \text{ m}^3 \text{ s}^{-1}$, which in wet season (June-September) with maximum daily discharge of $1000 \text{ m}^3 \text{ s}^{-1}$ and minimum of $10 \text{ m}^3 \text{ s}^{-1}$ in dry season (February-May).

Boundary conditions

In Thane creek, the domain calculation was done from the mouth of the creek to Kasheli (upstream) while in Ulhas estuary the tidal limit extended from mouth to Kalyan, which is indicated in Figure 1. The landward boundary Kalyan is the last permanent hydrometric station with long discharge records in the Ulhas river, with an average discharge of $200 \text{ m}^3/\text{s}$. Two seaward boundaries, one is in Ulhas estuary mouth at west with a mean tidal range of about 4.5 m and another is in Thane creek mouth at south (5.0 m tidal range).

Numerical model

In this study, depth averaged numerical simulations for Thane creek and Ulhas estuary was set up by using a Delft3D-FLOW modeling system developed by Deltares (Lesser *et al.*, 2004; Sathishkumar and Balaji, 2015). Delft3D is an open source community model which incorporated hydrodynamic and mass transport equations via curvilinear coordinate system. This model can represent spatial resolution according to complex geomorphology of the study domain.

Model setup and calibration

The bathymetry for this study was digitized from hydrographic charts supplied by the Maharashtra Maritime Board. In this work, grid with a resolution of 100 m in the x-direction and 100 m in the y-direction is developed. A triangular interpolation method was used to develop the

rectangular grid resulted in 379 cells in the x-direction and 500 cells in the y-direction. To optimize the computational time and better results, several simulations were performed to determine the ideal bottom roughness, time step and horizontal viscosity. The better model results were attained with a time step of 0.5 minutes, and horizontal viscosity of 15 m²/s. The bottom roughness was specified by Chezy's friction coefficients (C), which is varied between 75 m^{1/2}/s to 85 m^{1/2}/s (Sathishkumar and Balaji, 2015). Boundary tide was specified at the southern and western boundaries of the model domain.

RMS error

The root-mean square (RMS) error of the predicted and observed water elevation was used by several authors to evaluate the accuracy (Fortunato *et al.*, 1997; Dias and Lopes, 2006).

$$\text{RMS} = \left\{ \frac{1}{N_0} \sum_{i=1}^{N_0} [\zeta_o - \zeta_p]^2 \right\}^{\frac{1}{2}} \quad (1)$$

ζ_o = Observed water elevation

ζ_p = Predicted water elevation

N_0 = number of measurements in the time series

According to Dias *et al.*, 2009, the RMS values should be compared with the local tide range and if they are less than 5% of the local amplitude, the correspondence between the model results and observations is excellent. If these values vary between 5% and 10% of the local amplitude, the match is considered very well.

Skill assessment

The model predictive Skill is being recently used to evaluate the quantitative agreement between model and observations. This statistical method was developed by Wilmott, 1982 and recently used by Warner *et al.*, 2005; Dias *et al.*, 2009.

$$\text{Skill} = 1 - \frac{\sum |\zeta_p - \zeta_o|^2}{\sum (|\zeta_p - \bar{\zeta}_o| + |\zeta_o - \bar{\zeta}_o|)^2} \quad (2)$$

A Skill value equal to one corresponds to a perfect match between the model results and observations while a complete disagreement yields a Skill of zero.

Harmonic analysis

Harmonic analysis of predicted and observed tides is widely used by the researchers to appraise the accuracy of the model output (Dias and Lopes, 2006; Manoj *et al.*, 2009; Sousa and Dias, 2007; Vaz *et al.*, 2009) and it helps to determine the tidal characteristics of the system as

well. In this study harmonic analysis was performed using Tidal Analysis Software Kit (TASK-2000) developed by the Proudman Oceanographic Laboratory, UK was determined the amplitude and phase of the major constituents (Bell *et al.*, 2000). The harmonic analysis was done with 27 independent constituents and 8 related constituents for premonsoon, monsoon and postmonsoon.

Form number

The form number (F) which is the ratio of the sum of the diurnal constituents (K_1 and O_1) to that of the semi-diurnal constituents (M_2 and S_2) classifies the periodic nature of tide. In this study form factor of the entire system was assessed by the following expression (Defant, 1960; Pugh, 2004);

$$F = \frac{O_1 + K_1}{M_2 + S_2} \quad (3)$$

The tide is semidiurnal if $0 < F < 0.25$; mixed semidiurnal tides predominate if $0.25 < F < 1.5$; mixed diurnal tides predominates if $1.5 < F < 3.0$; and finally the tide is diurnal if $F > 3.0$ (Pugh, 1987).

RESULTS

The simulations from Delft3d model that configured for Thane creek and Ulhas estuary were subjected for validation and calibration using in-situ water level observations. The system dynamics elucidate from the model results were presented in the coming sessions: calibration of tide, amplitude and phase of diurnal, semidiurnal and shallow water constituents, tidal asymmetry.

Calibration of Tide

Boundary tides were specified at the southern and western periphery of the model domain. The predicted tides were compared with observed data (Tide Gauge) at Trombay, Kasheli, Mumbra during 2015. Similarly, modelled currents were also compared with data collected at Kasheli using current meter. The one-day model output was discarded as the instabilities due to the cold start simulation. The model was run by varying bottom roughness length (K) in the bottom friction formula. The modeled tides at Trombay, Kasheli, Mumbra were stored at 600 seconds interval and compared with the observations. The result showed that, modeled tides are in fair agreement with the observations and C is $81 \text{ m}^{1/2}/\text{s}$ (Figure 2).

The RMS and Skill were computed for each calibration and validation, which is presented in the Table. 1. Table. 1 depicted that the Skill values are very close to 1 and the RMS values are in between 0% to 15% of the local amplitude. Therefore the model has accurately predicted the tidal propagation in Thane creek and Ulhas estuary. The analysis was done with 27 independent constituents and 8 related constituents for different seasons. Comparison of observed and predicted constituents at Trombay and Kasheli were presented in the Figure 3.

Tidal characteristics of Thane creek and Ulhas estuary

The most necessary constituents for periodic oscillations in gulfs and estuaries of the west coast of India are M_2 , S_2 , K_1 , N_2 , O_1 , M_4 , and M_6 (Sanil kumar *et al.*, 2011). So the analysis of these tidal constituents along Thane creek and Ulhas estuary becomes essential to understand the seasonal variation of the tidal dynamics. In the present study, the dominant constituents M_2 and O_1 are emphasized based on previous studies by Manoj *et al.*, 2009 and Sanil Kumar *et al.*, 2011, they revealed that M_2 and O_1 are the major diurnal and semidiurnal constituents of the west coast of India. Similarly, M_4 and M_6 are the most important constituents to determine the local tidal asymmetry and bottom friction influence. The present section included the results of numerical simulations carried out in Thane creek and Ulhas estuary to establish the seasonal variation of tidal characteristics in the system. From the results, the phase and amplitude distribution of the tidal constituents were calculated. Also, from this data set, the form number and the tidal asymmetry were studied.

The model run was carried out to generate water level variation for three seasons under two scenarios, viz; a constant depth (5m; control run) and actual bathymetry. Since, Thane creek and Ulhas estuary experienced significant bathymetric variations with least (insignificant) variations in morphology over the years (Sastry, 1971), which was the motivation to run the model by actual and constant bathymetry. The results showed that, in constant run, the amplitude from mouth to head was almost similar for all seasons (Figures 4b, d, 5b, d & 6b, d). But gradual decrease of amplitude from mouth to head was found in actual bathymetry indicating a hyposynchronous system (Figures 4a, c, 5a, c & 6a, c). Influence of bathymetry on tidal propagation was very evident from the above results.

Amplitudes and phase patterns of Diurnal and Semidiurnal constituents

In general, it was observed that the variation in amplitude depend on the system morphology and distinction of depths. From Figures 4, 5 & 6 it is clear that tidal amplitude in Thane creek and Ulhas estuary depends on the bathymetry rather than morphology. From the results, the amplitude and phase of Diurnal and Semidiurnal constituents along the system were calculated. From Figure 7, M_2 amplitude increases gradually through Thane creek until north of Vashi (middle creek) and decreases towards upstream of the creek (Kasheli) and it varied from 1.16 m at the mouth to 1.34 m north of Vashi and 1.04 m in the upstream during premonsoon. Similarly in Ulhas estuary, M_2 was found to be high in the upstream (1.24 m), gradually decreased towards mid (1.10 m) and increased to 1.2 m towards the mouth region (Figure 7a). During heavy discharges, the M_2 amplitude in the Ulhas upstream was low and increased towards mouth of the estuary. But in Thane creek, the M_2 amplitude was low in the upstream, increased in the mid until south of Trombay and further decreased towards the mouth (Figure 7b). From the results it can concluded that, interaction between freshwater influx and tidal constituents resulting low amplitude (0.98 m) in the upstream and high amplitude towards mouth (1.18 m). As compared to premonsoon, similar pattern of M_2 was found during postmonsoon in Thane

creek and Ulhas estuary. The amplitude in postmonsoon varied between 0.9 m to 1.36 m in Thane creek and 1.1 m to 1.32 m in Ulhas estuary (Figure 7c).

Regarding M_2 phase, tidal propagation was found to be different along the two main areas of the system, the mouth and the head. The amplitude of M_2 was strongly reduced in the shallow areas. In fact, a phase change was observed as the tide propagated towards the upstream of the system. Figure 7 showed that the phase delay was minimal during premonsoon and postmonsoon, but large phase variation was observed in the monsoon. In Ulhas estuary, M_2 phase was $\sim 80^\circ$ near the mouth and $\sim 150^\circ$ in the Kalyan, which means that the propagation delay for this constituent is about 1 hour and 10 minutes ($\sim 70^\circ$) during monsoon (Figure 7e). Also in Thane creek, phase was $\sim 80^\circ$ near the mouth, which keeps relatively constant along the creek, reached $\sim 90^\circ$ near to Vashi and further increased ($\sim 140^\circ$) towards Kasheli.

