Study of Hydrodynamic and Sediment Transport in Gulf of Khambhat, Western Coast India—A Numerical Approach

Rajan Kumar Jha, A.K. Singh, L.R. Ranganath and Ajai Singh

Abstract Coastal sedimentation is a problem that needs to be addressed, more so in areas where any infrastructure development is planned. The research carried out in this article aims to develop a depth-averaged model to represent the hydrodynamics and sediment transport patterns prevalent during non-monsoon and monsoon in the entire Gulf of Khambhat along west coast of India. In this study, the spatial resolution of model is 100 m × 100 m and the freshwater discharge in monsoon and non-monsoon from the rivers (Narmada, Mahi and Sabarmati) joining the gulf had been considered. The model results were found to be in good agreement with the observed current data and it was found that the gulf is ebb dominated with a short falling period and a longer rising period. The sediment transport pattern is predicted along with expected total suspended sedimentation for non-monsoon and monsoon. The sedimentation studies indicated that there is a trend of siltation.

Keywords Hydrodynamics · Sediment distribution · Numerical modelling · Gulf of Khambhat

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1   Introduction

India is a country having coastal length of 7517 km. As a country with such a large coastline, India experienced various problems related to beach. The issue of shore erosion and accretion in India has received special attention from the government and the world because the effect has direct impact on social life, demolition of infrastructure, settlements along the bank, navigation, tourism and other coastal environment loss. Therefore, in order to develop coastal area with infrastructure we need to have a proper idea of the accretion/erosion in the selected area so that it should have a very less effect on it in the near future. Accretion problems generally occur at places where the sediment transporting capacity of the hydraulic system is reduced due to the minimal in steady (currents) and oscillatory (waves) velocities of flow and related turbulent motions. Problems related to sedimentation are mostly associated with human interference in the physical system such as the construction of the artificial structures or the dredging of sediment from the bed to increase the flow depth or width. However, accretion or erosion also is a basic phenomenon of nature dealing with loose sediments within the transferring cycle from source to drop locations. Natural sedimentation areas are known as shoals, flats, banks, sheets, bars, etc.

These studies were carried out at Central Water & Power Research Station (CWPRS), Pune, in (MMCE) laboratory to analyses the flow field and sedimentation pattern prevalent at the site.

2   Materials and Methods

Gulf of Khambhat lies in the northern part of the Arabian Sea as shown in Fig. 1. It is triangular shaped depression on the western part of India, between the Saurashtra peninsula and the Gujarat. The length of the proposed region is approximately 130 km, while its width varies between 20 km and 65 km. The gulf enclosed an area of about 3200 km^2 and a maximum depth of 35 m. The tidal currents in the gulf are very strong and multidirectional with two prevailing directions, i.e. on the way to upstream during peak flood and downstream during peak ebb. Due to the funnel shape of the gulf, the tide height increases vastly from the entrance to the upstream end [1]. The maximum current observed during tide is around 2.5 m/s in the entire gulf with high wave energy [2]. It receives drainage from Ambika, Purna, Kim, Tapti, Narmada, Mahi, Sabarmati and Dhadhar rivers. The large volume of suspended sediments and silts is carried by the discharge of these rivers. Narmada which is one of the major rivers of this region carries a large volume of suspended load from the eastern side of the gulf which forms Deltaic islands such as Alia Bet.

Fig. 1 Location map of study area (courtesy Google Earth)

2.1 Field Data Analysis

The data required for model studies such as bathymetry, tide, currents and sediment loads were collected and analysed. The data for bathymetry are obtained from C-MAP. Gulf has an open boundary at the seaward end connecting 72°1′ E to 72° 43′ E longitude and 21°8′ N to 22°18′ N latitude. The bathymetry used in the computational model is shown of area 130 × 65 km with grid spacing of 100 m as shown in Fig. 2. The tide level for non-monsoon (October) and monsoon (July) was extracted from C-MAP tidal database at the location of 72°30′ E and 21°42′ N, and it is found that the location has tidal range of 9.38 m as shown in Figs. 3 and 4. And the gulf is characterized by mixture of fine sand and clay. The average grain size diameter at the site of interest is recorded as between 0.05 mm and 0.15 mm. From the site investigations undertaken by CWPRS, it was found that the sediment in the
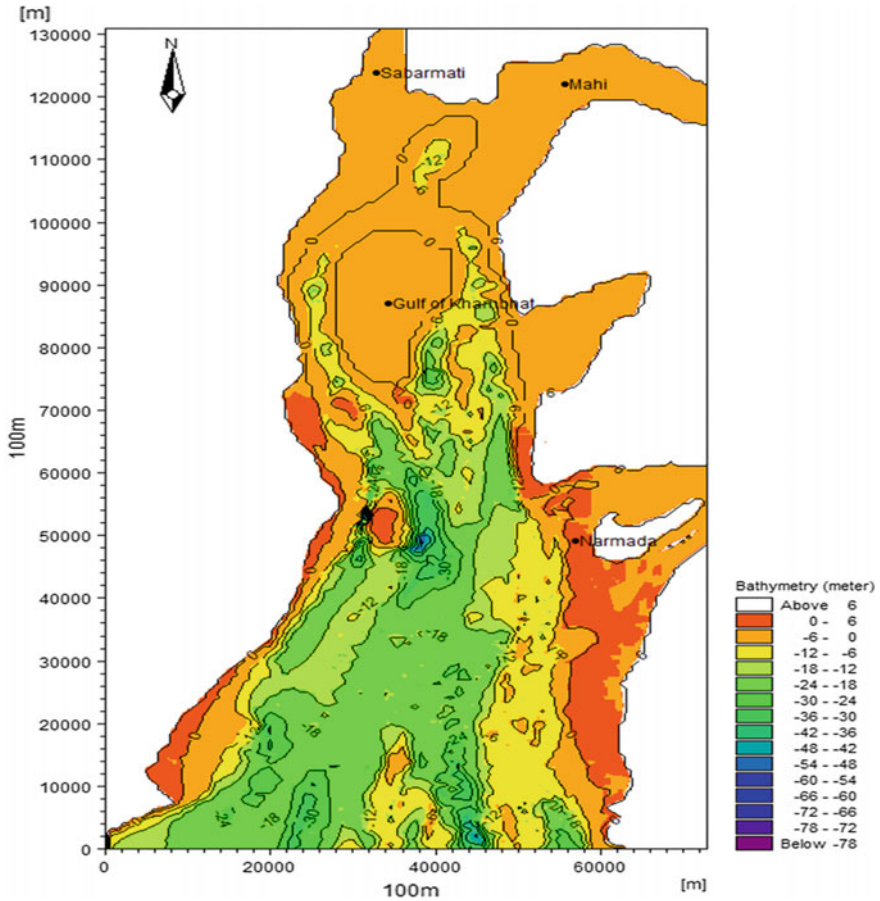
Fig. 2 Bathymetry-GoK (C-MAP)

