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Effect of Sea Level Rise in Gulf of Khambhat, West Coast of India

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Effect of Sea Level Rise in Gulf of Khambhat, West Coast of India

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ABSTRACT: Sea level change is one of the main factors which cause major impacts along the global coastlines and it vary widely in the past few decades due to global warming. Global sea level change is usually caused by melting of land-based ice and thermal expansion, as water warms. As the global warming based sea level rise (SLR) is alarming in ocean waters, it is increasingly important to assess the effect of the same in all the coastal processes. . In this study, the effects of SLR on the tidal hydrodynamics along the Gulf of Khambhat, India are investigated. Selected major diurnal and semi-diurnal constituents, M2, S2, N2, K1, O1 and P1, have been taken up for a detailed investigation through finite-element based numerical modelling, TELEMAC-2D. The numerical model results of the existing conditions are compared with available literature data and found to be in agreement. Tidal propagation is predicted for the above mentioned six tidal constituents with and without sea level rise conditions. Three sea level rise scenarios (0.1m, 0.5m and 1m) had been adopted for the study. The amplitudes and velocities of individual constituents, extracted along a specific stretch of gulf were compared with that of no SLR condition, to obtain the percentage variations.

Keywords: Tidal constituents, Bottom friction, Gulf of Khambhat, TELEMAC-2D

1 INTRODUCTION

Prediction of characteristics of tide in gulfs, estuaries and bays is one of the most important studies for any kind of engineering developments. The long term natural process like sea level rise will influence the tidal characteristics and the effect will be significant in the semi-enclosed basins, like gulfs and estuaries. Global sea level change is usually caused by melting of land-based ice and thermal expansion-as water warms. It is estimated that the sea-level for the year 1990-2100 will be rise to 280 to 340 mm (Church & White, 2006). However, as per NOAA data, the global mean sea level variation is estimated to be order of 3.16±0.4 mm/year. As the global warming based SLR is alarming in ocean waters, it is increasingly important to assess the effect of the same in all the coastal processes. In this study, an attempt is made to understand the effect of SLR on the tidal levels and induced currents, along the Gulf of Khambhat, India. The existing tidal hydrodynamics are also estimated to assess the percentage difference in the levels and currents due to the SLR.

Along the west coast of India, the tidal range significantly amplifies when it propagate into Gulf of Khambhat, to a maximum of about 10m. The dynamics of the entire gulf is varying over the space as well as time domain. The tidal current velocities reach up to 3 ms^{-1} in some places along the gulf (Giardino et al., 2014; Kumar and Kumar, 2010; Kumar et al., 2006, Broos & Wiersema, 1998) and dominantly influenced by M2 and K1 tidal constituents (Unnikrishnan et al. 1999; Unnikrishnan, 2010).

1.1 *Study area*

A relatively large model domain, covering entire Gulf of Khambhat and part of Arabian Sea, is considered for the numerical model with a size of about 650x750kms (16°N 68°E to 22°N 74°E). The seabed contours vary from 1m in the head of gulf to 3000m towards Arabian Sea (Fig. 1(a)).The influence of near coastal water bodies, such as creeks, estuaries and rivers are not considered in the present study, for sake of simplicity. The seabed contours of the gulf is extracted from various admiralty charts and the entire area is discretized into triangular grids, with a largest size of 50km along offshore boundary and smallest size of 2km near the coastline (Fig.1(b)). The offshore boundary is then forced with tidal constituents, obtained from global tidal model (Haigh et al., 2011)