The diurnal constituent (O_1) in Ulhas estuary has an amplitude of ~ 0.22 m in the mouth region, which decreased towards upstream and reached ~ 0.13 m irrespective of season. Similarly in Thane creek, O_1 was high in the mouth and diminished gradually to the upstream of the creek. But amplitude range in Thane creek was found to be low in monsoon as compared to premonsoon and postmonsoon (Figure 8). About phase, O_1 showed a phase difference of $\sim 14^\circ$, 8° and 40° for premonsoon, monsoon and postmonsoon in Ulhas estuary. Likewise the seasonal phase difference of $\sim 4^\circ$, 2° and 6° was found in Thane creek (Figure 8). The results revealed that the amplitude of the semidiurnal (M_2) constituent was more dominant than the diurnal (O_1) constituents in the system.

Amplitudes and phase patterns of Shallow water constituents

The over-tides M_4 and M_6 constituents represent the nonlinear distortion of tidal levels induced by shallow depths and friction effects delayed water movement in the system. The results of shallow water constituents were presented in Figures 9 & 10, which demonstrated that their amplitudes are low in the coastal region, but increase gradually inside the system. Being M_4 , the most significant of this constituent, it was strongly influenced by changes in system morphology and bathymetry. From Figure 9, the results showed that the amplitude was low in the mouth region of Ulhas estuary and gradually increased along the estuary until Kalyan in the upstream irrespective of season (Figure 9). Likewise in Thane creek, amplitude increased from mouth to upstream for all season. The amplitude varied from ~ 0.02 m near to the mouth to ~ 0.2 m in the upstream of Thane creek and Ulhas estuary. It is important to show that M_4 has higher amplitude than the diurnal constituents in the inner part of the system. About to the M_4 phase lag in Ulhas estuary, the propagation delay was very small in the estuary during premonsoon (Figure 9). But in monsoon, phase delay increased from mouth to upstream and the difference become more significant near Kalyan (varied from $\sim 80^\circ$ to $\sim 220^\circ$, which corresponds to 2 hours and 30 minutes). In postmonsoon, delay was minimum in the mouth of the estuary, which increased towards upstream and the difference was $\sim 60^\circ$. In Thane creek, the propagation delay was very small from the mouth to the upstream area, while the phase difference was about $\sim 60^\circ$ (Figure 9).

For M_6 , the amplitude of ~ 0.01 m was found near to Ulhas mouth, which keeps relatively constant along the estuary, reached 0.024 m near to upstream of the estuary. Also in monsoon, the M_6 amplitude was found high in the mid and upstream (~ 0.026 m), which decreased towards the mouth region (~ 0.002 m). But in postmonsoon, M_6 amplitude was almost constant throughout the estuary with average amplitude of ~ 0.012 m (Figure 10 c). In premonsoon and monsoon, low amplitude was found in the mouth of Thane creek, which increased gradually towards upstream. Similarly in postmonsoon, amplitude (0.046 m) increased with a strong gradient from Vashi to upstream (Figure 10). Regarding to the M_6 phase, the lower values are observed at the mid and upstream of Thane creek and Ulhas estuary (Figure 10). Seasonal variations in M_6 phase were evident in the Figure 10.

To know the tide pattern in Thane creek and Ulhas estuary, Form number (F) (Pugh, 2004) was calculated. The results revealed that tides are generally mixed semi-diurnal. The amplitudes of semi-diurnal constituents are significantly higher than that of diurnal constituents, being thus expected a low F in the system. From Figure 11, F value is less than 1.5 m which indicated that the tide is mixed semi-diurnal for all seasons and the amplitude ranged from ~ 0.285 to ~ 0.425 m. It was noticed that during high discharge F decreased in Ulhas estuary and increased in Thane creek due to high M_2 amplitude, as discussed earlier. In the upstream of Thane creek, F increased to ~ 0.425 m due to the strong decrease in the amplitude of semidiurnal constituents.

Tidal Asymmetry

Tidal asymmetry happens when the ebb and flood durations are unequal and it is caused by tidal wave distortion during propagation into shallow waters. Aubrey and Speer (1985) showed that the tidal asymmetry can be represented by harmonics of astronomical tide constituents. Thus, the ratio of M_4 and M_2 and of M_6 and M_2 amplitude ratios can be analyzed to determine the tidal asymmetry within the system. Similarly, relative phases of M_4 and M_2 and of M_6 and M_2 determine the asymmetry. Simultaneously, if the flow is flood dominant, $0^\circ < \text{phase} < 180^\circ$ and is ebb dominant, if $180^\circ < \text{phase} < 360^\circ$. Therefore, this helps to determine the net transport in and out of the system over a tidal cycle. Especially, tidal asymmetry is the dominant factor for the movement of particles in the coastal areas, creeks and estuaries (Castaing and Allen, 1981).

From Figure 12, the results revealed that there was a steady increase of M_4/M_2 amplitude ratio towards upstream in Thane creek and Ulhas estuary. The ratio of M_4/M_2 is 0.03 mouth of Ulhas estuary and 0.08 at Mumbra. This increase from mouth to upstream showed that the tide does not distorted much upto Mumbra whereas at Kalyan, tide is completely gets distorted due to very high amplitude ratio, which is about 0.19. Likewise in Thane creek, amplitude was steadily moved upto Vashi, further gets distorted towards the creek upstream with increased M_4/M_2 ratio of 0.18 (Figure 12). In Ulhas estuary, the amplitude ratio was always higher than 0.02 (excluding the mouth of the estuary), which allows to state that tidal asymmetry occurs in

the whole estuary. But in Thane creek, until Vashi the ratio was lower than 0.02, further increased towards upstream to reached an asymmetric state.

For relative phase is concluded that the system was dominated by the flood. Figure 12 showed that for the entire system (excluding mouth of Thane creek) relative phase values was less than 180° , indicated flood dominance. However, the mouth of Thane creek relative phase differ from rest of the system, indicated ebb dominance.

Researchers apply the importance of M_4 constituents to study the tidal asymmetry in any system. In this work, amplitude ratio of M_6/M_2 (Figure 13) and relative phase $3M_2-M_6$ (Figure 13) were also calculated from the harmonic results. The amplitude ratio of M_6/M_2 depicted a gradual increase along the system. In Ulhas estuary amplitude ratio ranged from ~ 0.002 to 0.022 m. But in Thane creek it varied from ~ 0.002 to 0.044 m. Maximum amplitude ratio was found in the upstream (~ 0.044 m) of Thane creek (Figure 13). Thus the amplitude ratio can be probably related to ebb dominance pattern. Amplitude ration was always higher than 0.01 throughout the system (excluding mouth), revealed that tidal asymmetry occurs in the whole system. For relative phase, values are always higher than 180° in the whole estuary for all seasons. At the mouth, relative phase values are about $\sim 340^{\circ}$ and it reached $\sim 190^{\circ}$ in the upstream (Figure 13).

DISCUSSION

Due to the shallowness of the system, the tidal properties are essentially driven by the oceanic tidal characteristics at its entrance and it's varied along the system. Consequently, the analysis of tidal characteristics was essential to understand the factors influence the tidal dynamics. The numerical simulations were carried out to establish the tidal dynamics along the system. The results indicated that, the water level generated from the mouth and the upstream clearly stated that the system was hyposynchronous for all seasons. In the hyposynchronous system, the effect of convergence is greater than that of the friction in the system and, therefore the tidal amplitudes are found to decrease towards the system head (Shivaprasad, 2013). From the above results it was confirmed that the seasonal variations of tidal constituent plays a major role in the system dynamics.

In the present study, the tidal constituents were calculated using harmonic analysis. The results showed that, M_2 tidal constituent was found to maximum, followed by K_1 , O_1 and S_2 in the system. Likewise, M_2 and O_1 were analyzed because they are the major semidiurnal and diurnal constituents. Also, M_4 and M_6 are the most important shallow water constituents and it was relevant in defining tidal asymmetry and bottom friction effects. The results of harmonic analysis depicted that the amplitude of semidiurnal constituents were found to be high in the middle region of Thane creek was unexpected. As tidal wave propagates along the system, a decrease in the amplitude of diurnal and semidiurnal were experienced due to bottom friction and nonlinear transfer of energy (Aubrey and Speer, 1985). Thus, the amplification found may be explained considering an estuarine/creek resonance mode with a period of 12 hours and the length of the system, which enhances the M_2 constituent in the system (Friedrichs and Aubrey, 1988). During river discharge, the M_2 amplitude was decreased in the upstream of Thane creek

and Ulhas estuary. In Thane upstream, the M_2 amplitude decreases to 0.88 m due to the complex bathymetry. But in the Ulhas upstream, the M_2 amplitude was clearly influenced by the river discharge, especially during periods of high river discharge (Reis *et al.*, 2009). From Figure 7, the amplitude and phase variations of the tidal constituents towards the upstream region are not linear, this was a strong indication of the presence of a reflected wave in the system. Hence the amplification of semi-diurnal constituents in Thane creek and Ulhas estuary can be mainly attributed between pressure gradient and friction. The superimposition of incident and reflected wave could be the reason of increase of the semidiurnal constituents at the upstream directions.

As a shallow water constituent, M_4 was strongly dependent on the bathymetric changes. Therefore, amplitude and phase variations occur in areas where significant changes in the system bathymetry (Vinita *et al.*, 2015). The results showed that M_4 amplitude is low in the coastal region, but increase gradually towards the upstream. The M_4 increases both in Thane creek and Ulhas estuary. A significant difference in the variation of the amplitude of M_6 was identified in the creek and the estuary. Estuaries behave similar to the observations of earlier researchers which were low in the mouth and gradually increase towards upstream and it will vary with respect to seasons (Srinivas *et al.*, 2003). The increase of M_6 inside the estuaries can be attributed to the quadratic friction (Blanton *et al.*, 2002). It can be seen from the Figure 10 that the non-linear increase of compound tides towards the upstream regions. But in the creek, the variation of the amplitude of M_6 was dependent upon the tidal amplification. These results clearly indicated that the behavioral difference between the creek and the estuary.