gulf has a specific density of around 2.65 g/m^3 [3] and the average sediment concentration recorded in month of October is 50 mg/l near Narmada estuary and in month of July it is nearly 500 mg/l.

2.2 Model Description

The study was carried out using the MIKE-21 hydrodynamic (HD) and mud transport (MT) model. The hydrodynamic model in the MIKE21 flow model (MIKE HD) is a general numerical modelling system for the simulation of water
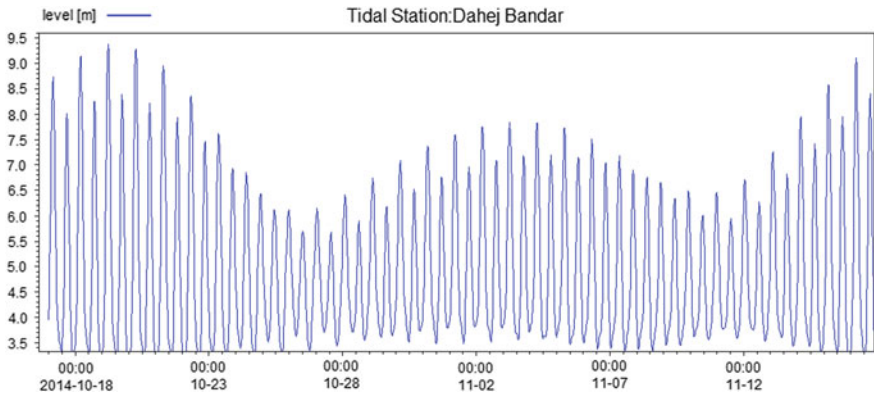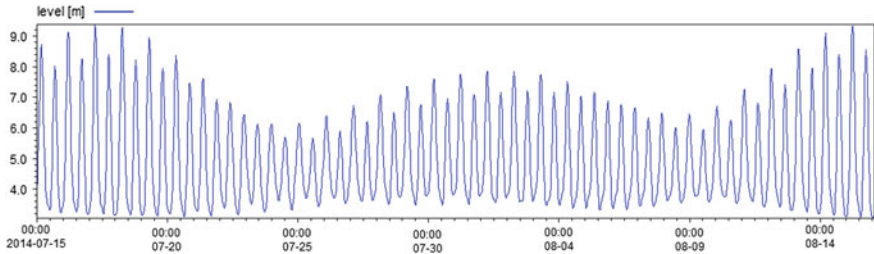
Fig. 3 Tide level in non-monsoon

Fig. 4 Tide level in monsoon

levels and flows in estuaries, bays and coastal areas. It simulates unsteady two-dimensional flows in one layer fluids and has been applied in large number of studies. The appropriate governing equations for studying water movement in coastal areas are the two-dimensional shallow water equations. These are obtained by vertically integrating the three-dimensional Navier–Stokes equations of motion making the following simplified assumptions:

The flow is incompressible, the flow is well mixed (no variation in density) and vertical accelerations are negligible. Simulation of hydrodynamics is based on these shallow water equations given below,

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \tag{1}$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial x} + \frac{gp\sqrt{p^2+q^2}}{C^2h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}\left(h\tau_{xx}\right) + \frac{\partial}{\partial y}\left(h\tau_{xy}\right)\right]$$
$$- \Omega_q - fVV_x + \frac{h}{\rho_w}\frac{\partial}{\partial x}\left(p_a\right) = 0 \qquad (2)$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial y} + \frac{gq\sqrt{p^2+q^2}}{C^2h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial y}\left(h\tau_{yy}\right) + \frac{\partial}{\partial x}\left(h\tau_{xy}\right)\right]$$
$$+ \Omega_p - fVV_y + \frac{h}{\rho_w}\frac{\partial}{\partial y}\left(p_a\right) = 0 \qquad (3)$$