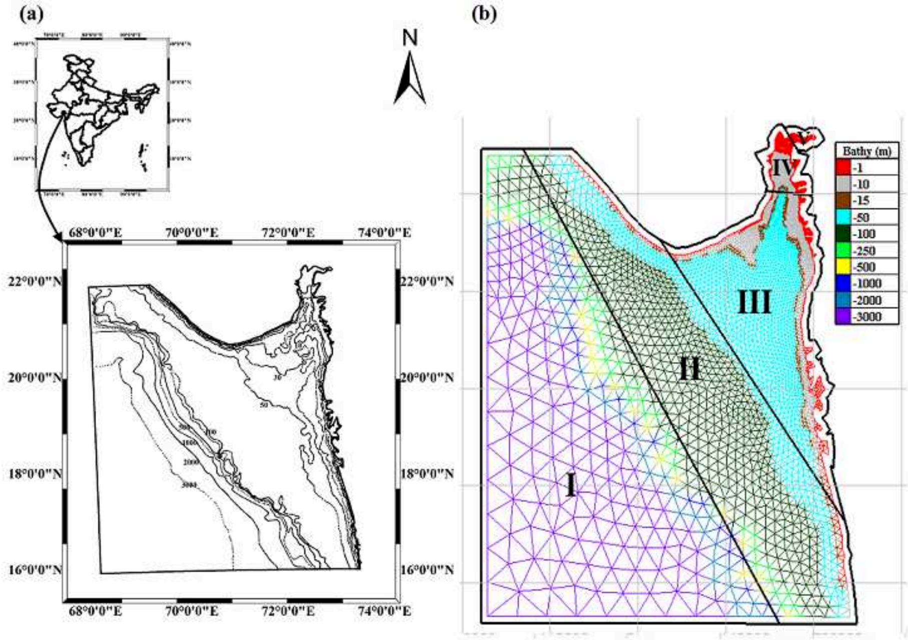

Figure 1. Study area- (a) Gulf of Khambhat and (b) bathymetry with friction zones

2 NUMERICAL MODELING

2.1 *Model description*

The numerical model has been developed using Telemac modelling system (Hervouet, 2007) which is capable of simulating free-surface flows in the two dimensions of horizontal space and solves the Saint-Venant equations using the finite-element method on a computation mesh of triangular elements. One of the Telemac modules called TELEMAC-2D has been used for this modelling. Basically, the Telemac-2D module solves the following hydrodynamic continuous and momentum equations simultaneously;

$$\frac{\partial h}{\partial t} + \vec{u}.\vec{\nabla}(h) + h\,\mathrm{div}(\vec{u}) = S_h \quad (1)$$

$$\frac{\partial u}{\partial t} + \vec{u}.\vec{\nabla}(U) = -g\frac{\partial Z}{\partial x} + S_x + \frac{1}{h}\mathrm{div}\left(hv_t\vec{\nabla}U\right) \quad (2)$$

$$\frac{\partial u}{\partial t} + \vec{u}.\vec{\nabla}(V) = -g\frac{\partial Z}{\partial y} + S_y + \frac{1}{h}\mathrm{div}\left(hv_t\vec{\nabla}V\right) \quad (3)$$

where *h* is the depth of water (m), *U* and *V* are the flow velocities (m s^{-1}) in x and y directions, *g* is the gravity acceleration (m s^{-2}), v_t is the momentum diffusion coefficient (m^2 s^{-1}), *Z* is the elevation of free surface (m), *t* is the time (s), *x*, *y* are the horizontal space co-ordinates (m), S_h is the source or sink of fluid and S_x, S_y are source or sink terms in the dynamic equations representing wind and atmospheric pressure, Coriolis force, bottom friction and additional sources or sink of momentum within the domain in two directions *x* and *y.*

2.2 *Applied forces in momentum equation*

2.2.1 *Bottom Friction*

Bottom friction, one of the applied forces, offers resistance to momentum of flow. In case of tidal propagation, the bottom friction in association with geometry and bathymetry, dictate the levels and magnitude of currents at any place of interest. Therefore, this parameter is crucial in any numerical modeling to represent hydrodynamic characteristics tidal propagation. The bottom shear for a depth averaged flow is commonly described by the quadratic law;

$$\tau = \frac{1}{2}\rho C_{fr} U|U| \tag{4}$$

Where C_{fr} is dimensionless friction coefficient and $U$is depth averaged flow velocity. The dimensionless friction parameter is defined by various dimensionless coefficients among which the most commonly used is Chezy friction factor (C_h) which is given by;

$$C_{fr} = \frac{2g}{{C_h}^2} \tag{5}$$

The frictional force at the bottom is equal to$-\frac{1}{\rho h}\vec{\tau}.\overrightarrow{n_f}$. The normal vector ($n_f$) is equal to$\sqrt{1+\left(\frac{\partial z}{\partial x}\right)^2+\left(\frac{\partial z}{\partial y}\right)^2}$which is reciprocal of cosine of steepest slope (α) at any point.