Symmetrical tide occurs when the tide rise and fall with identical duration and approximately equal velocities, which resulted in zero net sediment transport. Tidal asymmetry was found when the ebb and flood durations are unequal and it is caused by tidal wave distortion during propagation into shallow waters of the system. Also the results of tidal asymmetry are useful to determine the circulation in the system, including the flood or ebb current influence (Aubrey and Speer, 1985; Friedrichs and Aubrey, 1988; Sivakholundu *et al.*, 2006; Speer and Aubrey, 1985). From results, the relative phase (M_4/M_2) increased in the upstream of Ulhas estuary but it decreased in the Thane upstream. The increase (decrease) of a relative phase towards upstream is an indication of ebb dominance (flood dominance). The flood dominance had a strong impact on sediment which resulted in accretion in the system. But ebb dominance supported sedimentation processes in the system with resultant erosion. For the relative phase ratio (M_6/M_2), the system dominated by the ebb current for all seasons. The high amplitude ratio in the upstream of Thane creek revealed that the impact of bottom friction resulting in low water delay (Parker, 1991) and therefore decrease the time lag between low and high water. Thus the ratio at Thane upstream probably related to flood dominance. The amplitude was higher than 0.02 throughout the system, revealing that tidal asymmetry occurs in the system.

CONCLUSIONS

Thane creek and Ulhas Estuary is under Thane Municipal area near Mumbai, Maharashtra is connected through a narrow and shallow channel. With the urbanization and

industrial growth, Thane Creek and Ulhas estuary has become a reservoir of waste from surrounding area. Water quality of both Thane creek and Ulhas estuary has deteriorated badly due to various anthropogenic discharges. Past studies have indicated an alarming situation that there is an immediate need to prepare a conservation plan. A two dimensional numerical model has been used to studied the tidal dynamics of Thane creek and Ulhas estuary.

The model results concluded that, the system was classified as hyposynchronous, where a gradual decrease in the amplitude was noticed from mouth to upstream for all season. However, the model results indicated that, the entire system bathymetry plays a key role in setting the circulation pattern rather than morphology. This influence was observed in diurnal constituents, semidiurnal constituents, shallow water constituents and tidal asymmetry. Moreover, the results of form number revealed that the tide in Thane creek and Ulhas estuary was mixed semidiurnal. There was a phase delay as the tidal wave moved towards the inshore of the system. In the shallow areas the M_2 was strongly attenuated, while the M_4 and M_6 are strongly amplified, thus induced tidal asymmetry. The tidal asymmetry indicated that the ebb and flood current varied seasonally in Thane creek and Ulhas estuary, which helps the sedimentation processes in the system with consequent erosion and deposition. The shallow water constituents are mainly induced by nonlinear effects of advection and bottom friction, these patterns suggested that the advective forces are dominant from the mouth to mid region, while bottom friction played a major role in upstream.

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LITERATURE CITED

- Aldridge, J.N., 1997. Hydrodynamics model predictions of tidal asymmetry and observed sediment transport paths in Morecambe Bay. *Estuarine, Coastal and Shelf Science*, 44, 39-56.
- Aubrey, D.G., and Speer, P.E., 1985. A study of non-linear tidal propagation in shallow inlet/estuarine systems. Part I: Observations. *Estuarine, Coastal and Shelf Science*, 21, 185-205.
- Bell, C., Vassie, J.M., and Woodworth, P.L., 2000. POL/PSMSL Tidal Analysis Software Kit 2000 (TASK-2000). Birkenhead, Merseyside, U.K.: Permanent service for mean sea level, CCMS Proudman Oceanographic Laboratory, Bidston Observatory.

- Blanton, J., Lin, G., and Elston, S., 2002. Tidal current asymmetry in shallow estuaries and tidal creeks. *Continental Shelf Research*, 22, 1731-1743.
- Castaing, P., and Allen, G.P., 1981. Mechanisms controlling seaward escape suspended sediment from the Gironde, a macrotidal estuary in France. *Marine Geology*, 40, 101–118.
- Chandy John, V., 1992. Harmonic tidal current constituents of the western Arabian Gulf from moored current measurements. *Coastal Engineering*, 17(1-2), 145-151.
- Chouksey, M.K., Kadam, A.N., and Zingde, M.D., 2004. Petroleum hydrocarbon residues in the marine environment of Bassein-Mumbai. *Marine Pollution Bulletin*, 49, 637-647.
- Defant, A., 1960. *Physical oceanography*, 2. Peragamon Press, Oxford. 598p.
- Dias, J.M., and Lopes, J.F., 2006. Calibration and validation of hydrodynamic, salt and heat transport models for Ria de Aveiro Lagoon (Portugal). *Journal of Coastal Research*, 39, 1680-1684.
- Dias, J.M., Sousa, M.C., Bertin, X., Fortunato, A., and Oliveira, A., 2009. Numerical modeling of the impact of the Ancao Inlet relocation (Ria Formosa, Portugal). *Environmental Modeling & Software*, 24, 711-725.
- Dronkers, J., 1986. Tidal asymmetry and estuarine morphology. *Netherlands Journal of Sea Research*, 20, 117-131.
- Fortunato, A.B., Baptista, A.M., and Luettich Jr, R.A., 1997. A three-dimensional model of tidal currents in the mouth of the Tagus estuary. *Continental Shelf Research*, 17, 1689-1714.
- Friedrichs, C.T., and Aubrey, D.G., 1988. Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis. *Estuaries, Coastal and Shelf Science*, 27, 521-545.
- Gallo, M.N., and Vinzon, S.B., 2005. Generation of overtides and compound tides in Amazon estuary. *Ocean Dynamics*, 55, 441-448.
- Lesser, G.R., Roelvink, J.A., Van Kester, J.A.T.M., and Stelling, G.S., 2004. Development and validation of a three dimensional morphological model. *Journal of Coastal Engineering*, 51, 883-915.
- Manoj, N.T., Unnikrishnan, A.S., and Sundar, D., 2009. Tidal Asymmetry in the Mandovi and Zuari estuaries, the West Coast of India, *Journal of Coastal Research*, 25(6). 1187-1197.
- Naidu, V. S., and Sarma, R. V., 2002. Numerical Modeling of Tide-Induced Currents in Thane Creek, West Coast of India. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 127(4), 241-244.

- Nidzieko, N.J., 2010. Tidal asymmetry in estuaries with mixed semidiurnal/diurnal tides. *Journal of Geophysical Research*, 115.
- Parker, B.B., 1991. The relative importance of the various non-linear mechanisms in a wide range of tidal interactions (review). In: Parker, B.B. (Ed), *Tidal Hydrodynamics*, Wiley, New York, USA, pp. 237-268.
- Pugh, D.T., 2004. *Changing Sea Levels – Effects of Tides, Weather and Climate*. Cambridge University Press, Cambridge, 265p.
- Pugh, D.T., 1987. *Tides, Surges and Mean Sea-Level, A Handbook for Engineers and Scientists*, John Wiley & Sons, Chichester, 472p.
- Reis, L.J., Martinho, A.S., Pires-Silva, A., and Silva, A.J., ICS 2009. Assessing the influence of the River discharge on the Minho Estuary Tidal Regime. *Journal of Coastal Research*, SI 56, 1405-1409.
- Sanilkumar, V., Udhaba Dora, G., Sajive Philip., Pednekar, P., and Jai Singh., 2011. Variations in Tidal constituents along the nearshore waters of Karnataka, west coast of India. *Journal of Coastal Research*, 27(5), 824-829.
- Sastry, J.S., 1971. The mechanism of sediment transport in the environs of Bombay harbour, in: Proc., Symp. on Engrg. Properties of Sea-Floor soils and Their Geophys. Identification, UNESCO/University of Washington, Washington, D.C., 338-349.
- Sathishkumar, J., and Balaji, R., 2015. Inter-comparison of hydrodynamic models of Gulf of Khambhat. *International Journal of Ocean and Climate Systems*, 6(1), 35-46.
- Sharma, P., Borole, D.V., and Zingde, M.D., 1994. ²¹⁰Pb based trace elements fluxes in the nearshore and estuarine sediments off Bombay, India. *Marine chemistry*, 47, 227-241.
- Shetye, S.R., 1999. Tides in the Gulf of Kutch, India. *Continental Shelf Research*, 19, 1771-1782.
- Shivaprasad, A., 2013. Tide and River runoff interaction in the cochin estuary. Cochin University of Science and Technology, Ph.D thesis, 214p.
- Sivakholundu, K.M., Kathioli, S., Mani, J.S., and Idichandy, V.G., 2006. *Evaluation of river regulatory measures in Hughly estuary using tidal asymmetry characteristics*. IEEE.
- Sousa, M.C., and Dias, J.M., 2007. Hydrodynamic model calibration for a mesotidal lagoon: the case of Ria de Aveiro (Portugal). *Journal of Coastal Research*, 50, 1075-1080.
- Speer, P.E., and Aubrey, D.G., 1985. A study of non-linear tidal propagation in shallow inlet/estuarine systems. Part II: Theory. *Estuarine, Coastal and Shelf Science*, 21, 207-224.

- Srinivas, K., Revichandran, C., Maheswaran, P.A., Mohamed Asharaf, T.T., and Nuncio Murukesh., 2003. Propagation of tides in the Cochin estuarine system, southwest coast of India. *Indian Journal of Marine Science*, 32(1), 14-24.
- Sundar, D., and Shetye, S.R., 2005. Tides in the Mandovi and Zuari estuaries, Goa, West coast of India. *Journal of Earth System Science*, 144, 493-503.
- Swamy, G.N., and Suryanarayana, A. 1984. Tidal flow characteristics at Kasheli (Kalwa /Bassein Creek), Bombay. *Indian Journal of Marine Sciences*, 13, 168-171.
- Unnikrishnan, A.S., Gouveia, A.D., and Vethamony, P., 1999. Tidal regime in the Gulf of Kutch, west coast of India by 2D model. *Journal of Waterways, Port and Harbour Engineering*, 125(6), 276-284.
- Unnikrishnan, A.S., and Luick, J.L., 2003. A finite element simulation of tidal circulation in the Gulf of Kutch, India. *Estuarine, Coastal and Shelf Science*, 56, 131-138.
- Van de Kreeke, J., and Robaczewska, K., 1993. Tide-induced residual transport of coarse sediment; application to the Ems Estuary. *Netherlands Journal of Sea Research*, 31, 209-220.
- Vaz, N., Fernandes, L., Leitao, P.C., Dias, J.M., and Neves, R., 2009. The Tagus estuarine plume induced by wind and river runoff: Winter 2007 case study. *Journal of Coastal Research*, 64, 1495-1499.
- Vinita, J., Shivaprasad, A., Manoj, N.T., Revichandran, C., Naveenkumar, K.R., and Jineesh, V.K., 2015. Spatial tidal asymmetry of Cochin estuary, West Coast, India. *Journal of Coastal Conservation*, 19, 537.
- Warner, J.C., Geyer, W.R., and Lerczak, J.A., 2005. Numerical modelling of an estuary: a comprehensive skill assessment. *Journal of Geophysical Research*, 110, C05001.
- Wilmott, C.J., 1981. On the validation of models. *Physical Geography*, 2, 184-194.