where

$h(x, y, t)$—water depth ($=\zeta - d$, m); $d(x, y, t)$—time varying water depth (m); $\zeta(x, y, t)$—surface elevation (m); p, $q(x, y, t)$—flux densities in x and y direction (m^3/s/m) = (uh, vh); (u, v) = depth-averaged velocities in x and y direction; $C(x, y)$—Chezy resistance $\left(m^{\frac{1}{2}}/s\right)$; g—acceleration due to gravity (m/s^2); $f(V)$—wind friction factor; $V, V_x, V_y(x, y, t)$—wind speed and components in x and y direction (m/s); $\Omega(x, y)$—Coriolis parameter, latitude dependent (s^{-1}); $p_a(x, y, t)$—atmospheric pressure (kg/m/s^2); ρ_w—density of water (kg/m^3); t—time; and $\tau_{xx}\tau_{xy}\tau_{yy}$—components of effective shear stress.

The governing equations are solved using alternating directions implicit (ADI) finite difference technique based on Crank–Nicholson scheme. This entails covering the area with a mesh or grid and discretizing elevations and velocities in space and time to fit on this grid. Having discretized the variables, derivatives are approximated by simple differences divided by the distance between consecutive grid points. The space differences involve variables at the unknown time level calculated; thus, a system of equations involving the boundary conditions has to be solved before the value of the variables at the next tie step can be obtained by alternating direction implicit scheme. It implies that in one time step, there are two half time steps. In one half time step, the scheme is implicit in the east–west direction and explicit in north–south direction. In the next time step, computations are implicit in the model north–south direction and explicit in the model east–west directions. ADI scheme is computationally efficient and widely used. The solution of equation at every grid point results in simulation if flow conditions over a period of time.

The MIKE 21 flow model, mud transport (MT) module describes erosion, transport and deposition of mud or sand/mud mixtures under the action of currents and waves. The purpose of sediment transport modelling at this stage is to gain some understanding on the rate of bed level changes within the natural and man-made canals and water ways as a result of tidal flow.

3 Results and Discussion

3.1 Model Studies Conducted

Series of model experiments were conducted for the evaluation of hydrodynamic circulation and sediment distribution along gulf of Khambhat. Kumar and Kumar [4] studied hydrodynamics based on measurement of waves, currents and tides off Dahej in Gulf of Khambhat. It was concluded from the study that tide at 14 m was larger than that at 24 m water depth with an increase of 0.19 m in the mean tidal range. The maximum current speed was 3 m/s with average value of 1 m/s at 24 m water depth and 3.3 m/s with average value of 0.8 m/s at 14 m water depth. Also during peak flood, the concentrations of sediment were found to vary from 60 to 500 mg/l in the upper part and from 40 to 508 mg/l in the lower part of gulf. However, the sediment concentrations varied from 110 to 517 mg/l in the upper part and from 100 to 530 mg/l in the lower part during the ebb period [1]. The tidal amplitude in the gulf increases up to 10 m and the velocity up to 4 ms^{-1} [5].

3.2 Simulation of Flow Field for Non-monsoon

Initially the studies were conducted with non-monsoon in the Narmada, Mahi and Sabarmati estuaries and the adjoining sea portion of Gulf of Khambhat. From the computational model, it could be seen that there are four open boundaries where flow conditions are required to be defined. Initially the flow simulations were carried out by providing tide with tidal range of 9.4 m. The tidal boundaries were provided along the southern boundary with appropriate phase lag. It can be observed that the model results match well with the field data, and hence, there is good agreement indicating that the model is proved as shown in Fig. 5. The
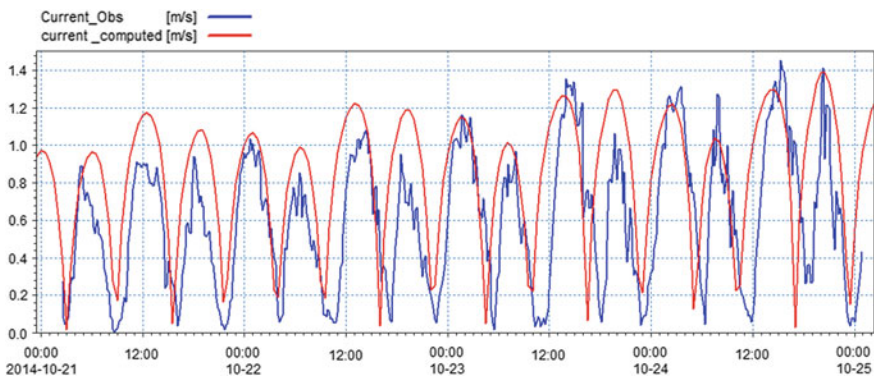