Then, the Chezy's formula for friction force at the bottom, to be added to the momentum equation in the non-conservative form, takes as;

$$F = -\frac{1}{Cos\ \alpha}\frac{g}{hC_h^2}U|U| \tag{6}$$

2.3 *Calibration and validation*

Initially, the available data from various earlier studies are collected, part of which is used for calibration and rest are used for validation of the developed numerical model. The locations of various data available from earlier studies fairly covers the entire gulf are shown in Fig. 2(a). In order to obtain the spatially varied friction coefficients, data from both west and east coastlines of the gulf is considered for calibration, as distinguished by two different colors of symbols in Fig. 2(a). To start with, a single friction value (C_{fr} = 50) is applied for entire model domain and the results obtained from numerical model, though found to agree with measurements available in offshore region, significantly differ along gulf coast. Then, the domain is divided into five zones, as indicated in Fig.1, based on the water depth, observed or reported tidal level variations towards head of gulf. By trial and error method, different friction coefficients are applied so as prediction of numerical model agree with that of available data. The final friction values obtained for the different zones are shown in Fig. 2(b).

Comparisons of estimated tidal levels and currents with available data, shown in Fig.3 (a), exhibit a fair agreement, for final set of friction coefficients as discussed earlier. The numerical model results are also extracted at locations, where the data are available for validation. The comparison of results obtained from the present numerical model with that of validation data, shown in Fig. 3 (b), clearly demonstrates the agreement. Typical scatter plots, shown in Fig.3 (c), for tidal levels and currents, confirm the agreement.

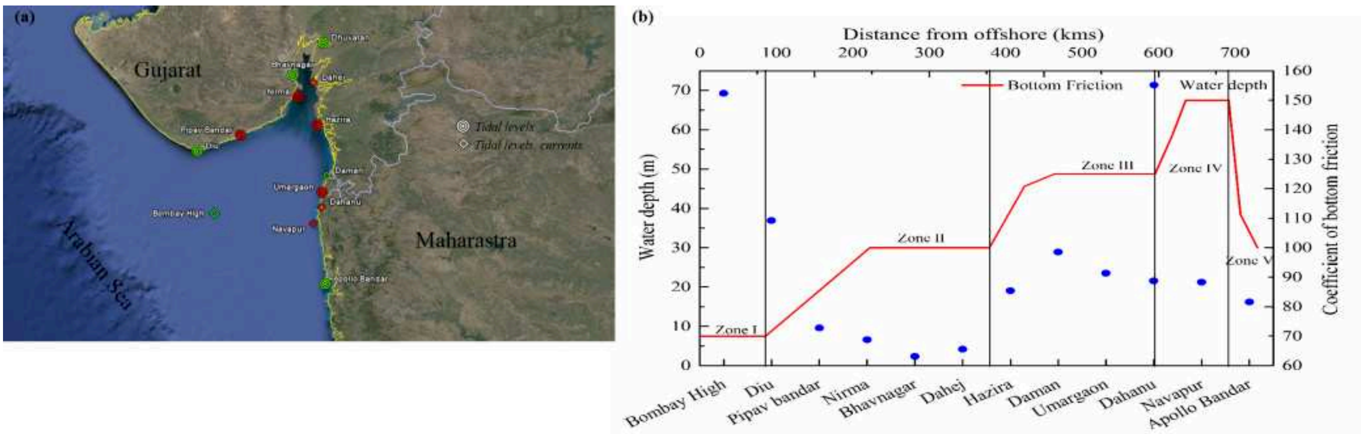

Figure 2. (a) locations used for calibration and analysis, (b) bottom friction values and the respective water depth