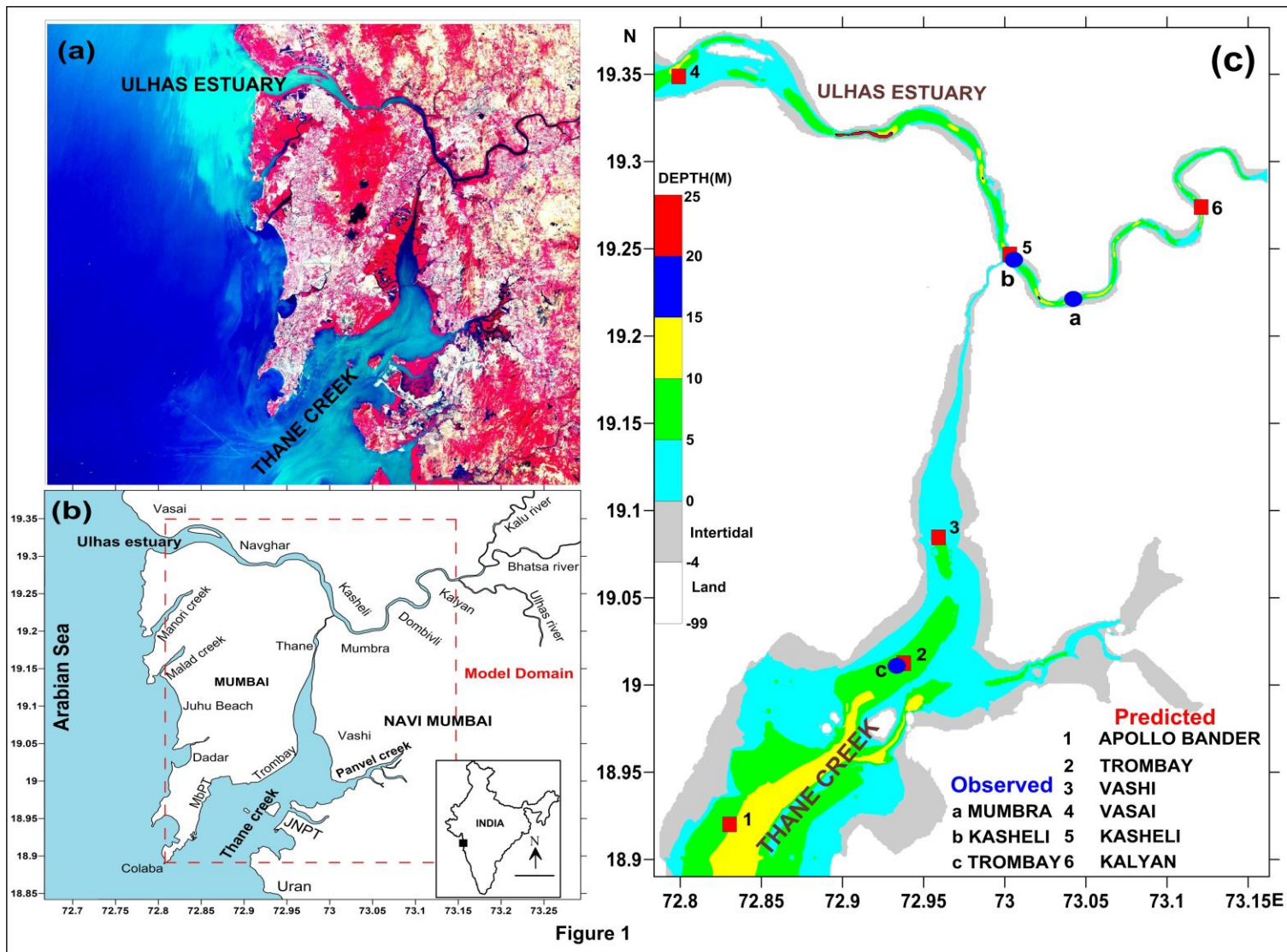
List of Figures

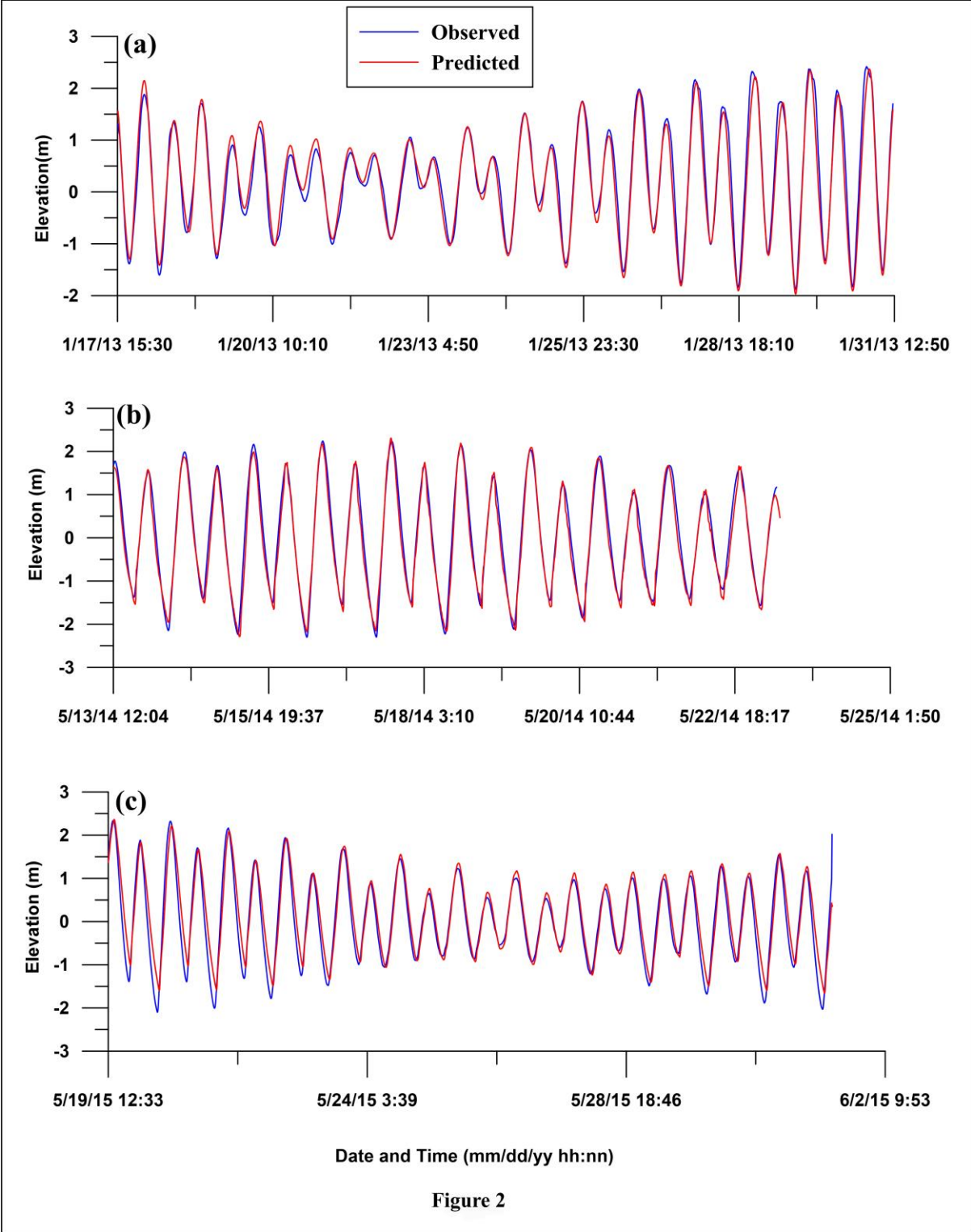
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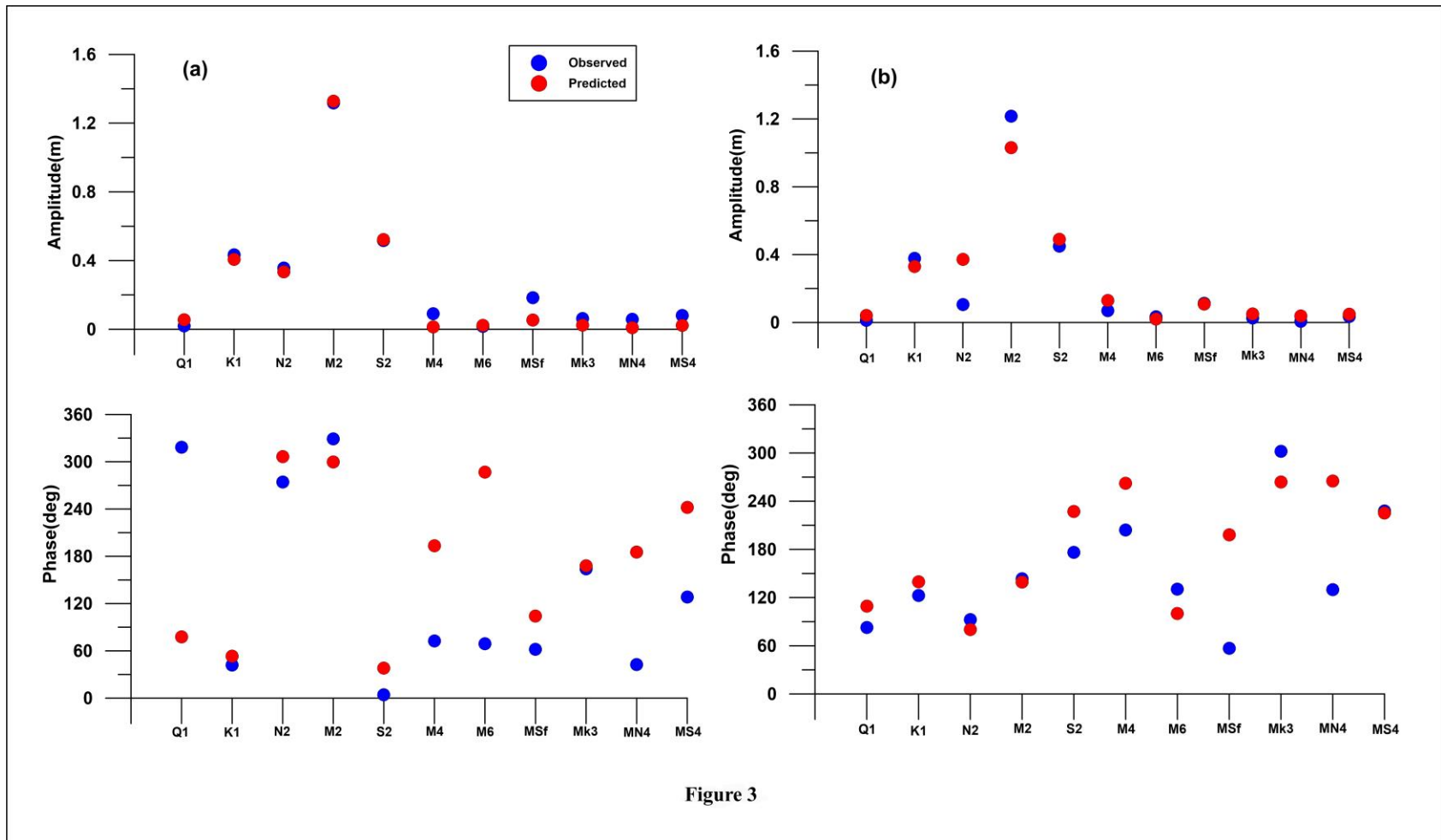