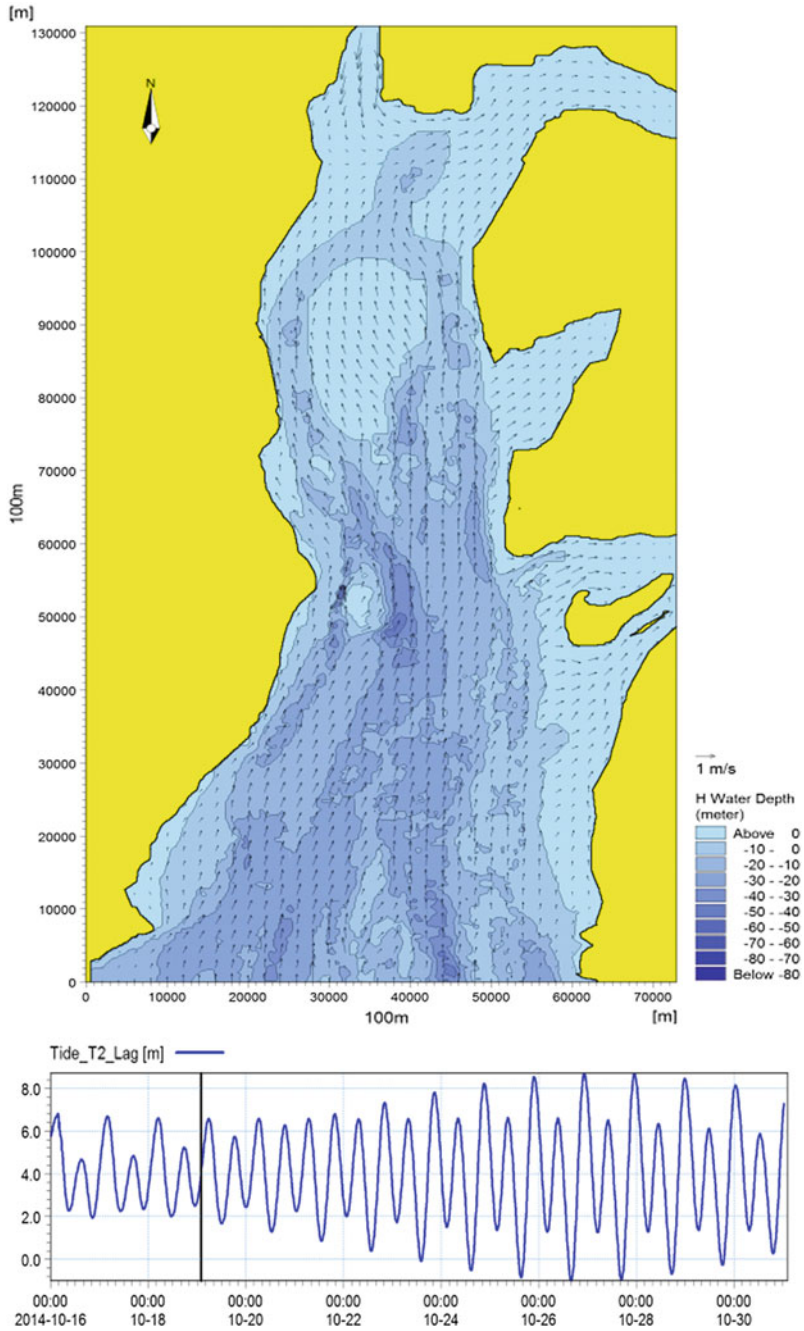**Fig. 5** Comparison of currents (computed vs. observed)
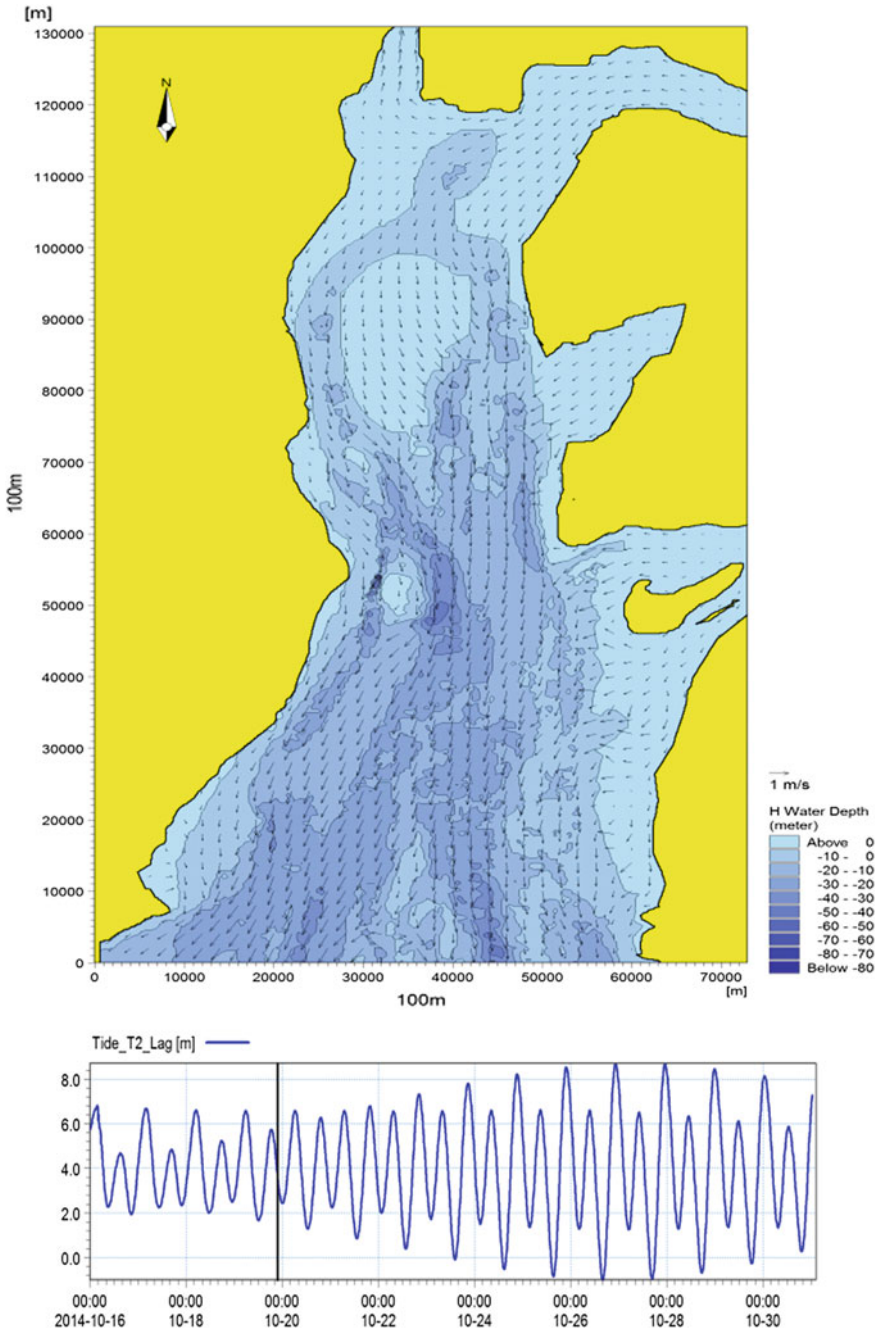
Fig. 6 Flow field during peak flood (non-monsoon)
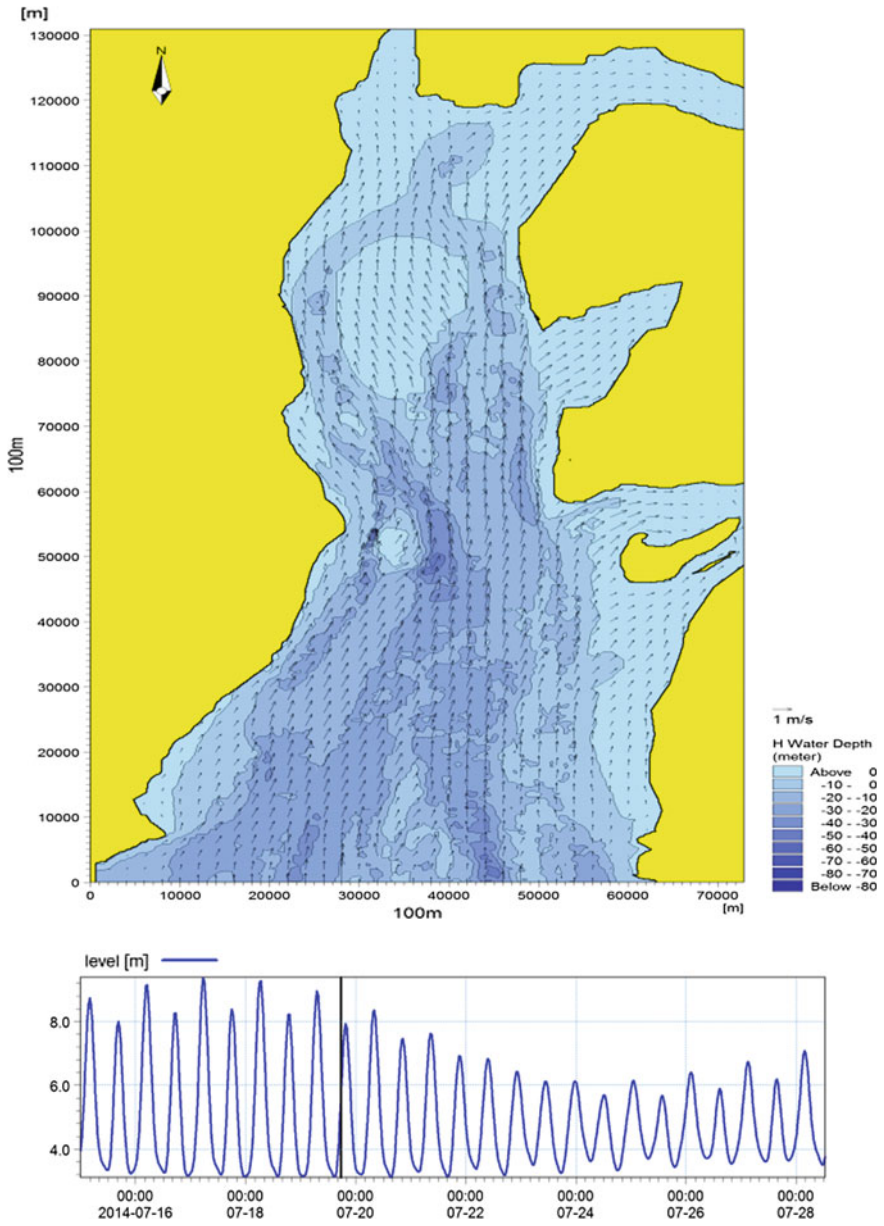
Fig. 7 Flow field during peak ebb (non-monsoon)