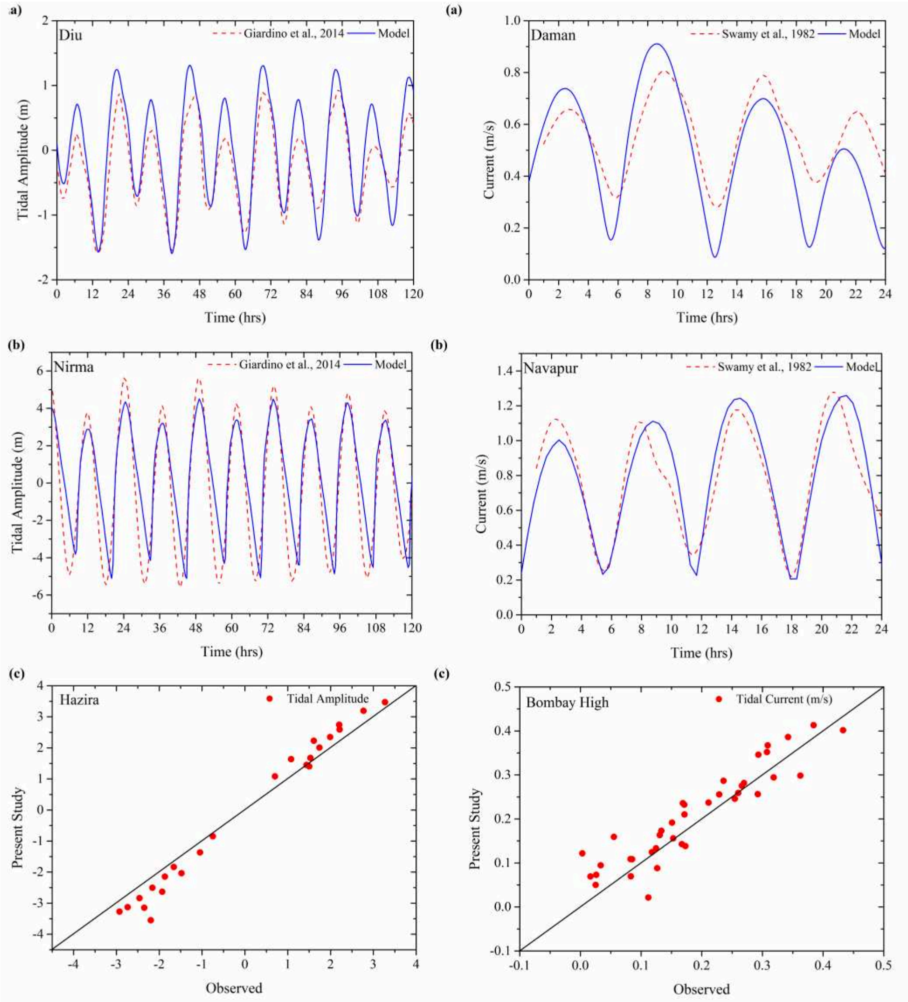

Figure 3. Typical comparison of tidal amplitude and currents with the available data - (a) calibration, (b) validation and (c) scatter plot

3 RESULT AND DISCUSSIONS

3.1 *Existing condition*

The temporal tidal ranges of six major diurnal and semi-diurnal tidal constituents, K1, M2, N2, O1, P1 and S2, are simulated with heterogeneous friction coefficients, as described in earlier section, and the typical constituents M2 and K1 are shown in Fig. 4 (a). It is observed from the results that the maximum tidal amplitudes are observed in the region between Hazira and Bhavnagar. Among the six selected major tidal constituents, M2 is observed to be predominantly influencing the tidal amplitudes along the gulf, followed by K1, S2, O1, N2 and P1. It is also clear from results that the contributions of semi-diurnal constituents, in tidal amplification, are more than that of diurnal constituents. A maximum of about 7.2m of amplitude is observed for M2 constituent in the water depths ranging from 10 to 20m. The maximum temporal tidal amplitude range for the total tide is reach about 8.5m and the velocity reach about 4ms^{-1} are shown in Fig. 4 (b, c)