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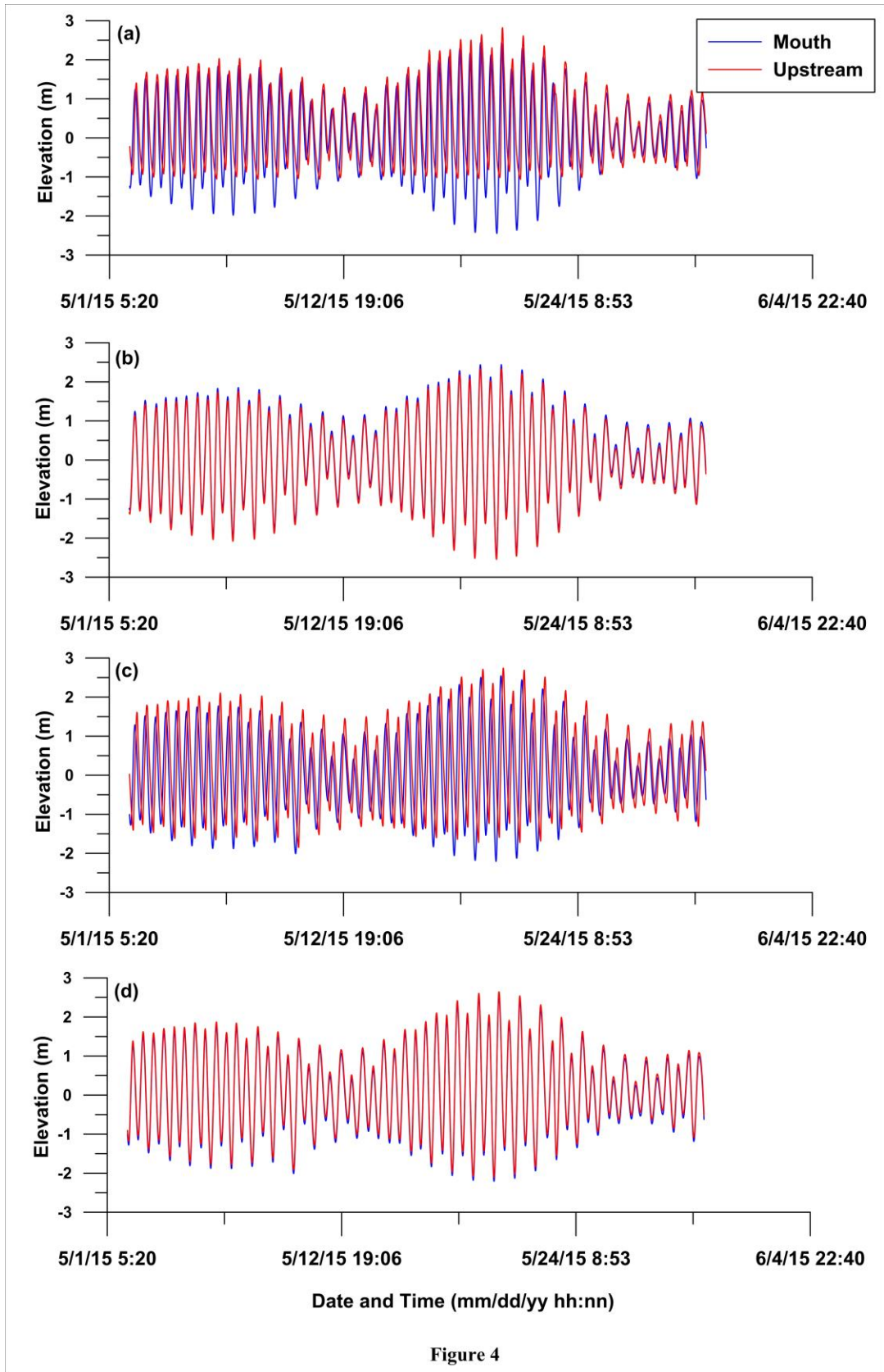


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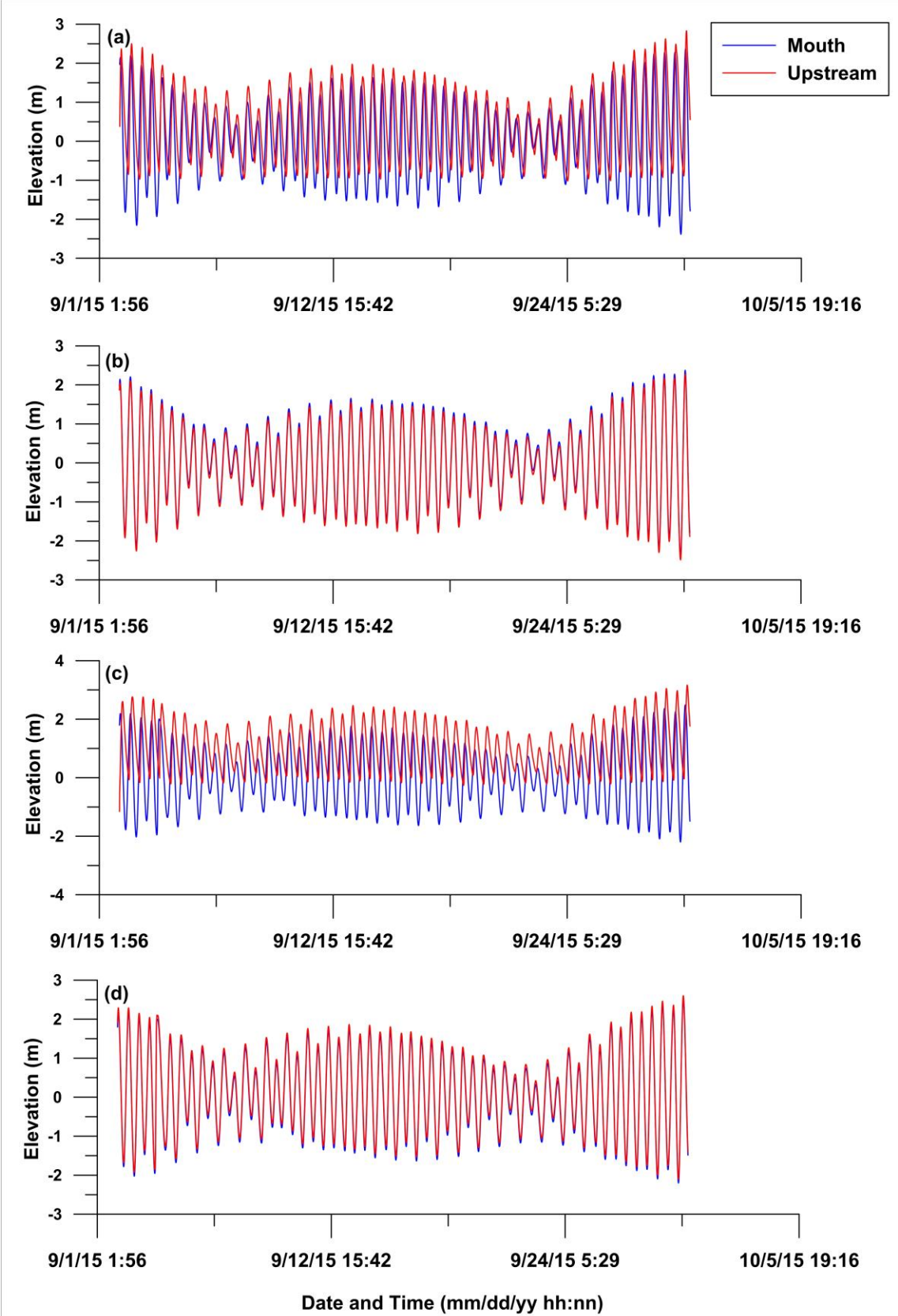