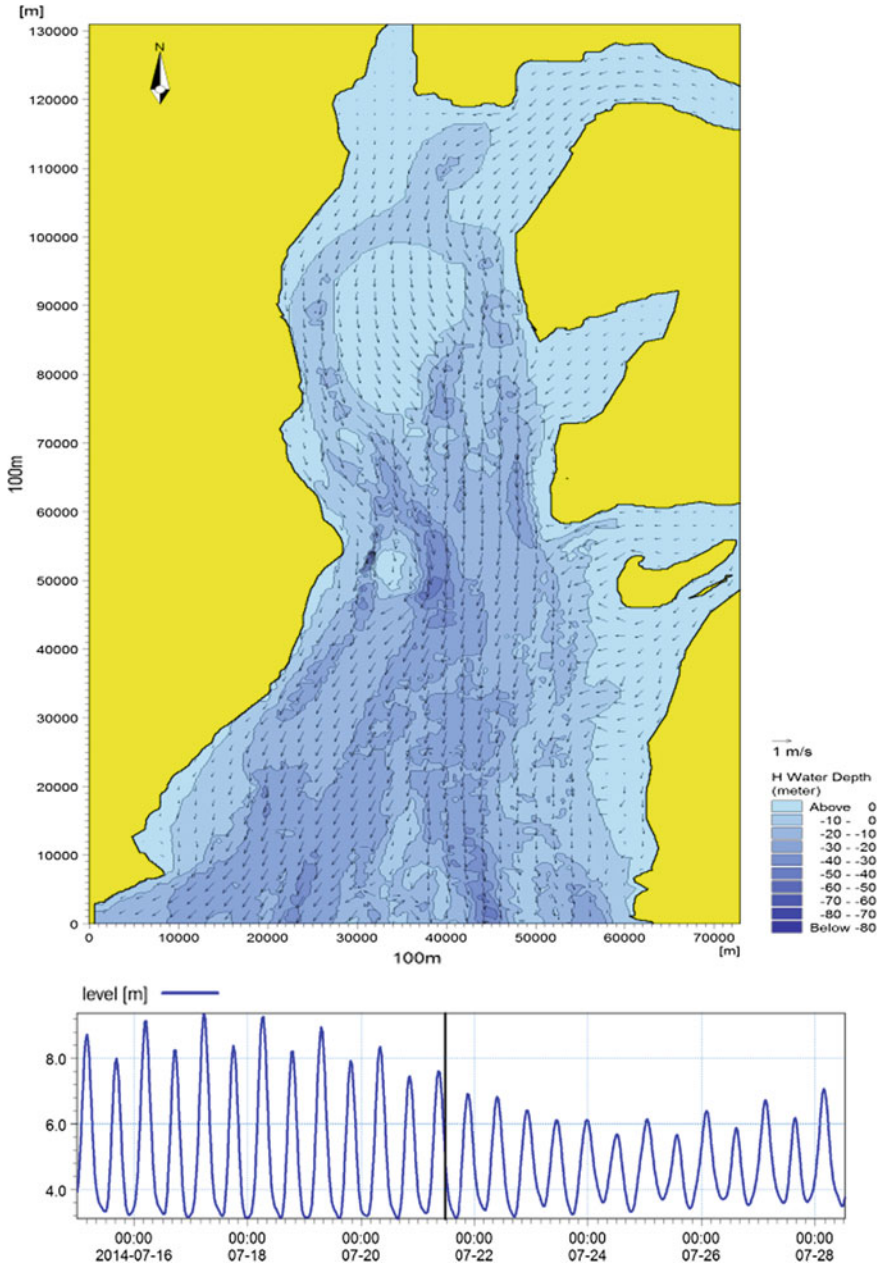**Fig. 8** Flow field during peak flood (monsoon)