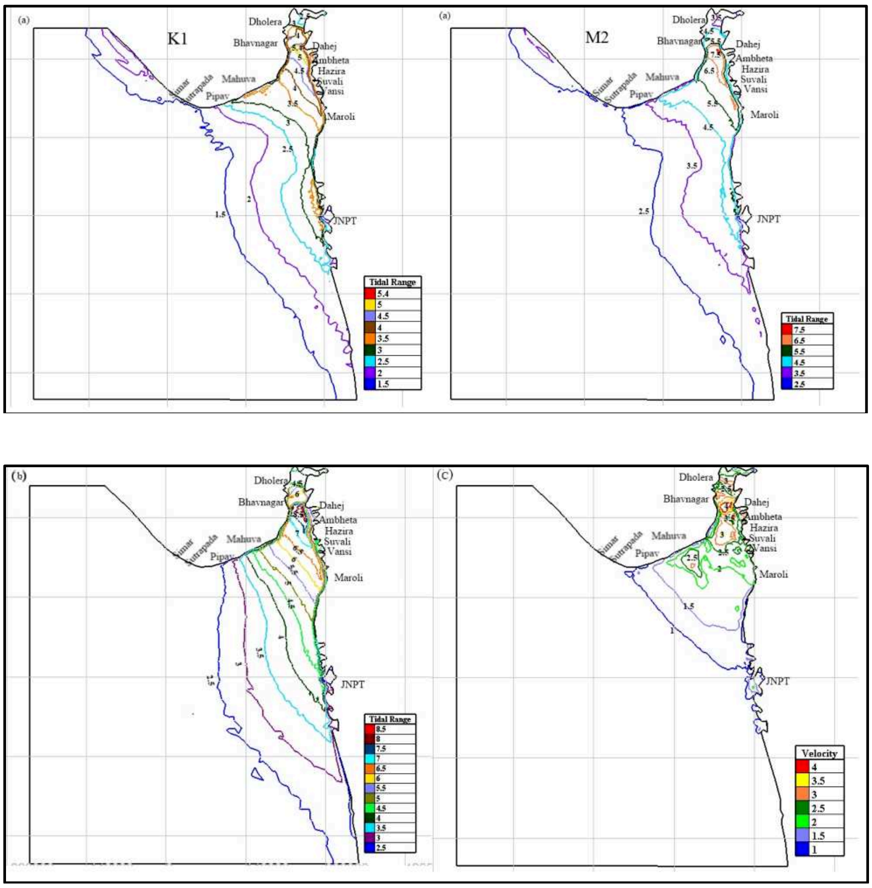

Figure 4. Variation of temporal tidal range of (a) M2, K1 tidal constituents, (b) temporal tidal range of total tide (in meters) and (c) temporal currents variation of total tide (in m s $^{-1}$)

3.2 *Effect of SLR*

The effects of SLR on the tidal characteristics are then taken up for detailed investigation. The increased water surface levels such as 0.1 m, 0.5 m and 1 m are introduced in the numerical model and the resulting tidal levels and currents are obtained for each of the selected tidal constituents. To understand the effect of SLR, few important locations (Bombay High, Diu, Pipav Bandar, Nirma, Bhavnagar, Dahej, Hazira, Daman, Umergaon, Dahanu, Navapur and Apollo Bandar) are selected along the Gulf of Khambhat, as shown in Fig. 2 (a), from where the tidal levels and currents are extracted for existing and SLR induced tidal models. The water depths at these points vary from few meters to 70m, as can be seen in Fig. 2 (b).From the numerical results, the percentage variations for the above mentioned locations are calculated based on the non-SLR condition and the percentage variations for the twelve locations are shown in Fig.5