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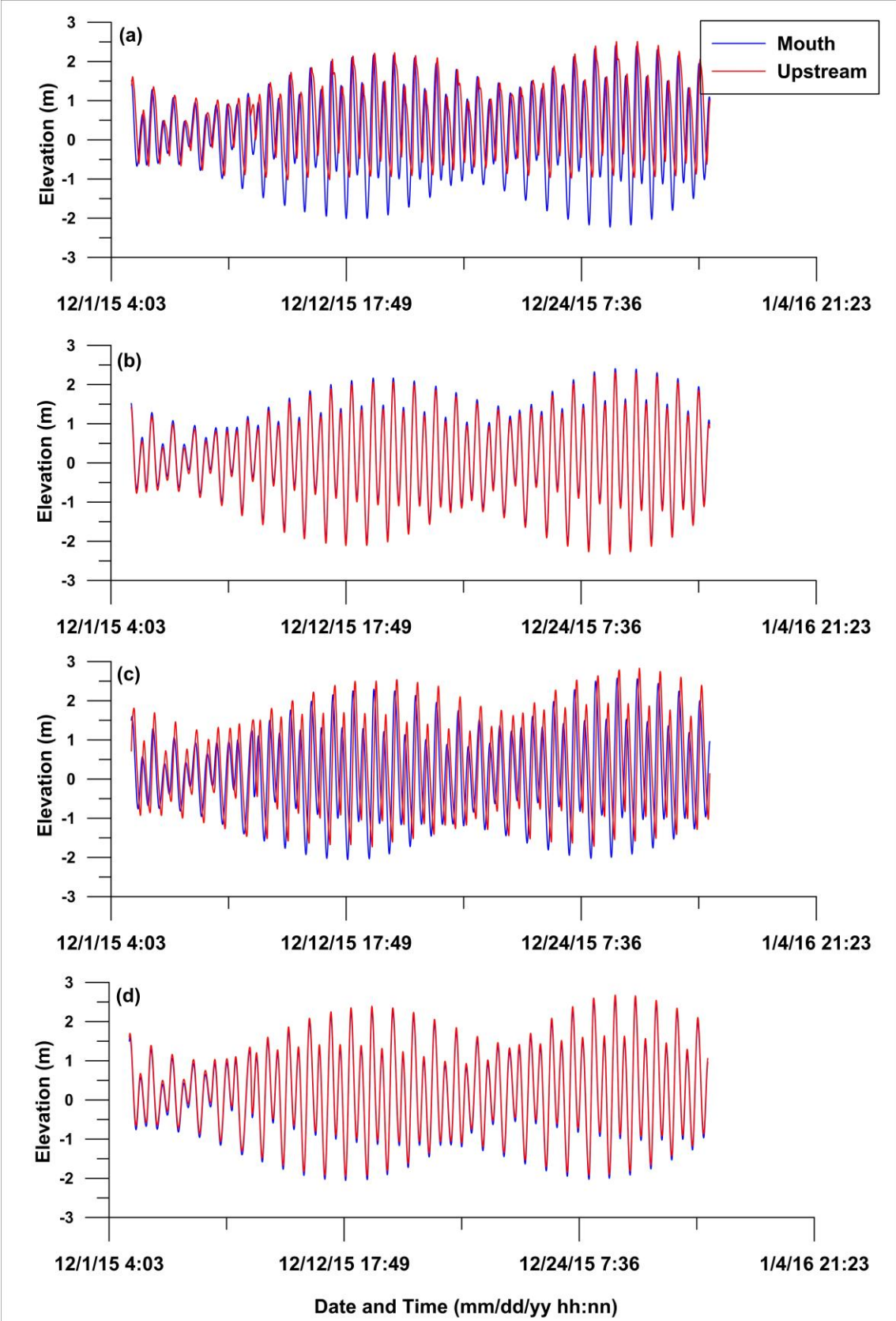


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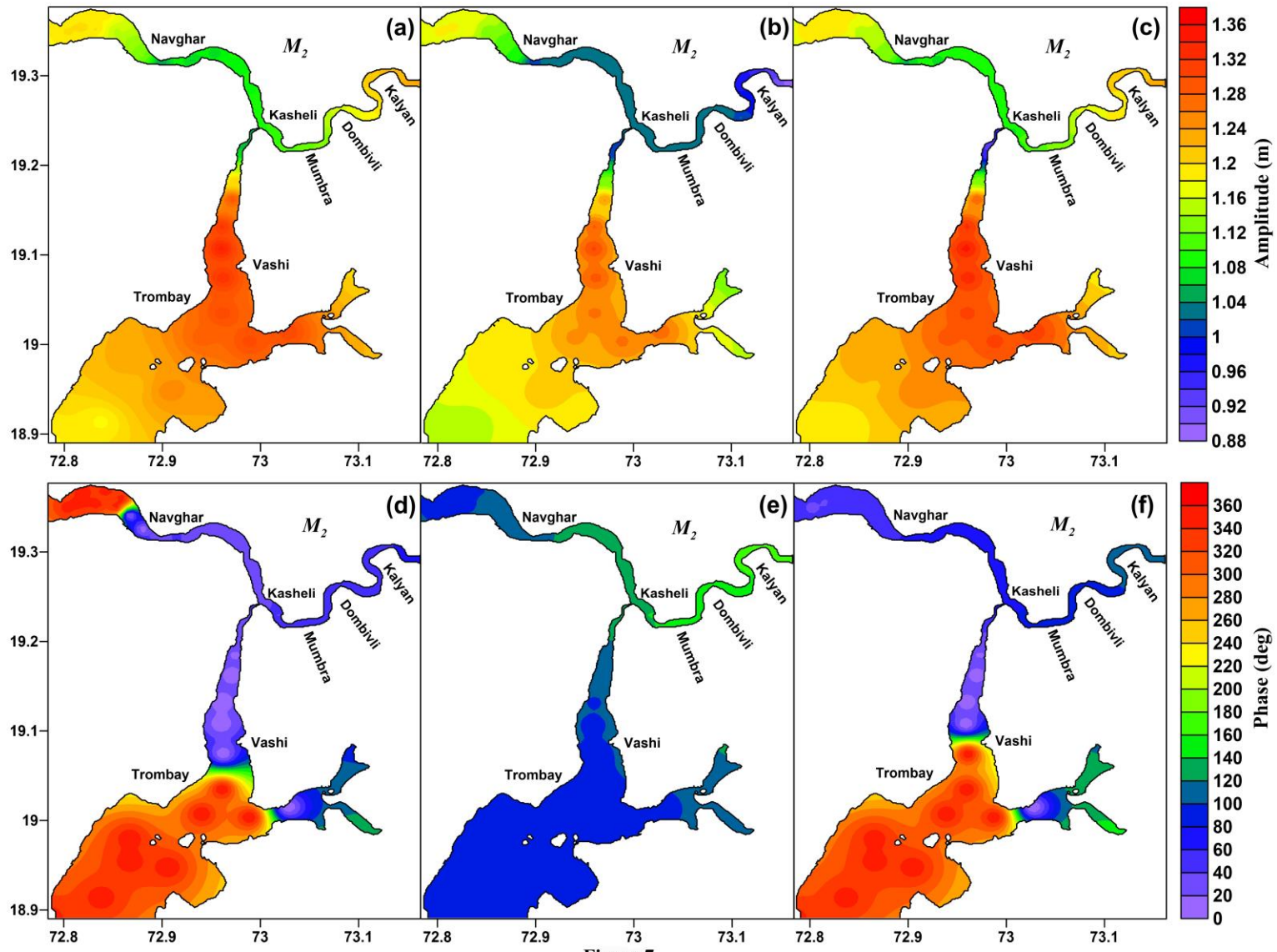
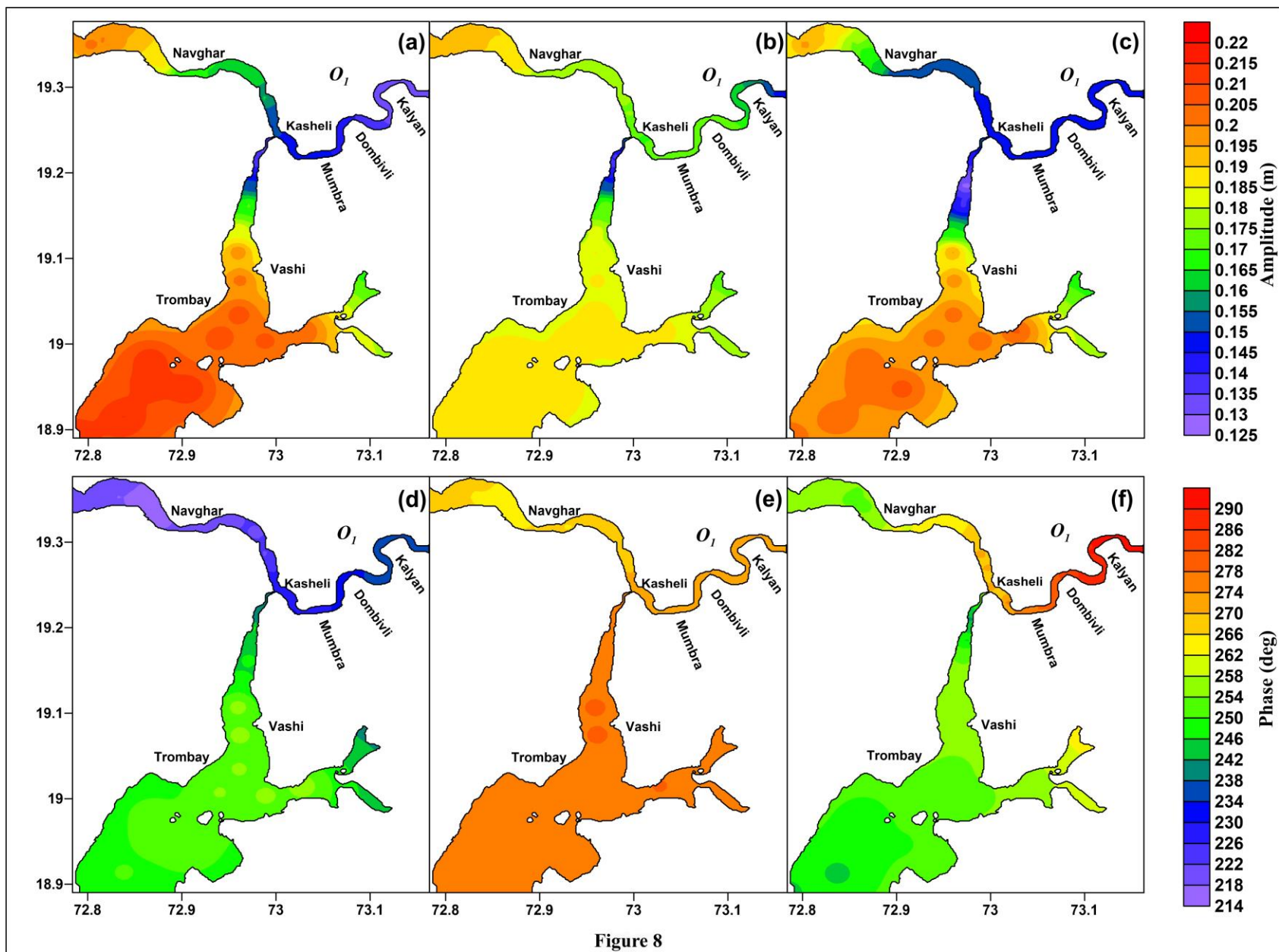