Fig. 9 Flow field during peak ebb (monsoon)

maximum current speed is about 1.45 m/s in peak flood condition which is shown in Fig. 6. The flood currents are stronger than EBB, LW and HW tide condition, and in peak ebbing, the maximum current speed is about 1.5 m/s as shown in Fig. 7.

3.3   Simulation of Flow Field for Monsoon

The same model set up of that of non-monsoon was modified by increasing the fluxes at different estuary and by incorporating the tide of monsoon that is for July month. It can be observed that the maximum current speed is about 1.5 m/s during
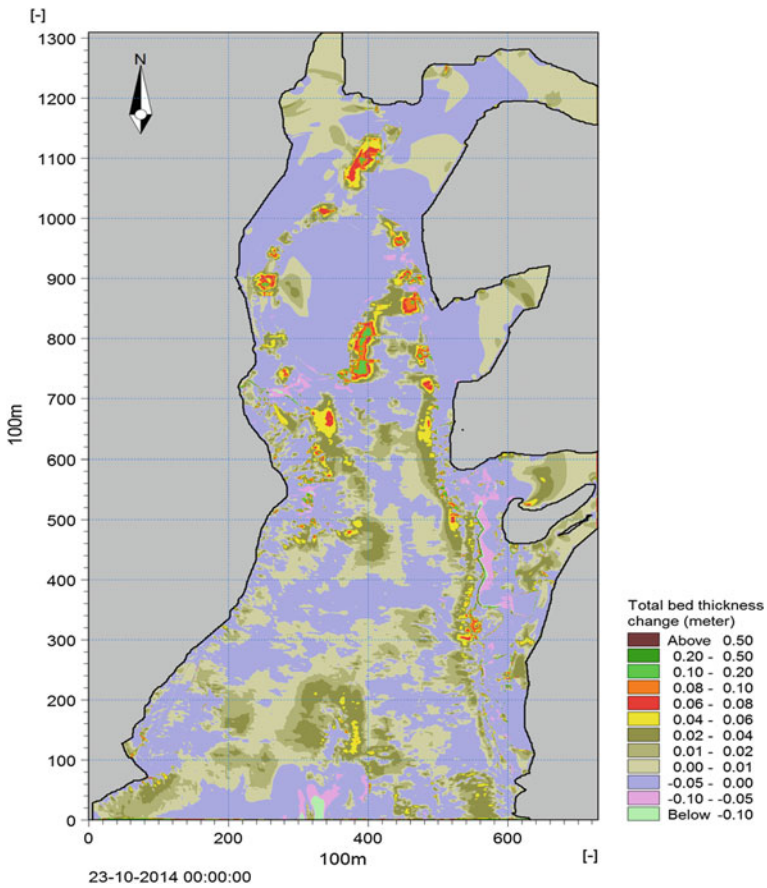