The maximum velocity variation of 2.5% (0.1m SLR), 6% (0.5m SLR) and15% (1m SLR) in the M2 tidal constituent is seen at Bhavnagar which has a water depth of about 2m. The maximum amplitude variation of 1% (0.1m SLR) found at Dahej which has a water depth of about 4m and 6% (0.5m SLR), 6.5% (1m SLR) in M2 constituent is found at Bhavnagar. The maximum velocity variation of K1 tidal constituent is 15% for 1m SLR condition found at Bhavnagar and maximum amplitude variation is 3.5% (0.5m SLR) and 6% (1m SLR) which is found at Bhavnagar and Diu (water depth of 37m). The maximum velocity variation of K1 tidal constituent is -1.5% (0.1m SLR), -8% (0.5m SLR) and amplitude variation is -2% (0.1m SLR) is seen at Apollo Bandar which has a water depth of about 16m. Negative percentage variation of K1 tidal constituent seen only at Apollo Bandar and the maximum amplitude and velocity variations of the M2 and K1 tidal constituents are found at Apollo Bandar, Diu, Bhavnagar and Dahej which is located near the mouth and head of the gulf. Apollo Bandar, Diu lies on zone III which has a bottom friction coefficient of 125 and Bhavanagar, Dahej lies on Zone IV which has a highest bottom friction coefficient of 150. The maximum values are experienced because of the geometry of the gulf, Apollo Bandar and Diu is located at the starting point of the gulf funnel shape and Bhavnagar, Dahej located at the contracted section of the gulf.