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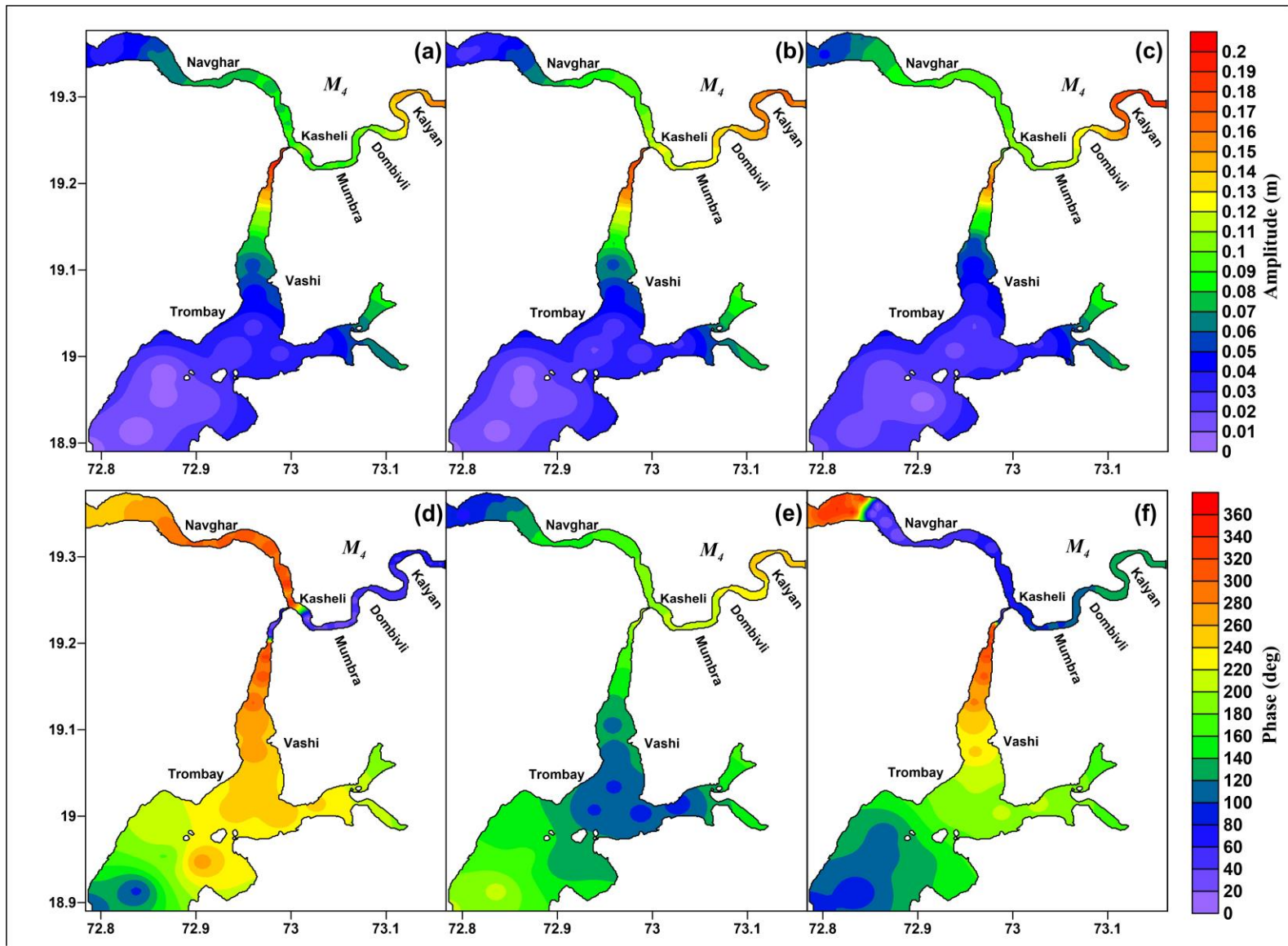
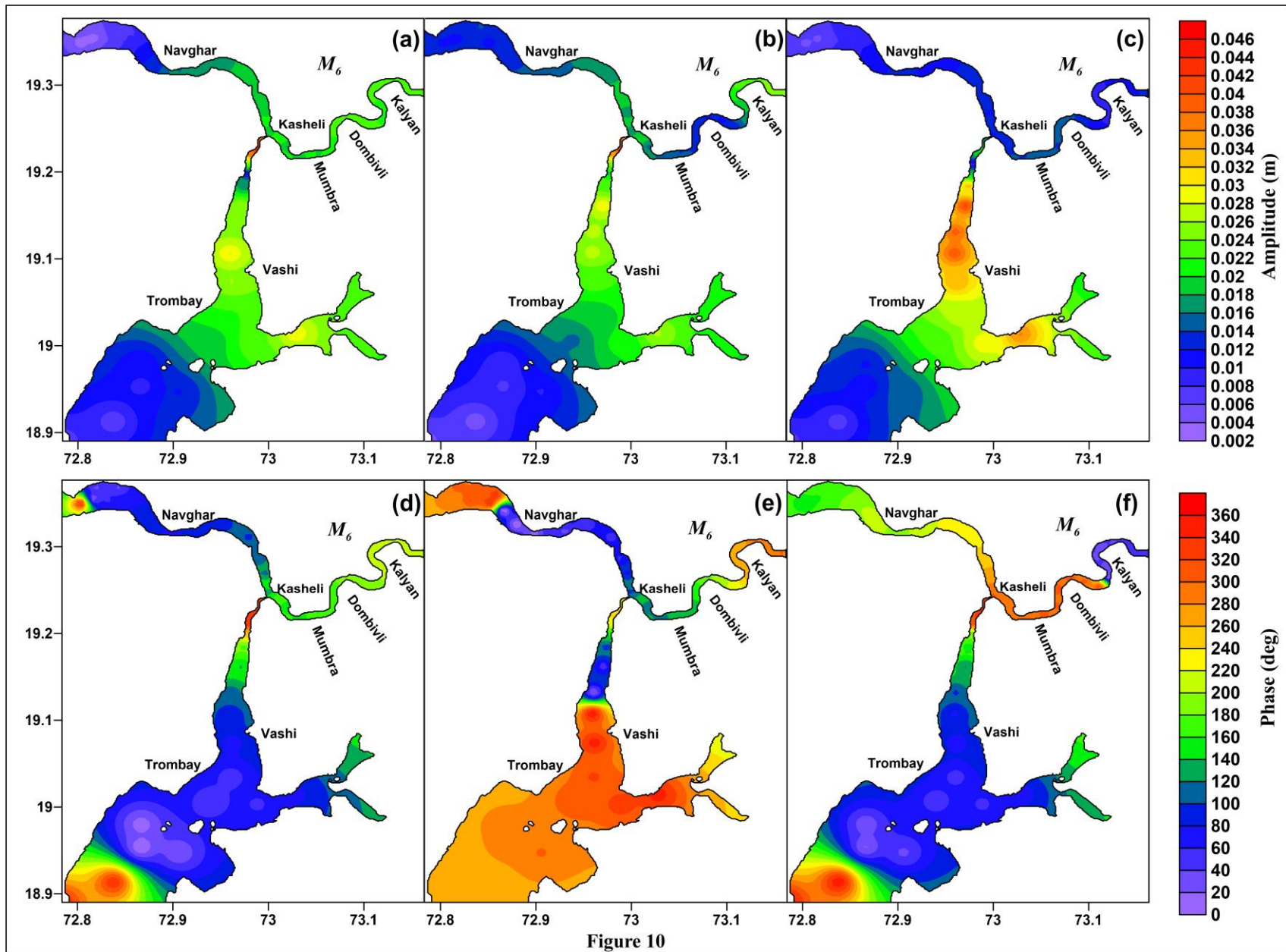