Fig. 10 Total bed thickness change (m) during non-monsoon

peak flood and the flood currents are stronger than EBB, LW and HW tide condition shown in Fig. 8. And during ebbing, it is increases up to 1.9 m/s. It is shown in Fig. 9.

3.4 Sedimentation Studies

The model was simulated for a simulation period of 15 days. The sedimentation during different phases of the tide was observed. The siltation pattern during non-monsoon is shown in Fig. 10 and SSC is shown in Fig. 11. It is found that siltation is high in the middle of gulf and there is slight erosion near the open sea and at Narmada estuary and the mud flats surrounding the mainland is prone to siltation, and during monsoon, it is found that there is slight siltation in the middle
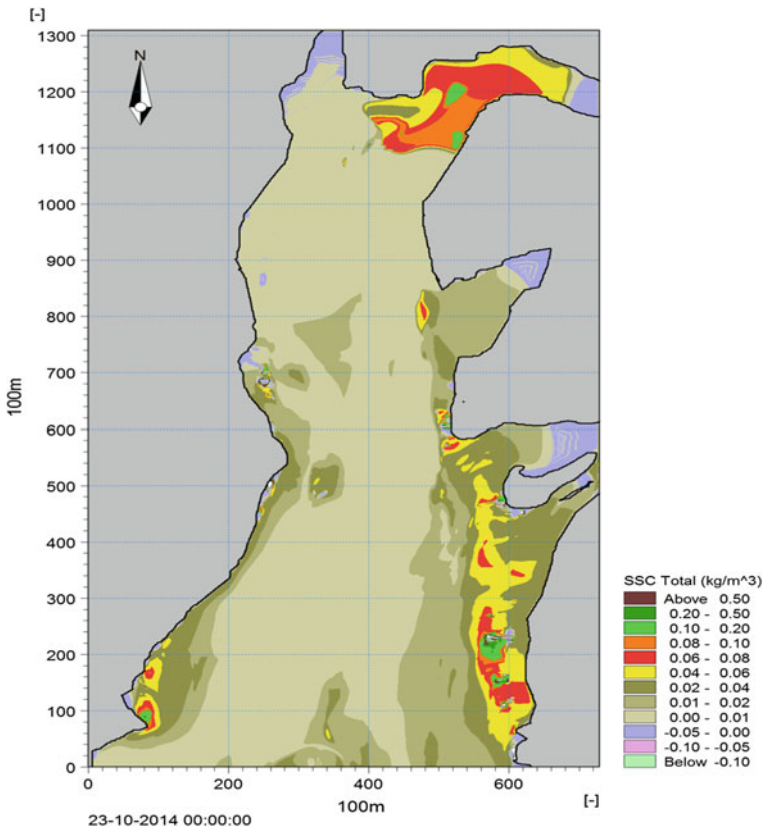

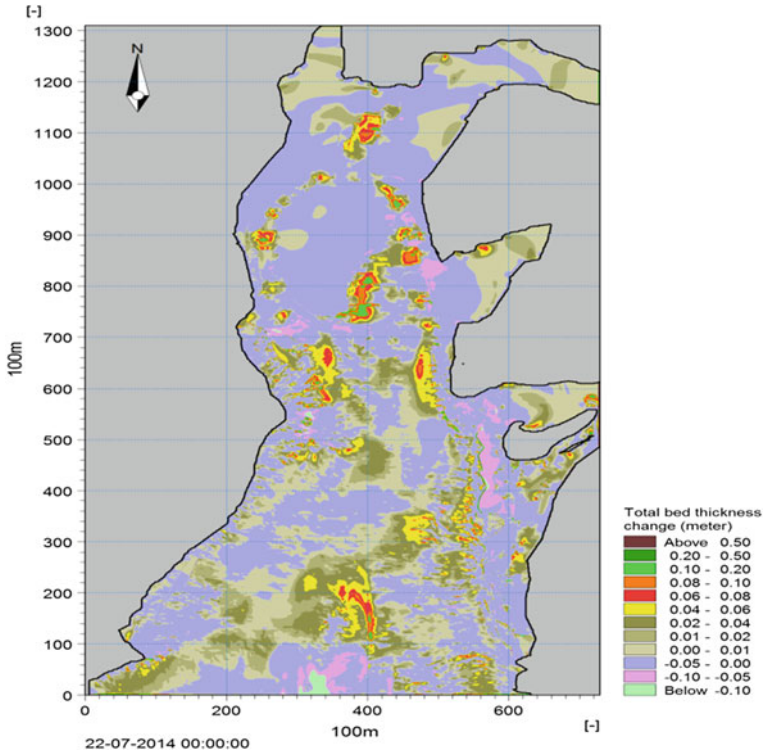**Fig. 11** Total SSC (kg/m^3) during non-monsoon

Fig. 12 Total bed thickness change (m) during monsoon

of gulf and there is slight erosion near the Narmada estuary and it is shown in Fig. 12 and SSC for monsoon is shown in Fig. 13.