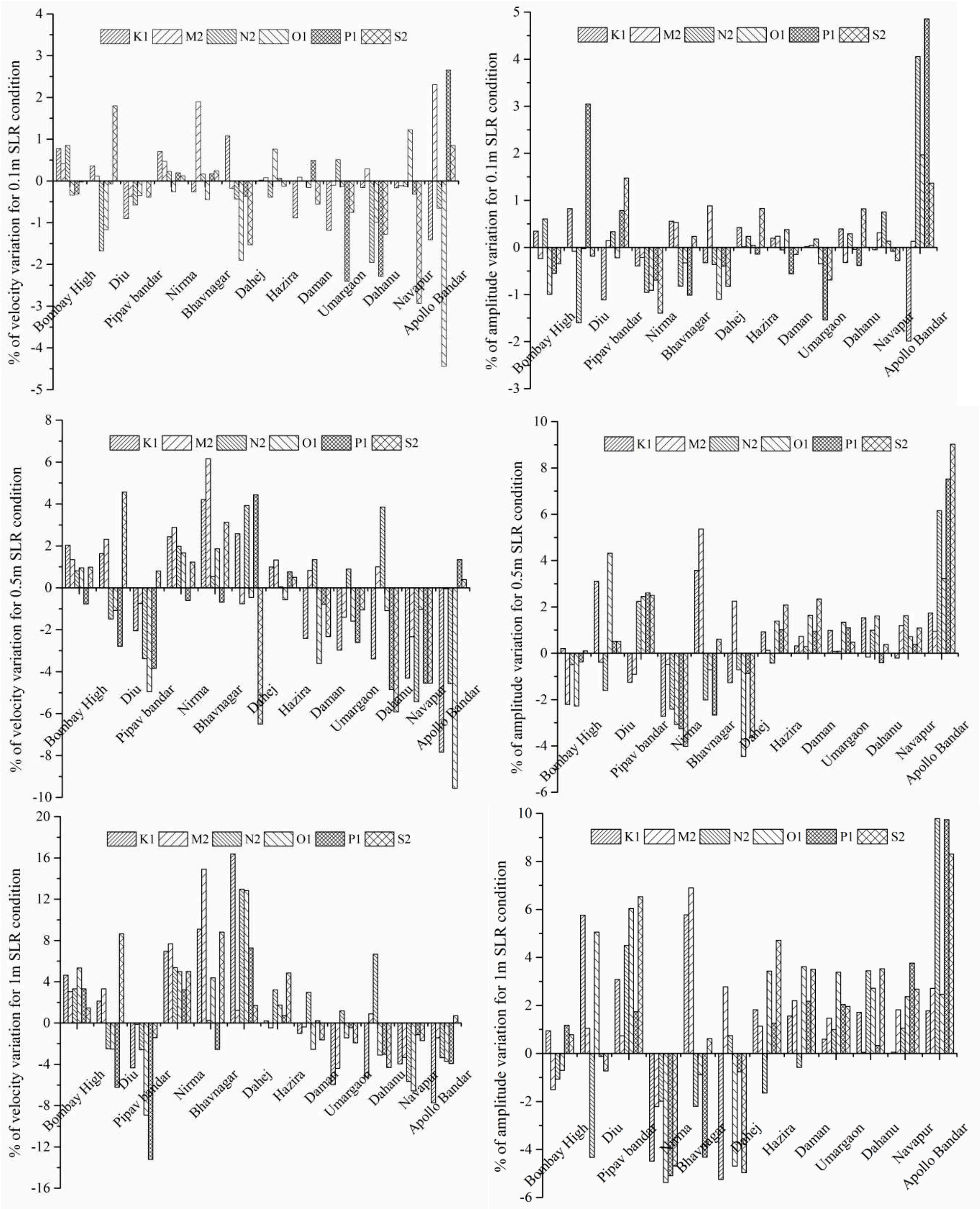

Figure 5. Percentage variation of amplitude and current of important locations along the Gulf for 0.1m, 0.5m and 1m SLR scenarios

4 SUMMARY

A finite-element based numerical model is developed for the Gulf of Khambhat to estimate the tidal hydrodynamics. A mean sea level rise of 0.1m, 0.5m and 1m is considered for the projection and the effect of the SLR on the tidal constituents and current velocities are estimated. Typical extraction of the tidal amplitudes and currents along a stretch revealed interesting features of percentage variations in the parameters for different tidal constituents. In general, the tidal amplitudes are found to be increasing towards nearshore due to SLR. Thus, the present study indicates a need for further detailed nearshore modelling studies including the dominant coastal features such as creeks, estuaries and river inlets.

NOTATION

h	depth of water
g	gravity acceleration
U,V	flow velocities
v_t	momentum diffusion coefficient
Z	elevation of free surface
C_{fr}	friction coefficient
n_f	normal vector

REFERENCES

Broos, E. J., & Wiersema, K. J. (1998). Closure of Gulf of Khambhat, Delft University of Technology, pp. 1–164.

Church, J. A., & White, N. J. (2006).A 20th century acceleration in global sea-level rise, 33(December 2005), pp.94–97.

Giardino, A., Elias, E., Arunakumar, A., Karunakar, K., (2014) Tidal modelling in the Gulf of Khambhat based on a numerical and analytical approach, Indian Journal of Marine Sciences, Vol.43 (7).

Haigh, I. D., Eliot, M., &Pattiaratchi, C. (2011). Global influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. Journal of Geophysical Research, 116, pp.1–16.

Hervouet, J.-M. (2007). Hydrodynamics of Free Surface Flows. Chichester, UK: John Wiley & Sons, Ltd.

Kumar, V.S., Kumar, K.A., (2010). Waves and Currents in Tide-Dominated Location Off Dahej, Gulf of Khambhat, India. Mar. Geod. 33, pp.218–231.

Kumar, V.S., Pathak, K.C., Pednekar, P., Raju, N.S.N., Gowthaman, R., (2006). Coastal processes along the Indian coastline. Cureent Sci. 91, pp.530–536

Unnikrishnan, A. S. (2010). Tidal propagation off the central west coast of India. Indian Journal of Geo-Marine Sciences, 39(4), pp. 485–488.

Unnikrishnan, A. S., Shetye, S. R., & Michael, G. S. (1999). Tidal propagation in the Gulf of Khambhat, Bombay high, and surrounding areas. Proc. Indian Acad. Sci. (Earth Planet. Sci.), 108(3), pp.155–177.