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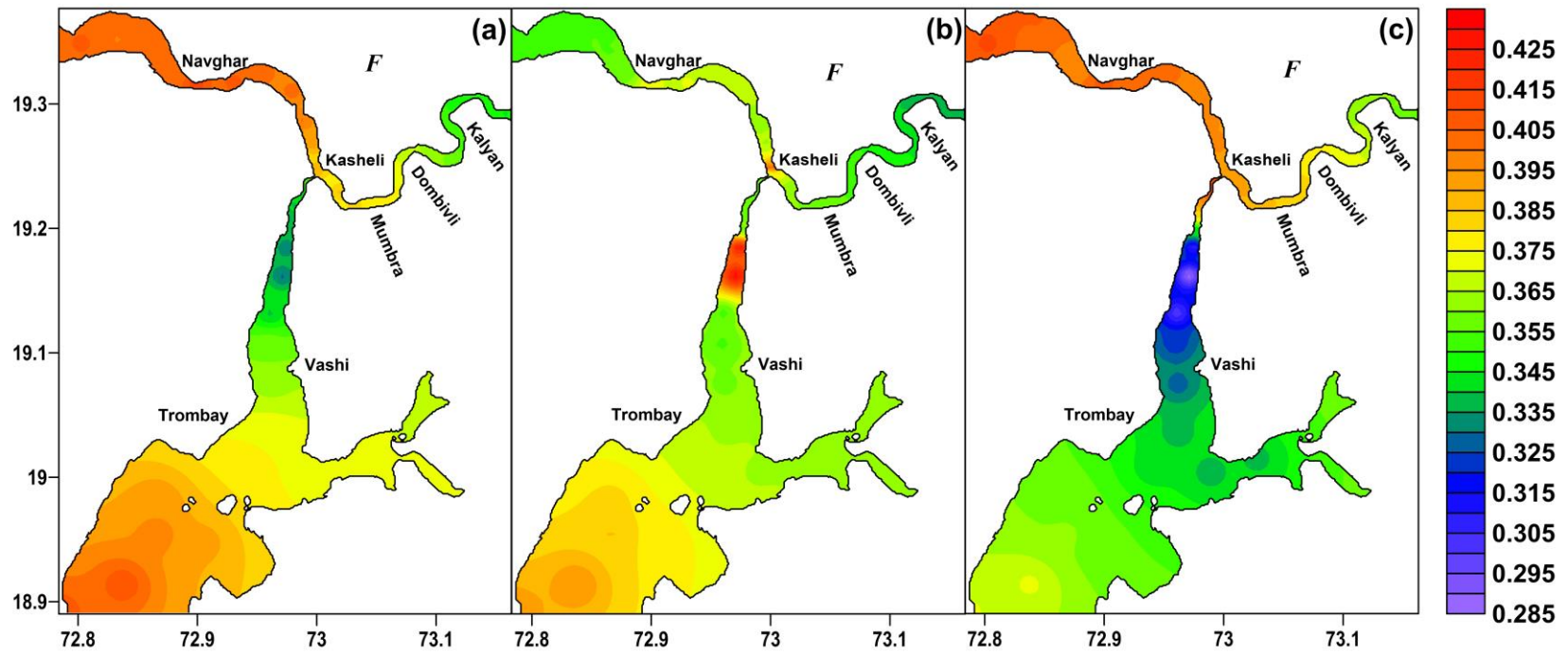


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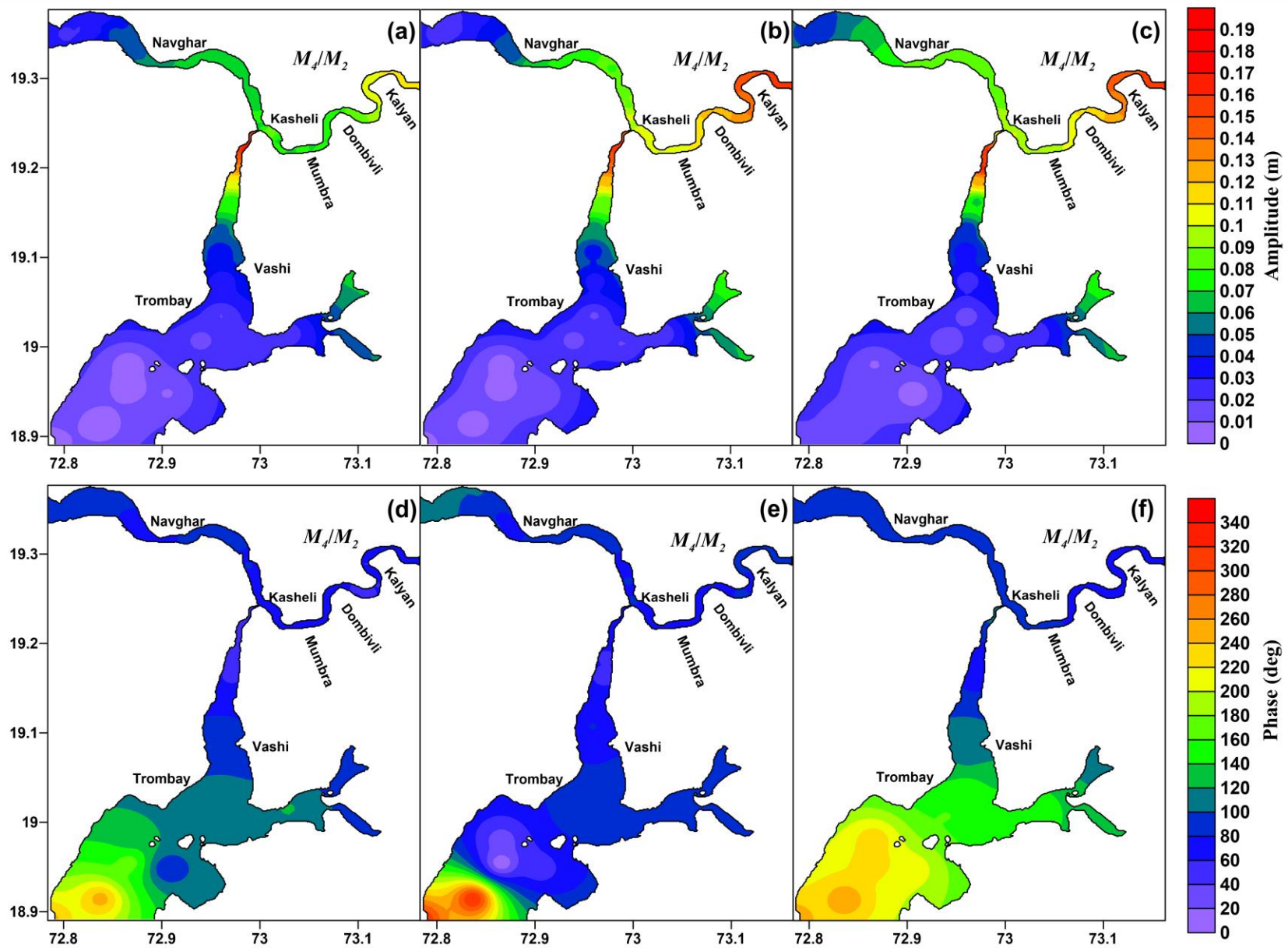


Figure 12

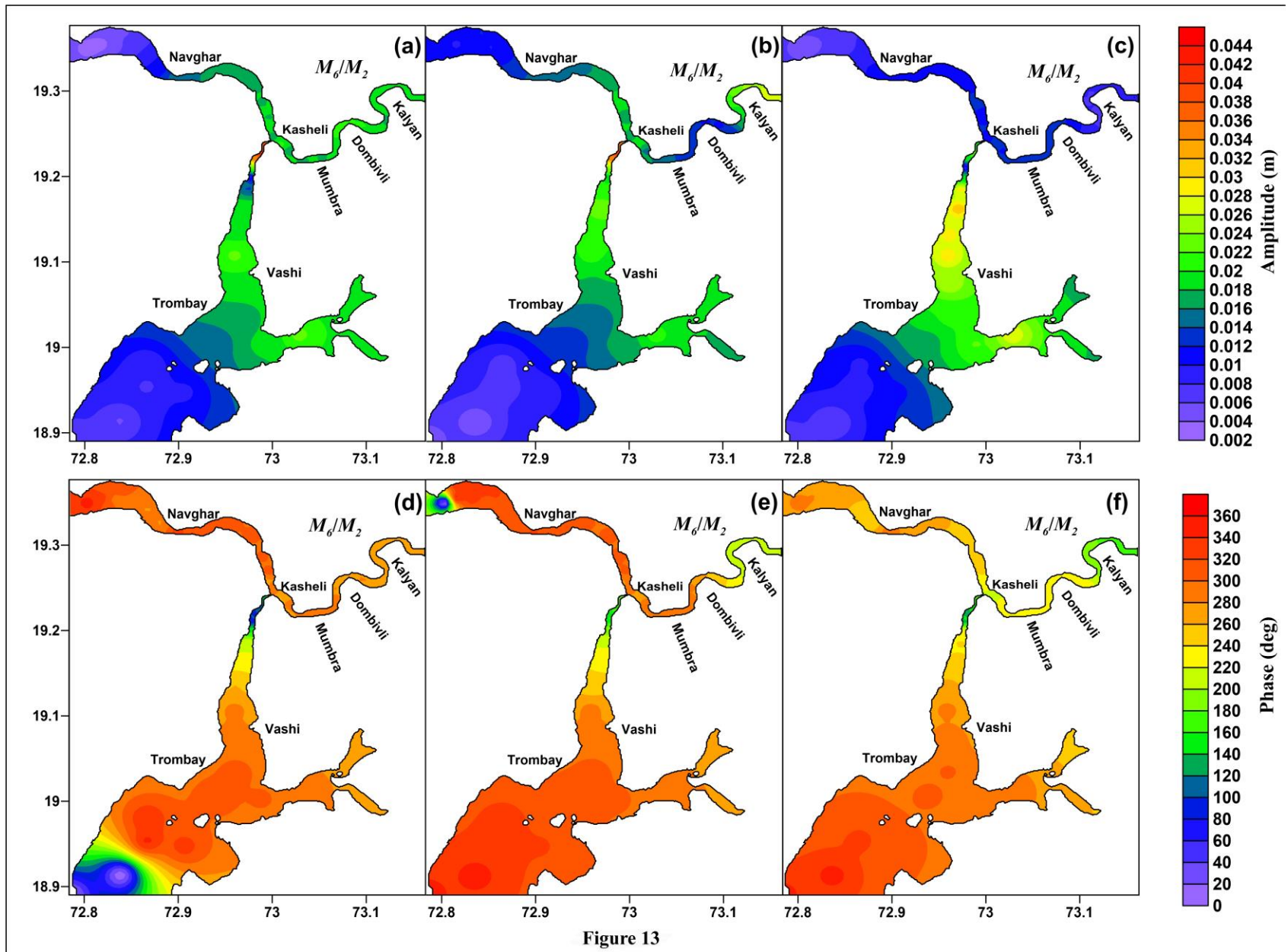


Figure 13

Station	RMS (m)	Skill
Trombay 2013	0.24	0.985
Mumbra 2014	0.20	0.992
Kasheli 2015	0.25	0.989

Table. 1