4 Conclusions

An attempt to understand the hydrodynamic and sedimentation conditions prevalent in the entire gulf of Khambhat during non-monsoon and monsoon was successfully made in the present research. Two-dimensional finite difference-based mathematical models MIKE-21 HD and MIKE-21 MT were used for simulation of hydrodynamics and sedimentation in and around the area. The model was calibrated with the current data available for the location. The model showed good correlation with the observed current data. The model is considered to simulate the hydrodynamic behaviour to a good extent inside the Gulf. The important findings can be summarized as follows:
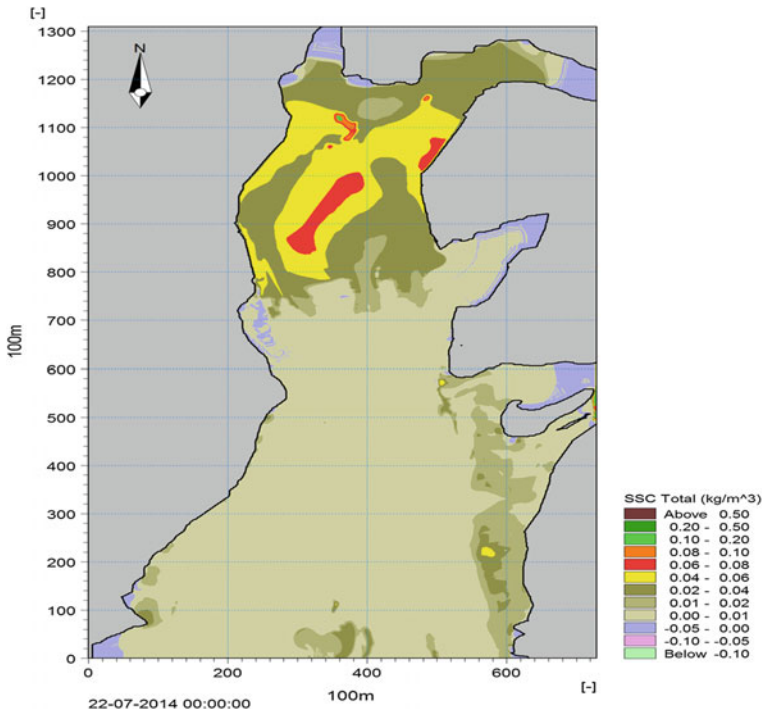
Fig. 13 Total SSC (kg/m^3) during monsoon

- Hydrodynamic simulations indicate an average current speed of 0.75 m/s inside the gulf during non-monsoon and in monsoon it is around 1 m/s and near the shore during non-monsoon it is 1.45 m/s and 1.5 m/s during monsoon.
- The gulf is found to be ebb dominated with a short falling period and a longer rising period. The currents during ebb tide are found to be stronger than during the flood tide.
- It can be concluded that during monsoon the sediment deposition at the mouth of Narmada estuary is large in comparison with non-monsoon.
- Initial hydrodynamic and sedimentation studies with the non-monsoon and monsoon indicated that flow conditions are conducive with no adverse circulations. The sedimentation studies indicated that there is a trend of siltation.
- The relation between sediment grain size and sediment transport is not linear and is interdependent on many other factors such as, bed slope and bed resistance.

4.1 Recommendation for Further Research

There is definite scope of further improvement in the model for the region. The following points should be considered for any further research to be carried out for the location:

A much better calibration could be achieved with detailed field surveys containing data regarding the surface elevation at the site, wave and wind parameters, and current speed vectors at the location of interest. A time series for a minimum of a year would improve the quality of the model predictions.

A survey showing the sediment grain size distribution at the gulf will also help in realizing a realistic bed resistance value and bottom friction parameter. Both the parameters were kept at a constant value in the model and the variations from the measured value can be attributed to this assumption.

The confidence in the results can be further improved by obtaining field data containing detailed sediment gradation and sediment diameter (D50) variation along the gulf. MIKE-21 can be utilized effectively to model the current and sediment transport occurring at the site. Further research may also include development or improvement of any existing model (CoSMOS, Telemac). This would provide a comprehensive modelling tool to understand the coastal processes active in the Arabian region.

References

1. Sinha, P.C., Jena, G.K., Jain, I., Rao, A.D., Husain, M.L.: Numerical modelling of tidal circulation and sediment transport in the Gulf of Khambhat and Narmada estuary, West Coast of India. J. Sci. Technol. **18**(2), 293–302 (2010)
2. Sen Gupta, R., Deshmukhe, G.: Coastal and Maritime Environment of Gujarat. Gujarat Ecological Society, Vadodara, India (2000)
3. Central Water & Power Research Station (CWPRS): Technical Report (2014)
4. Kumar, V.S., Kumar, K.A.: Waves and currents in tide dominated location off Dahej, Gulf of Khambhat. J. Mar. Geod. **33**, 218–231 (2010)
5. Kumar, S.S., Balaji, R.: Tidal hydrodynamics along Gulf of Khambhat, West Coast of India. International Conference on Water Resources, Coastal and Ocean Engineering. Aquat. Proc. **4**, 41–48 (2015)